ELECTROSTATICS 1979

Institute of Physics Conference Series number 48

Electrostatics 1979

Invited and contributed papers from the Fifth Conference on Electrostatic Phenomena held at St Catherine's College, Oxford, 17–20 April 1979

Edited by J Lowell

Conference Series Number 48

The Institute of Physics
Bristol and London

CODEN IPHSAC 48 1–351 (1979)

British Library Cataloguing in Publication Data

Conference on Electrostatic Phenomena, 5th, Oxford, 1979
Electrostatics 1979. – (Institute of Physics. Conference series; no. 48 ISSN 0305-2346).
1. Electrostatics – Congresses
I. Title II. Lowell, J III. Institute of Physics IV. Series
537.2 QC570

ISBN 0-85498-139-X
ISSN 0305-2346

The Fifth Conference on Electrostatic Phenomena was sponsored by the Institute of Physics Static Electrification Group.

Published by the Institute of Physics, Techno House, Redcliffe Way, Bristol BS1 6NX, and 47 Belgrave Square, London SW1X 8QX, England.

Set by Preface Ltd, 1–3 The Malverns, Cherry Orchard Lane, Salisbury SP2 7JG, and printed in Great Britain by William Clowes (Beccles) Ltd, Beccles

Preface

This volume, Electrostatics 1979, contains the papers presented at the Fifth Conference on Electrostatic Phenomena organised by the Institute of Physics. Like its predecessors, the conference attracted scientists and engineers who were not only international in origin but catholic in their interests in electrostatics. For a long while electrostatics has been a dead science; like Latin, a dead language, rigorous and logical and good for training our scientific souls but useless in the market-place of practical application. It was Stephen Leacock who, giving the layman's view of electricity, also gave the scientist's view of electrostatics when he wrote:

> 'Electricity is of two kinds, positive and negative. The difference is, I presume, that one comes a little more expensive, but is more durable; the other is a cheaper thing, but the moths get into it.'

We have, in recent years, moved a very long way from that position and have been conscious for some time of the growing importance of electrostatics in very many industrial situations. The confluence in electrostatics of ideas and developments from so many areas of science and technology is the charm, the stimulation and the vigour of the subject.

There are many examples that could be quoted, but one or two will suffice. For example, we now recognise that the serious fire and explosive hazards attending the handling of highly insulating materials, whether they be liquids, particulate clouds, granulated solids, films or fabrics, arise from frictional and contact electrification and we know in some detail how to reduce those hazards to acceptable levels. Another example has been the harnessing of not one or two but a whole set of electrostatic principles to the important techniques of powder coating and electrophotography. In natural phenomena also, electrostatics has an ever increasing role. Investigations of the morphology of thunderstorms suggests that they are essentially vertical dipoles of immense moment, charge separation being achieved by complex charge-transfer processes in streams of ice crystals.

In these and other examples we see an initial empiricism, which in the past has unfortunately persisted for too long in many cases, being replaced by precise data and scientific explanation. This comes about, not only by clever advances in measurement techniques, but also by a realisation that the fundamental concepts in many other areas of science may be taken over and applied to electrostatic phenomena. Gas discharge physics was an early example of such take-over procedures and in liquids also, fundamental knowledge of conductivity and breakdown, of boundary layer phenomena and streaming potential has been invaluable. At the moment another and perhaps the most exciting take-over is gathering momentum. The concepts of the amorphous solid state that were developed relatively recently and are still developing are already being used to explain contact electrification. There is much to be done, but already we see a most interesting turn of events, namely that contact electrification itself is capable of being developed and refined to become a valuable tool to study surface states on a wide variety of solids. Such a turn must be encouraged at all costs.

The conference, like its predecessors, by way of invited and contributed papers ranged over all these topics and this volume puts on record our progress and our problems. The success of the conference and of this volume depends, as always, on the dedication of the Organising Committee. That a meeting of such international appeal should be organised by such a small committee is a measure of their skill and enthusiasm. We owe them a great deal, as indeed we do also the staff of the Institute of Physics. Together they conspired with St Catherine's College, Oxford, to provide an ideal physical and mental haven where scientists could do what they like to do best—talk—in this case about achievements and prospects in electrostatic science.

T J Lewis

It was with deep regret that the Committee heard, soon after the Conference, of the death of Professor A W Bright. A pioneer in applied electrostatics and a past Chairman of the Institute of Physics Electrostatics Group, his engaging personality will be missed by all of us.

Contents

Session V: Measuring techniques and atmospheric electricity

The scientific basis of electrophotography

P K Watson
Xerox Corporation, Rochester, New York, USA

Abstract. Electrophotography was developed empirically but is now well understood from a scientific point of view. The sensitisation of the photoconductor – an amorphous semiconductor – involves the interaction of corona ions with surface states on the semiconductor surface. The photo-induced discharge of the photoconductor involves the photogeneration of the charge carriers and the transport of the carriers in the amorphous semiconductor. The development of the electrostatic image requires the combined effect of electrical and mechanical forces on the tribo-electrically charged mixture of toner particles and carrier beads. The scientific basis of these various steps is described.

1. Introduction

The two steps which characterise the electrophotographic process are the formation of a latent electrostatic image on a charged photoconductor and the development of that image by electrostatically charged particles (Carlson 1942, Dessauer and Clark 1965, Schaffert 1965, 1975).

The former step has been widely studied and is now well understood, whereas the development process is more difficult to characterise from a scientific point of view. Our understanding of this step therefore remains in a somewhat qualitative state.

2. Charging the photoconductor

In order to sensitise the photoconductor to light it is uniformly charged by ions from a corona discharge. The identification of the ions in the corona is clearly of vital importance if one is to understand the charging process. The analysis of the ions from corona discharges in air was first carried out by Shahin (1966, 1969). He showed, by means of a mass spectrometer, that the dominant species in a positive corona discharge in air are hydrated protons, members of the series $(H_2O)_nH^+$. The magnitude of n depends strongly on the relative humidity; for example, at atmospheric pressure and 20 per cent relative humidity the most frequently occurring ionic species correspond to $n = 6$. Figure 1 shows the relative intensities of the various ions in the positive corona discharge at levels of humidity from 1–20 per cent relative humidity.

The mass spectrometer was also used by Shahin to study negative corona discharges in air. In this case CO_3^- is the dominant ionic species at atmospheric pressure, with about 10 per cent of the ions in the hydrated form $CO_3^-(H_2O)_{1,2}$, at 50 per cent relative humidity.

0305-2346/79/0048-0001$01.00

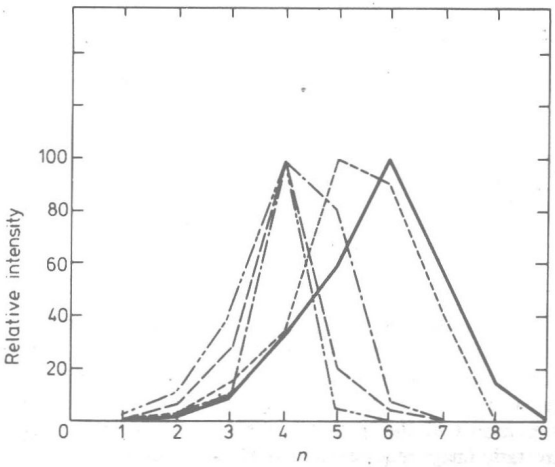

Figure 1. Relative abundance of species of hydrated protons, $(H_2O)_nH^+$, for corona discharges in air at different levels of water concentration (Shahin 1966). Water concentration (mol %): ——, $65{\cdot}0 \times 10^{-2}$; — — —, $12{\cdot}0 \times 10^{-2}$; – – –, $6{\cdot}5 \times 10^{-2}$; – – –, $4{\cdot}1 \times 10^{-2}$; – · – · –, $3{\cdot}0 \times 10^{-2}$.

This relatively weak dependence of the negative ions on humidity contrasts with the strong humidity dependence of the positive species. The precursor of CO_3^- has been shown to be CO_2 which is present in air at a level of 300 ppm. The CO_2 apparently reacts rapidly with the primary ionic species (O^- or O_3^-) to form the CO_3^- ions. Shahin has shown that only minute quantities of CO_2 are required to convert all other species to CO_3^-, and has estimated from known reaction rates that only 40 ppm of CO_2^- is needed at atmospheric pressure to allow total conversion.

Some electrophotographic processes use an AC corona. No measurements have been published on the ions from this type of discharge, but one may speculate that both hydrated protons and CO_3^- ions will be present.

The ions from the corona discharge drift in the applied field onto the photoconductor where they interact with the surface; this interaction is governed by the nature of the ions and of the surface involved. The processes involved in this step have been examined by Vance (1968). He has shown that the charge interaction phenomena are similar to those which occur when ions collide with metal surfaces (Hagstrum 1954). In the case of positive ions these processes depend on the relative magnitudes of the ion recombination energy, RE, and the effective workfunction of the surface, ϕ^*. Thus, for $RE < \phi^*$ no electrons are available in the solid with sufficient energy to neutralise the ions, which are then either held to the surface by electrostatic forces or leave the surface. If $RE > \phi^*$, ion neutralisation by electrons tunnelling from the solid is energetically possible. For metals this neutralisation process is observed to occur with nearly 100 per cent efficiency. In the case of insulators the ion neutralisation results in a trapped positive hole located in a surface state. The interaction of hydrated protons with selenium falls into this class, as shown in figure 2. Thus, as a result of the process of charging selenium with a positive corona positive holes are trapped in surface states and charge decay can only occur through electron excitation from the valence band of the photoconductor.

If these surface states are not present, then neutralisation of incident ions can result in the liberation of a free hole in the photoconductor; it is known that if a selenium surface

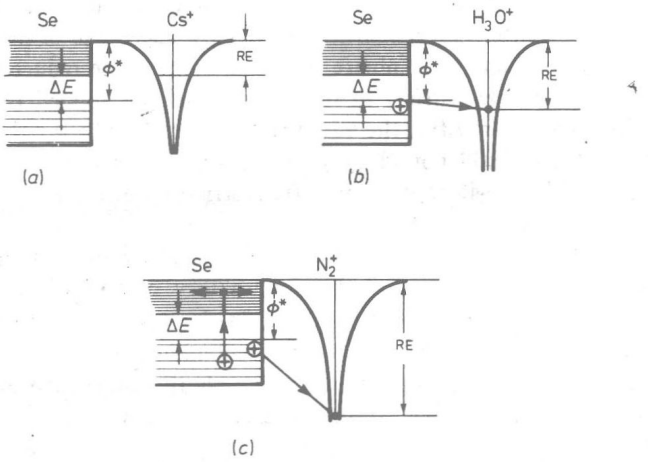

Figure 2. Energy level diagram illustrating the interaction of positive ions and electrons at the surface of selenium (Vance 1968). (*a*), No neutralisation (RE$< \phi^*$); (*b*), neutralisation, no electron excitation (ϕ^* + AE) > RE > ϕ^*; (*c*) neutralisation plus electron excitation (RE > ϕ^* + ΔE).

is quite clean and free from oxide, then high dark decay rates are observed after corona charging. To avoid this problem the photoconductor surface may be treated with an electron donor, though this may not be essential since most surfaces will have sufficient surface states through oxidation.

3. Discharge of the photoconductor

Once the photoconductor has been charged, it is exposed to light from the optical image which is to be copied. The resulting photo-induced discharge reduces the surface potential in approximate proportion to the incident light, thus producing the required electrostatic image on the photoconductor surface.

It is important to distinguish two steps in the photo-induced discharge: the photogeneration of charge carriers, and the transport of these carriers in the electrostatic field. Both of these processes are complex ones; the former has been placed on a secure footing in the past few years and rapid progress is being made in the latter area.

The process of photogeneration in the amorphous chalcogenides (of which amorphous selenium is the most studied and best understood) is characterised by a strong dependence of photogeneration efficiency on photon energy, on temperature, and on applied electric field. These characteristics are not exhibited by conventional semiconductors, but they are observed to a greater or lesser extent in a wide range of low mobility materials including the amorphous chalcogenides (Se, As_2Se_3 As_2S_3) molecular crystals such as anthracene, and organic polymers including polyvinyl carbazole (PVK) and PVK–TNF.

The process of photogeneration of charge carriers is best seen as a competition between separation of electron–hole pairs in the applied electric field and their rapid recombination. (This is referred to as geminate recombination.) A number of different models have been used to explain the details of the photogeneration process,

particularly the Poole–Frenkel model and the Onsager model of high field dissociation (Onsager 1934, 1938). The latter has proved to be the most successful of these theories. Onsager showed that the problem of geminate recombination can be reduced to that of Brownian motion of the charge carriers in the presence of the applied field and the Coulomb field of the carrier pair. After the initial step of photo-ionisation the electron–hole pair is thermalised while still bound by its mutual Coulomb field; there is then a finite probability that this pair will separate into free carriers by diffusion, subject to the combined effects of the two electric fields.

Measurements of the field and temperature dependence of carrier quantum yield for anthracene at low fields have confirmed the applicability of this theory to photoconductivity in molecular crystals (Batt *et al* 1968). In the case of selenium there are complicating factors due to the presence of surface recombination which dominates at low fields; measurements by Enck, however, using two-photon generation of carriers in the bulk of the photoconductor have confirmed that quantum efficiency tends to a constant value at low fields (figure 3) as required by the Onsager theory (Pai and Enck 1975).

Once the carriers are separated in the field the hole is free to drift through the photoconductor and the electron moves to the surface of the photoconductor where it neutralises the trapped hole left behind from the charging step.

The process by which charge is transported through the amorphous solid is itself the subject of considerable interest and some controversy. Electronic transport can be of the conventional band type, with the carriers interacting with localised trapping states, or it can consist of hopping amongst these localised states.

Two models have been developed to describe the electronic transport process in amorphous solids: a stochastic transport (hopping) model due to Scher and Montrol (1975), and a multiple trapping model due to Schmidlin (1977) and Noolandi (1977).

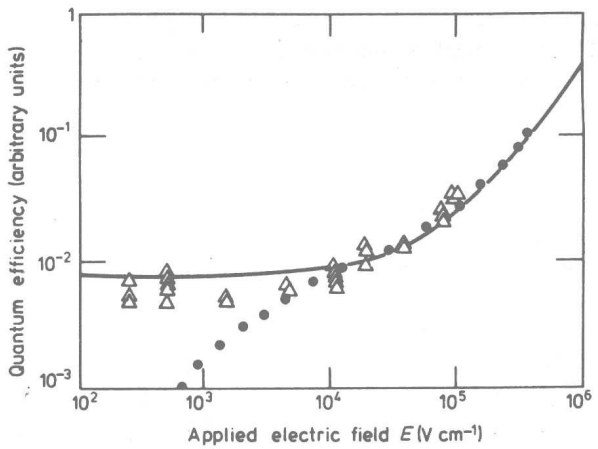

Figure 3. Quantum efficiency versus applied field for the generation of holes in amorphous selenium. Results are shown for one-photon and two-photon generation. Calculated values from the Onsager theory are shown for comparison (Pai and Enck 1975). Two-photon generation, △; one-photon generation, ●; Onsager theory, –.

Although in the limit these tend to the same result, there are considerable differences in the two approaches and these have not yet been resolved.

4. Development of the electrostatic image

The electric field above the photoconductor surface provides the link between the electrostatic latent image and the development process. The field creates the driving force for development by coupling to the charged toner particles in the developer, and it is the particular structure of this field which gives rise to one of the most characteristic features of the xerographic image.

Calculations of the electric field above the photoconductor have been made by several workers (Neugebauer 1965, Schaffert 1965, 1975, Schmidlin 1972, Kao 1973). Following Schmidlin's treatment we consider a periodic charge pattern on the photoconductor surface of the form $\sigma(x, y) = \sigma_0 + \sigma_k \cos kx$, where k is the wavenumber of the periodicity, wavelength λ, ($k = 2\pi/\lambda$). The vertical component of the electric field at a point z above the photoconductor surface is then given by

$$E(z) = \left(\frac{\epsilon_p V_b - \sigma_0 L}{\epsilon_d L + \epsilon_p d} + \frac{\sigma_k \cos kx}{\epsilon_p} f(k) \right)$$

where

$$f(k) = \frac{\cosh k(d - z)}{\cosh kd} \left(\frac{\epsilon_d}{\epsilon_p} + \frac{\tanh kd}{\tanh kL} \right)^{-1}$$

V_b is the bias potential on the electrode (see figure 4), ϵ_p and ϵ_d are the relative permittivities of the photoconductor and the developer, respectively, and L and d refer to the thickness of the photoconductor and the distance to the development electrode.

The function $f(k)$ gives the relationship between the amplitudes of the modulation of the charge pattern and the resulting field. The function is rather unwieldy but limiting cases for large and small values of k are very informative. For small values of k (i.e. large value of λ, corresponding to broad image areas) the function tends to the limit

$$[(\epsilon_d/\epsilon_p) + (d/L)]^{-1},$$

so that for a distantly spaced counter electrode, as in early xerographic machines, the function tends to a small value of the order L/d. This low value of field may not exceed the threshold for development (see below) in which case the image density tends to zero

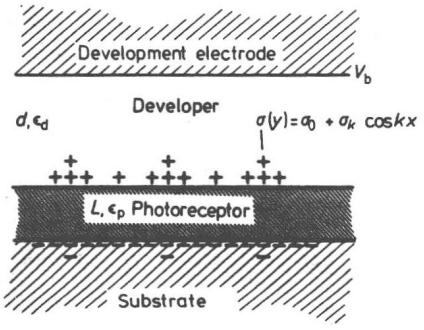

Figure 4. Dielectric slab model used in the calculation of the electric field above the photoconductor.

for broad, uniform areas. This image deficiency, so characteristic of early xerographic machines, can be corrected by controlling the ratio of electrode spacing to plate thickness.

The function $f(k)$ increases with increasing k to a maximum value in the vicinity of $kL = \pi$. This indicates that images comparable in width to twice the photoconductor thickness should develop preferentially. For large values of k (roughly corresponding to $kz > 2$) the function $f(k)$ tends to the limit $e^{-kz}\ (\epsilon_d/\epsilon_p + 1)^{-1}$. Thus, images should exhibit a high frequency fall-off which depends critically on the coupling distance z. Junginger *et al* (1978) have used an electrostatic probe to measure the electric field above charge patterns of various spatial frequencies and found excellent agreement with the theoretical result.

Witte and Szczepanik (1978) have measured the modulation transfer function (MTF) for the xerographic process. That is, they have measured the response of the process to a wide range of optical sinewave inputs. It was found that the transfer function of the system exhibited the characteristic high frequency and low frequency fall-off, with a peak response in the vicinity of 2 cycles/mm as shown in figure 5. Analysis of these results indicates that the system response corresponds closely to the calculated values of normal electric field at a height of about 20 μm above the photoconductor, suggesting that the development process (magnetic brush in this case) is dominated by events in that region.

Although this and other work demonstrate the close relationship between the electric field and the developed image, it does not tell us exactly how the development process takes place. The actual development step depends on the electric field detachment of the charged toner particles from the developer.

Xerographic developers consist of a mixture of toner particles and carrier beads, and the materials are chosen to have a strong, tribo-electric charge-exchange relationship; typically the toner particles acquire a negative charge and the carrier bead surface retains

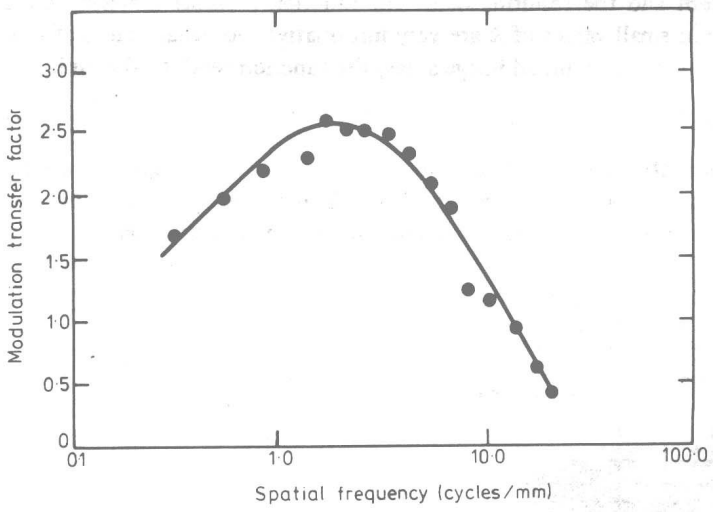

Figure 5. Modulation transfer function (MTF) for a typical xerographic system with magnetic brush development (Witte and Szczepanik 1978).

the positive countercharge. This developer mixture is transported over the photoconductor bearing the electrostatic charge pattern and some of the toner particles are detached from the carrier beads and transferred to the photoconductor surface.

An important property of the toner release mechanism can be demonstrated by the following simple experiment. A developer mixture may be dropped several millimetres onto a surface without significant release of toner particles, yet this same developer releases an appreciable amount of powder if an electric field as small as 1000 V cm^{-1} is superposed on the impact. (A field of this magnitude strips a negligible amount of toner from the carrier in the absence of mechanical agitation.)

In the practical case, an electrostatic latent image pulls quantities of powder from the xerographic developer as it flows over the photoconductor, and it has been shown that the combined effect of both electrostatic and mechanical forces is involved in the development process (Donald and Watson 1972). Thus the development of an electrostatic image involves a dynamic situation; the developer undergoes mechanical agitation, and the combined effects of the mechanical impulse and the applied electric field strip the less tightly held particles from the carrier bead surface. In effect, the field due to the electrostatic image lowers the Coulomb barrier that normally constrains the toner to the bead surface. A calculation of the potential function adjacent to the bead surface in the presence of typical electrostatic image fields shows that the Coulomb barrier is reduced by a significant amount, and that with reasonable amounts of developer agitation, sufficient mechanical energy is available for the toner to overcome the potential barrier. Thus, xerographic development may be regarded as analogous to the Poole–Frenkel effect in solid state conduction.

Hays has measured toner detachment forces by means of the experiment shown in figure 6 (Hays 1978). A carrier bead with toner particles attached is held in an electrode structure and high voltage pulses are applied to cause detachment of toner particles. The toner which is detached from the bead passes into a field-free cavity where the particle charge is measured. Knowing the charge on the toner particle and the field required to detach the toner, the force of adhesion can be calculated. This detachment field is greater than that measured in developers, and Hays concludes that some mechanical forces must be involved in toner detachment.

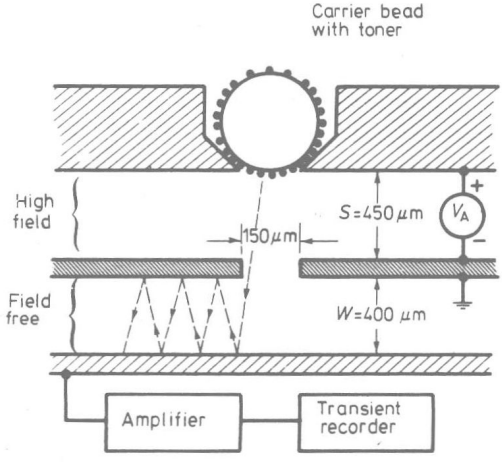

Figure 6. Experimental measurement of force of adhesion and toner charge. A toner particle is detached by the high electric field and passes into the field-free cavity where its charge is measured (Hays 1978).

In conclusion, we note that the individual steps in electrography were brought under technical control before they were understood at a scientific level. Although at first sight some of the process steps appeared to have a rather mundane quality about them, if one looked beyond the superficial aspect, the underlying mechanisms presented a series of intriguing scientific challenges. As a consequence of these scientific studies most of the process steps in xerography are now well understood and technical progress is being made as a consequence of this enhanced understanding.

References

Batt R H, Braun C L and Hornig J F 1968 *J. Chem. Phys.* **49** 1967
Carlson C F 1942 *Electrophotography U S Patent No.* 2297691
Dessauer J and Clark H 1965 *Electrophotography and Related Processes* (London: Focal Press)
Donald D K and Watson P K 1972 *IEEE Trans. Electron Devices* **19** 458
Hagstrum H D 1954 *Phys. Rev.* **96** 336
Hays D A 1978 *Photo. Sci. Eng.* **22** 232
Junginger H G, Schmidt R F and Strunk R 1978 *Photo. Sci. Eng.* **22** 213
Kao C C 1973 *J. Appl. Phys.* **44** 1543
Mort J and Pai D M (ed) 1976 *Photoconductivity and Related Phenomena* (Amsterdam: Elsevier)
Neugebauer H E J 1965 *Appl. Opt.* **4** 453
Noolandi J 1977 *Phys. Rev.* **B16** 4466, 4474
Onsager L 1934 *J. Chem. Phys.* **2** 599
—— 1938 *Phys. Rev.* **54** 554
Pai D M and Enck R C 1975 *Phys. Rev.* **B11** 5163
Schaffert R M 1965 *Electrophotography* (London: Focal Press)
—— 1975 *Electrophotography* (London: Focal Press) revised edition
Scher H and Montroll E W 1975 *Phys. Rev.* **B12** 2455
Schmidlin F W 1972 *IEEE Trans. Electron Devices* **19** 448
—— 1977 *Phys. Rev.* **B16** 2362
Shahin M M 1966 *J. Chem. Phys.* **45** 2600
—— 1969 *Appl. Opt. Suppl. No. 3, Electrophotography*
Vance D W 1968 *Phys. Rev.* **169** 252
Witte J C and Szczepanik J F 1978 *J. Appl. Photo. Eng.* **2** 52

Lateral propagation of back-discharge in a tri-electrode system

S Masuda, S Obata† and Y Ogura‡
Department of Electrical Engineering, Faculty of Engineering, University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo, Japan 113

Abstract. In a tri-electrode system which has a DC main field, a corona ion source and is covered with high resistivity deposit layers, back-discharge, once it has occurred in a space-streamer-mode in front of the corona ion source, tends to propagate in the lateral direction throughout the entire gap of the main field, and causes serious troubles. The secondary back-discharge as a consequence of this propagation becomes self-sustaining if well developed, and does not disappear unless the main field strength is lowered. The initiation and extinguishing of this propagation are governed, apart from by the resistivity of the layers, primarily by the magnitudes of the main field strength and corona current. The threshold value of the main field strength for initiation of propagation is about 5 kV cm^{-1} in atmospheric conditions, nearly coincident with the threshold of streamer propagation. Its extinguishing threshold is slightly lower than that for initiation. Use of pulse corona can decelerate the occurrence of the propagation to a great extent. The problems caused by this propagation phenomenon can be avoided by keeping the main field strength below the extinguishing threshold, and also by using the pulse corona.

1. Introduction

One of the authors observed a curious propagation of back-discharge in a powder coating experiment using a tribo-gun and a parallel plate electrode system as illustrated in figure 1(*a*) (Masuda *et al* 1977b). After several tens of seconds of powder feed back-discharge occurred, without the aid of corona current, in the region A, which, then, caused the secondary back-discharge in the opposite region B through negative ions supplied from A. This in turn caused the tertiary back-discharge at C. Thus, back-discharge propagated in the lateral direction to the entire surfaces of power deposits on both electrodes. This strange phenomenon occurred again in the experiments by the authors on an electrostatic precipitator of tri-electrode type as illustrated in figure 1(*b*). The detailed explanation and inherent merits of this precipitator, including suppression of back-discharge, have been reported separately (Masuda *et al* 1976, Masuda *et al* 1977a, Masuda 1978). After the electrodes had been covered with high resistivity dust deposit, back-discharge occurred at first at the region A in front of the discharge electrode. This propagated under suitable conditions to the entire surfaces of the counter and third electrodes to cause a serious problem. In this paper are reported the results of preliminary investigations made to clarify this phenomenon.

†Research Center, IHI Heavy Industries Ltd, 3-2-16, Toyosu, Koto-ku, Tokyo, Japan 135.
‡Kyushu Electric Power Co., Ltd, 2-1-82, Watanabedori, Chuo-ku, Fukuoka-shi.

0305-2346/79/0048-0009$01.00