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Electrical characteristics of contaminated corona systems

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ABSTRACT

The electrical performance of a point-to-plane corona system with electrodes coated by porous insulating materials is investigated and interpreted.

The point-to-plane configuration (0.9 mm dia point, 40 mm gap, applied DC voltages up to 30 kV) has been chosen as representative for asymmetrical corona systems, including those used in electrostatic precipitators, and because it provides more information on basic processes than other geometrical configurations. The electrode coating, described as contamination, simulates operating conditions in electrostatic precipitators. Fly-ash and experimentally more suitable substitutes, paper and Millipore filters, are used as contaminators.

The presented results of comparative measurements of the average current-voltage characteristics, current waveforms, and contaminator surface potentials provide experimental data on the correlation between the clean-system, contaminator, and contaminated-system characteristics, for positive and negative coronas, in the temperature range 25 to 90° C and relative humidity range 10 to 90%. The effects of unilateral and bilateral contamination are compared.

In interpreting the specific experimental results, an attempt has been made to formulate the electrical characteristics in terms of more generally applicable lumped parameters.

The current-conduction mechanisms in the clean system, regarded as a fundamental mode of operation, are analysed and semi-quantitatively characterized by three suitably defined lumped elements representing
processes in the ionization, buffer, and transport regions of the air gap. The plate-current waveform is formulated as a composition of the space-charge-limited drift current of ions and, in appropriate corona regimes, the displacement current due to the pulsed generation of current carriers in the ionization region.

A model representing common properties of contaminators is used for an interpretation of their non-linear current-voltage characteristics. The operating conditions for a plate contaminator, characterized by one non-equipotential surface and non-uniform current injection, are analysed by means of a lumped-element circuit model.

In the contaminated system, two modes of operation are distinguished: non-interacting and interacting, with subdivisions according to the occurrence of distinctly different corona regimes. The interacting mode is characterized by the bilateral ionization processes, space-charge neutralization, localized current flow and relatively low sparkover voltage. Conditions for the onset of ionization at the plate (back corona) are formulated. The models for the clean system and contaminator are combined to describe the contaminated-system performance. The lumped-parameter concepts are implemented in the design of an electronic (solid-state) analog to simulate the performance of contaminated corona systems.
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March, 1970.
ELECTRICAL CHARACTERISTICS OF CONTAMINATED CORONA SYSTEMS

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1.0 INTRODUCTION

The corona discharge in electrical devices and networks is mostly an undesired phenomenon causing the loss in power, insulator deterioration and noise. Devices utilizing electrical coronas are few. However, in air-pollution control there is a prominent industrial application of coronas in the gas cleaning equipment using "electrostatic" precipitation.

The electrostatic precipitator is essentially an asymmetrical, unipolar corona-discharge system. Ions generated by the unipolar corona charge the dust particles suspended in gas stream. The charged particles are separated from gas by electrostatic forces. This is the principal and desired mode of operation.

The electrical characteristics and basic physical mechanisms in corona systems have been investigated and interpreted mainly for clean, dust-free conditions. Electrical design parameters for electrostatic precipitators are determined from known dust-free characteristics with empirical precautions, because the electrode contamination by dust is an inherent operating condition for precipitators. Moreover, the deposited dust can affect the electrical characteristics and performance of a precipitator to the extent that the precipitator will operate only as a settling chamber. Although the associated phenomena are known, the state-of-the-art in interpreting them has been indicated by Rose and Wood in their book on electrostatic precipitation (1966) [1] by the conclusion that "much more investigation is required before any possible explanation of these phenomena can be finally dismissed". This also
defined the scope for the work presented here.

In this study an attempt has been made to correlate the current-conduction mechanisms for the air gap and contaminator in forming the composite, contaminated-system characteristics, as formulated in chapter 2. To determine the modes of operation for a contaminated system, comparative measurements have been done by the author on a basic point-to-plane system in air, with facilities for varying the ambient conditions and simulating the electrode contamination in electrostatic precipitators. The experimental techniques and procedures are described in chapter 3. The experimental results, systematized according to the electrode contamination (i.e. for the clean, unilaterally and bilaterally contaminated systems), are presented and discussed in chapter 4, with the conclusions summarized in section 4.3. In interpreting the results (chapter 5), a parametric formulation of characteristics is proposed for a generalized approach. The clean-system, contaminater, and contaminated-system characteristics are analysed in sections 5.1, 5.2, and 5.3 respectively. The conclusions on analytical results are embodied in respective sections, and the most significant aspects of bilateral contamination are extrapolated to electrostatic precipitators in section 5.3.5. To illustrate the lumped-parameter model for a contaminated corona system, an analog using solid-state circuitry has been also designed (chapter 6).
2.0 PROBLEM FORMULATION

2.1 DEFINITION OF CONTAMINATION

Generally, the presence of solids in the air gap between the electrodes of a corona system is regarded as contamination. To study its effects on electrical characteristics of a corona system, it is necessary to specify the location, geometrical configuration and electrical properties of the contaminator.

In electrostatic precipitators, the contamination by dust can be systematized according to the dust location, with respective characteristic formation densities, i.e.,

(a) The dust particles suspended in gas;
(b) The deposited dust coating the collecting, low-stress electrode; and
(c) The deposited dust coating the discharge, high-stress electrode.

This systematization is adopted both for the experimental investigation and interpretation of contaminated-system characteristics. The significance of contamination in different locations is assessed in the following survey of already available information, and the objectives of this study are formulated subsequently.

2.2 KNOWN EFFECTS OF CONTAMINATION

The behaviour of corona-discharge systems with clean, relatively dust-free electrodes has been investigated for various geometrical configurations and ambient conditions. A comprehensive survey of
research in basic processes has been presented by L.B. Loeb in his book on electrical coronas [2], but research in contaminated systems, as defined here, has not been included in Loeb's survey.

(a) Airborne particles

The electric charge carried by airborne dust particles increases the density of space charge formed by ions, resulting in a decrease of corona current. For normal operation of an electrostatic precipitator, which includes an adequate charging of dust particles, it is required that the ion concentration by far exceeds the dust concentration. This requirement is easily met with dust burdens normally found in industrial effluent gases. Under such conditions, even with relatively low drift velocities of dust particles, the increase in space-charge density is not significant. P. Cooperman [3] has analysed the effect of particle space charge. He has expressed the effect as an apparent increase in the corona onset voltage. Consequently, as the effective enhancement of space-charge density does not change the basic discharge and transport mechanisms, and if quantitatively small, as in normal operating conditions, it is of little significance for precipitator operation.

(b) Coating of the low-stress electrode

The electrostatic precipitator as an applied corona-discharge system has been treated in monographs written by H.J. White [4]
and H. E. Rose and A. J. Wood [1]. They have described the effects, detrimental to the precipitator operation, of a phenomenon known as "back corona". Back corona is a local discharge from a low-stress, collecting electrode when the electrode is covered with a porous insulating material. Resistivity of the material in excess of $10^{10}$ ohm-cm certainly contributes to this effect. The most conspicuous resultant changes in the voltage-current characteristics are (i) increase in corona current and (ii) reduction in sparkover voltage. The sparkover and pulses preceding sparkover under such conditions were studied by G. W. Penney and S. E. Craig [5][6][7]. They use the term "flare" for a discharge of the same type, characteristically shaped, appearing on the contaminated anode irrespectively whether the anode is electrically highly stressed or not. Their results show that the contamination of the anode is of primary importance, and this is consistent with the concept of a breakdown streamer being formed at the anode.

To summarize, the basic conditions for the formation of back corona are known to be the high resistivity coating and presence of pores. The mechanism producing back corona and the correlation between resistivity, porosity and thickness of the coating have yet to be found.
(c) Coating of the high-stress electrode

The importance of discharge-electrode contamination has been emphasized by H. J. Lowe, J. Damon and E. T. Hignett [8]. They have observed difficulties in the precipitation of high-resistivity dusts, associated with reduced corona current. Experiments showed that the corona current was reduced mainly due to the discharge-electrode contamination. Their interpretation is based on the IR voltage drop across the dust layer. This voltage drop was calculated by the same method for layers of dust covering the collecting and discharge electrode respectively, without offering a justification for the assumption that the ionization process and its uniformity are not affected by the dust layer covering the discharge electrode. This also implies the same current-conduction mechanism and boundary conditions for layers in both positions. As a result, the calculated voltage drop is most significant for the layer adhering to the discharge electrode, where the current density is maximum.

2.3 OBJECTIVES AND APPROACH CONCEPTS

The primary objective of this work is to gain better insight into mechanisms and conditions causing undesirable (for engineering purposes) characteristics of contaminated corona systems. An obvious conclusion from the background survey in section 2.2 is that the contamination by porous, high-resistivity layers covering one or both electrodes should be considered as significant. However, it is not against the
experimental evidence to assume that the same mechanism producing a localized ionization in the low-field region (i.e. back corona) can also restrict the discharge at an already highly stressed electrode. Using this extrapolation as a reasonable hypothesis, a corona system with the contaminated low-stress electrode is regarded as typical for the problem, without ignoring a possibility that the discharge-electrode contamination might affect the corona process by producing a different discharge mode.

Between the electrodes of such typical systems there are two obvious physical media: the air in the gap and the porous insulating layer.

It is suitable to approach investigation of the system characteristics by considering the current-conduction mechanisms for the two media separately.

In the air gap of a highly asymmetrical corona system there are two distinct regions:

(i) the ionization region at the discharge, high-field electrode, where the charge carriers of both polarities are generated, but only ions of one polarity (the discharge-electrode polarity) are transferred into

(ii) the transport region, which is the passive, low-field region of the air gap extending to the surface of an insulating layer covering the low-stress electrode, or to the electrode itself if not contaminated.

The boundary conditions for contaminating layers covering the discharge and collecting electrodes respectively will be different and
determined by the current-conduction mechanisms in adjacent regions of
the air gap.

For the porous insulating layers there are two basic mechanisms
that should be taken into account:

(a) conduction in solid, regarded as an insulator with structural
irregularities resulting in nonlinear current-voltage
characteristics; and

(b) possible ionization in pores or voids providing an
alternative current path under breakdown conditions, but
this gaseous process is not likely to remain independent
of the current-conduction mechanism in the air gap.

The composite characteristics of a system comprising the two media
will depend on the simultaneous occurrence, or mutual coupling of
respective conduction mechanisms. It is convenient to assume two
principal modes: non-interacting and interacting. The onset of
back corona would mark a transition between the two modes.

(1) Non-interacting mode

For a typical system, with low-stress electrode contamination, in
the non-interacting mode, the air gap and insulating layer can be
regarded as two non-linear elements electrically connected in series.
An operating point is established without mutual interaction in the
respective conduction mechanisms. Boundary conditions for the air gap
are the same as for a clean system, i.e. a highly stressed discharge
electrode on one side, and a sink on the other low-field side. For an
insulating layer considerably thicker than the average size of pores, it can be assumed that the current is conducted through solid and that the penetration depth of arriving ions is negligible. Particular conditions apply for the boundaries of that layer. Contact with the metal (low-stress electrode) is presumably ohmic, but the boundary with air is equivalent to a rectifying contact, because charge carriers of only one polarity are injected. This single-carrier injection is determined by the ion distribution in the air gap. In a typical negative-corona system, for example, the positive carriers exist only in the high-field region very close to the active electrode, within about 1% of the air-gap width [9]. Consequently it must be assumed that the conditions for the onset of back corona are created within the porous insulating layer, because corona in the low-field region of the air gap without contamination does not occur in highly asymmetrical systems.

(2) Interacting mode

It is conceivable that the transition to the interacting mode is initiated by ionization in pores or voids close to the metal electrode, where the highest field strength can be anticipated if the carriers injected into the insulator form a space charge rather than a surface charge solely on the boundary with air. If such ionization remains within the layer, corresponding to a partial breakdown of the layer, it will be only an intermittent process limited by a relatively slow recovery of the voltage across the ionization path [10][11].

To develop into the steady, visible back corona it is necessary for the ionization in pores to reach the surface and become sustained by
the ion current directly. For the layer, this condition can be described as a current-limited breakdown. In terms of current conduction in the system, the back-corona ionization creates a minimum-energy path through the insulating layer, channelling a significant proportion of the total current. This non-homogeneous current distribution must be associated with a change in the electric field configuration, which was relatively uniform and normal to the layer surface before the onset of back corona. Such field distortion in the vicinity of flares was measured by Penney and Craig [5] as a radial potential gradient on the layer surface, but regarded more as a likely cause rather than a consequence of back corona.

Those processes determining the behaviour of the two media in the non-interacting mode are fundamentally changed when the interaction sets in. Current in the insulating layer flows mainly through the back-corona channels and only indirectly depends on solid. The conditions in the air gap are changed from uni-polar to ambi-polar ionization. In the interacting mode, the asymmetrical contaminated corona system can be perhaps compared with a more symmetrical clean system having high-field regions at both electrodes.

The concepts described in this section, although based on information from publications, require sufficient experimental evidence to support or disprove them. This thesis attempts to provide such evidence.
2.4 PARAMETERS AND MEASUREMENTS

The approach concepts have been implemented in devising an experimental program, based on comparative measurements of corona characteristics under clean and contaminated conditions, and aiming

(a) to determine quantitatively the influence of contaminator parameters, specifically its thickness, porosity and resistivity; and

(b) to identify processes in contaminated corona systems.

Resistivity of an insulator is a function of temperature and humidity, but these same ambient conditions influence also the corona discharge. To isolate the effects produced by the contaminating layer only, the changes in corona characteristics are considered as most indicative. This necessitates comparative measurements of electrical characteristics for the clean system, contaminator and composite (contaminated) system respectively, all under identical ambient conditions.

In specifying the gaseous environment for experiments, the air at normal pressure is taken as a first-order approximation (for pressure and composition) of industrial effluent gases, with temperature and humidity as the most significant variables.

The terminal voltage and current characteristics are regarded as representative manifestations of conduction processes for the two media (the air gap and porous insulator), consistently with the author's circuit-element concept. Electrical properties of individual elements
can be described in terms of lumped or distributed parameters, depending on the purpose of a particular circuit model.

Terminal characteristics that can be conveniently measured are:

(i) The average (DC) voltage-current relationship for the clean and contaminated system respectively, using positive and negative corona alternatively.

(ii) The average (DC) current-voltage characteristics for a particular contaminating layer, measured in parallel-plate configuration, by attaching metal electrodes to both surfaces of the layer, which is a standard method for defining the conduction properties of an insulator.

(iii) The surface potential, or voltage across the layer in the corona system with the layer covering one of the electrodes, typically the low-stress electrode. The layer surface facing the air gap is analogous to the junction between components in a circuit model, provided that the surface is either an actual equipotential (as in a coaxial cylindrical system) or a suitably defined effective equipotential area (as for a point-to-plane system).

(iv) The current waveforms for negative corona, with characteristic Trichel pulses [2] providing useful information on the ionization process and transport of ions, and for positive corona, to distinguish its steady, continuous-discharge regime from pulsed regimes, such as burst and streamer.
The system geometry becomes important if the Trichel pulses are to be measured. In systems with long discharge electrodes (e.g. a wire), negative-corona discharge occurs only at discrete points, with manifestations of discontinuity both in visual appearance and in current distribution as far as the collecting electrode \([12]\). As there is no synchronization between pulsating ionization processes at individual spots, it would be necessary to have a measuring arrangement capable of detecting currents produced by individual discharge spots, which tend to wander along the wire.

The point-to-plane geometry is inherently suitable for observations of one negative-corona spot only. To take the advantage of additional information contained in the current waveform, the point-to-plane geometry has been selected for experimental work. This geometry, in terms of ionization process, is seen as a building block for more complex systems like wire-between-planes or coaxial geometry. As such, the point-to-plane configuration is representative for asymmetrical corona systems, and provides more information on basic processes than other geometrical configurations.

The circuit-model concept is applied in formulating what electrical measurements are necessary, if not sufficient, to provide conclusive experimental data. A typical experiment is to be conducted at constant temperature and humidity, using a particular electrode configuration and contaminator material, including its thickness and porosity. The following quantities are to be measured:
(1) the clean-system DC voltage-current characteristics, both for positive and negative corona;

(2) the clean-system current-pulse waveform and repetition frequency as a function of applied voltage;

(3) the contaminated-system DC voltage-current characteristics, for positive and negative corona;

(4) the DC voltage across the contaminating layer (i.e. its surface potential), for positive and negative corona, and preferably measured simultaneously with (3);

(5) the current-pulse waveform and repetition frequency in the contaminated system, and

(6) the DC voltage-current characteristics of the contaminating layer in parallel-plate configuration, including breakdown strength.

These measurements, designed to provide experimental data on terminal characteristics are adequate for lumped-parameter interpretation. To obtain some information on field-pattern changes in the contaminated system, it is desirable to elaborate the basic terminal measurements by including the radial and axial potential distribution for the insulating layer, and also a provision for current density measurements.
3.0 EXPERIMENTAL TECHNIQUES

3.1 LABORATORY MODEL

In designing the experimental set-up, the basic idea was to simulate conditions relevant for electrical characteristics in electrostatic precipitators, rather than reproducing the operating conditions in a scaled-down plant. This approach has been chosen not as a second-best method, just because a scaled-down model was impracticable to build and a full-scale precipitator was inaccessible for measurements. Simulation is considered by the author to be a superior method for experimentation in basic electrical characteristics.

In an operating electrostatic precipitator it is not feasible to perform comparative measurement of clean and contaminated characteristics, determine the thickness and surface potential of the precipitate, measure current waveform and its distribution. Layers of deposited dust often evade geometrical definition because of their mechanical instability. For instance, the appearance of back corona in dust layers is associated with the formation of craters and removal of dust. Then it becomes difficult, if not impossible, to define the contaminator geometry. To enable observations and measurements of basic corona characteristics, it is appropriate to select an electrode configuration unlike that in precipitators and an insulating material which is not identical with the mechanically unstable precipitate.

A point-to-plane geometry offers the best resolution in observations of current-conduction mechanisms. Also, an insulating porous material of higher cohesion than deposited dust (paper, for example) is more
suitable for measurements with back corona. It should be emphasized that the author's justification for using the point-to-plane geometry and paper to simulate an operating precipitator is in the specialized purpose, to study the basic electrical effects of contamination. For other aspects of precipitator operation this would be only a poor or completely inadequate model.

(1) Corona jig

The availability of laboratory equipment influenced the size of the experimental point-to-plane system. An apparatus was desired, suitable for quick modification of electrode geometry, providing connections necessary for the measurements outlined in section 2.4, and fitting into a laboratory environmental chamber.

The corona jig, shown in figure 3.1, has been designed to satisfy these requirements. It consists essentially of a supporting frame and interchangeable corona-system electrodes. The frame comprises base 1, with vertical and horizontal stand rods 2 and 3.

The plate electrode 8 is mounted on four teflon stand-off insulators. Being insulated from the base (and ground) it enables current measurements with grounded (i.e., single-ended input) instruments. The central disc, or probe of 2 cm$^2$ is insulated from the plate and intended for the current-density measurement in the central region. The area of 2 cm$^2$ has been selected as a compromise between opposing requirements for a probe small enough to have current uniformly distributed over its surface, and also producing sufficiently large signal for the current-waveform measurements, when only a 100-ohm shunt
is used to reduce the time constant of the measuring circuit to less than $10^{-8}$ sec. The DC measurements of the collector-plate current distribution for various discharge electrodes carried out by O. J. Tassicker [13] show, for a clean point-to-plane configuration with a 40 mm gap and 1 mm diameter point, that the current density does not vary more than 10% in the central region of 8 mm radius. In these measurements, the average-current distribution was determined with a probe of only 1 mm$^2$, which is unsuitable for oscillographic observations. Specifically for this project, the area with a relatively constant current density is desired to be also large enough for representative sampling of the contaminating layer. Under corona conditions, the current-voltage relationship for an insulating layer covering the plate electrode is determined by measuring its surface potential and the probe (central disc) current. This relationship is to be compared with the results obtained when the layer is placed between parallel-plate electrodes. Considering a possible inhomogeneity of the porous layer, an area of 2 cm$^2$ is regarded as a reasonable minimum sample to determine the representative, average characteristics for the whole layer.

The point electrode 10, a hemispherically capped platinum wire of 0.9 mm diameter and a nominal distance between electrodes of 40 mm have been selected following the recommendations by Loeb, Parker, Dodd and English [14]. For standardization of data (originally in breakdown studies of clean systems) they have suggested using either a point radius of 0.25 mm and a gap width of 4-cm, or a 0.5 mm radius with an 8-cm gap. In this project, preference is given generally to
smaller dimensions, in order to obtain higher currents with an available 30-kV power supply, and also to ensure that the walls of the environmental chamber (working volume 50 cm x 50 cm x 55 cm) and the support rods do not influence appreciably the electric field between the electrodes. Furthermore, the length of the point electrode has to be at least of the same magnitude as the gap width. However, a point radius of 0.45 mm has been actually used instead of the recommended 0.25 mm (with a 40 mm gap). This modification was made after preliminary experiments with points of different sizes, shapes and materials. Needle-shaped electrodes (steel and platinum) with a tip radius of up to 0.1 mm were found unsuitable for prolonged experiments at currents and voltages well above the corona onset level, approaching breakdown. Operating under such conditions, the needle-electrode tips virtually disappear within a few minutes. The metal is removed by sputtering. The effect of sputtering is proportional to the corona current, which can easily rise by an order of magnitude if back ionization occurs at the contaminated plate. Such gradually changing geometry produces particularly significant changes in the Trichel-pulse amplitude and repetition rate. With a larger point, the amplitude of Trichel-pulses increases - making oscillographic observations easier, and also the corona discharge is not concentrated on one single spot all the time, conveniently spreading the sputtering damage over the larger tip area. Therefore, to optimize the performance of the electrode system for relatively lengthy measurements comparing the clean and contaminated-system characteristics, a point radius of 0.45 mm was selected instead
of 0.25 mm, which reduces the field strength and current for clean conditions, but has the advantages of

(a) geometrical stability of the point, essential for reproducible results in measurements requiring hours of operation without changing or polishing the electrodes, and

(b) uniform (within 10%) current distribution at the plate electrode, over an area of 2 cm$^2$, which was previously chosen as the minimum for representative sampling of the contaminating layer.

A symmetrical support arrangement for the discharge electrode, although not indicated for the point electrode, was provided to make the jig suitable for other applications, particularly for the wire-to-plane and wire-between-planes configurations.

The teflon frame 11 around the plate electrode is to confine and/or flatten the contaminating layer when applied.

(2) **Contaminator materials**

It would be highly desirable to use a typical precipitate, like fly-ash from an electrostatic precipitator, to study the electrical effects of contaminated electrodes, because of its technical relevance. However, the difficulties in applying layers of fly-ash of uniform thickness and compactness, in attaching a surface-potential probe, and mechanical instability under corona conditions make the results of experiments with fly-ash and similar dust rather obscure and ambiguous. Nevertheless, a certain number of experiments with fly-ash (obtained
from the Tallawarra power station) was necessary to demonstrate that the basic phenomena and characteristics with fly-ash are the same as with the other materials chosen as more suitable for observation of these phenomena.

For systematic experimental observations, alternative materials have been selected, having at least some if not all of the following properties:

(a) resistivity high enough for back-corona conditions,
(b) resistivity varying with temperature, humidity and applied electric field in a similar manner as the resistivity of fly-ash,
(c) coherent form, preferably sheets of uniform thickness and density,
(d) well defined porosity of similar magnitude as the average porosity of compacted dust (or fly-ash) layers, and
(e) readily available at reasonable cost.

An ideal material, incorporating all these properties has not been found.

The overall most convenient material is paper. In preliminary experiments, various grades of paper have been tested and finally a cheap, plain writing paper, available in scribbling blocks, was selected for systematic measurements. This paper (manufacturer's designation Forme 16, 500 Run) has a thickness of about 70 \( \mu \)m. Its relatively smooth surface (in comparison with blotting paper, towel paper, Kleenex etc.) allows stacking, to vary the total contaminating thickness,
without producing unduly large discontinuities at the interfaces. The basic fibrous structure of paper is similarly inhomogeneous as in a layer of dust, and the non-linear resistivities of paper and dust are influenced by moisture in a similar manner. Both with fly-ash and paper as contaminators it is possible to produce the non-interacting and interacting mode conditions by varying the relative humidity only (at least for temperatures up to 100°C). An inconvenient effect is wrinkling of paper at high humidities. Another deficiency is a poorly defined porosity, although it has been found in subsequent experiments that back corona carves passages larger than the original pores in all materials used, indicating only a limited significance of the original pore size and distribution.

However, to investigate the effects of porosity in detail, a material with more precisely defined porosity than paper is desired. The Millipore filters satisfy this requirement. The following types of these filters have been used:

(a) two MF (mixed esters of cellulose) types with the mean pore size of 3.0 μm and 8.0 μm, and the pore rise variation of ± 0.9 μm and ± 1.4 μm respectively;

(b) two Mitex (Teflon) types with corresponding figures of 5.0 ± 1.5 μm and 10 ± 2 μm, respectively.

The availability and cost of Millipore filters determined utilization of standard 142 mm discs. The size of these discs allows only partial coverage of the plate electrode (200x200 mm). The remaining part of the plate was covered (with a 5 mm overlap) by a
rubber mask of 1 mm thickness. This was necessary in order to prevent the corona current from being diverted to an uncovered part of the plate, due to the field distortion produced by a charged disc. In experiments with Millipore filters and fly-ash, the rubber mask was regarded as an integral part of the clean system, i.e. the clean-system characteristics were measured with the mask in position. Within the experimental range of temperature and humidity, the mechanical and electrical properties of these filters are relatively insensitive to ambient conditions, maintaining the resistivity unconditionally above the critical value for interacting-mode operation.

The discharge-electrode contamination was simulated with the same materials. The point electrode was covered by one or more layers wrapped smoothly around the hemispherical tip and secured with teflon adhesive tape far from the tip. Visualizing the contaminated discharge electrode as an insulated electrode with faulty insulation, an alternative method was also used to produce typical effects of contamination. A teflon sleeve, fitting tightly around the discharge electrode was extended a certain distance beyond the tip. This arrangement enhances the screening and focusing effects observed with porous layers covering the point, where corona clears a passage much larger than the pore size.

The environmental chamber procured for the project permitted the experiments to be conducted at various combinations of temperature and humidity, within the range 10°C to 100°C and 10% to 90% RH. Although the accuracy of temperature setting and stability was ±1°C,
the humidifier performance was much inferior, allowing the humidity setting and stability not better than \( \pm 6\% \) RH.

3.2 INSTRUMENTATION

The essential experimental evidence outlined in section 2.4 is obtained by combined measurements of three basic electrical quantities:

(a) average corona current,

(b) current waveform, and

(c) contaminator surface potential,

all as functions of the applied voltage, with ambient and geometrical conditions as parameters.

(a) The arrangement used to plot the average plate and central disc currents simultaneously, is shown in Fig. 3.2. Plotting the current-voltage characteristics with a moderate accuracy (3\% to 5\%) is compatible with the objectives of these measurements, to detect significant changes in characteristics under different conditions, rather than to obtain readings of high accuracy at fixed points. Storage facilities of the Tektronix 564 CRO with the dual-trace 3A6 vertical amplifier in chopped mode permitted the two curves to be plotted during a single high-voltage sweep. Polaroid photographs of the results were taken after storing a convenient number of curves. The unregulated DEL power supply provided a continuously variable output from zero to 30 kV at a current of up to 3 mA. Voltage sweep was manual at a rate of approximately 10 kV per minute. Input voltage to the horizontal amplifier (2A63) was derived from a potential
divider within the power supply. Horizontal deflection was calibrated against the Keithley 610B electrometer with Model 6103A, 30 kV probe to an accuracy of about ± 5%. The 1-M Ω input resistance of the vertical amplifier was used as a shunt for the central-disc current I₀. To maintain approximately equipotential conditions, an external shunt resistance of 68 kΩ was added for the other channel measuring the plate current I₁. The current distribution, and consequently the proportion of the total corona current flowing to the central disc depends on the applied voltage, gap width, point diameter, ambient conditions, and contamination. With the selected shunt resistances, near-equipotential conditions were obtained for the clean system and voltages up to 20 kV, at room temperature and humidity. However, for other conditions except in the presence of back corona, voltages across the shunt resistances remained of the same order of magnitude, differing by less than a factor of 2. The chosen time constants of about 1 sec were required to obtain a smooth trace on the storage oscilloscope, particularly for the pulsed negative corona. Miniature neon indicators were used to protect the instruments against sparkover voltages.

(b) For the (negative) corona current-waveform measurements, Fig. 3.3, it is desired that the time constant of the shunting circuit does not exceed 10⁻⁸ sec [15]. With an estimated shunt capacitance of 100 pF, the resistance is limited to 100 Ω. The shunt capacitance is determined mainly by the amplifier input (47 pF) and protective Shockley diodes (about 40 pF). The 95-ohm characteristic impedance of
properly terminated coaxial cables satisfies the resistance requirement. The protective Shockley diodes were built into the 95-ohm coaxial terminations. Additional shunting for the plate current established approximately equipotential conditions, minimizing the effect of capacitive coupling between the central disc and plate. Measured value of this capacitance is 10 pF, for the geometry shown in Fig. 3.1. The signal transmission was tested for reflections and rise time by applying current pulses of about 0.5 µ sec duration from a pulse generator, simultaneously to the central disc and plate. A reflection-free response was obtained, with an estimated rise time of 20 n sec. The most significant limitations for the measuring system response is the 3A6 plug-in amplifier having a rise time of 35 n sec and 10 MHz bandwidth. The resolution is also limited by the maximum sweep rate of 100 n sec/div. The duration of Trichel-pulses is of the same order of magnitude. Limited accuracy and resolution of these measurements is not considered as a serious shortcoming for the intended observations of changes in the current waveform (including the repetition frequency). However, this system is inadequate for measuring the DC pedestal of Trichel-pulses, because the pre-amplifier is AC-coupled and the 3A6 plug-in amplifier is not sufficiently sensitive at 10 mV/div. The DC pedestal of Trichel-pulses was identified by using a more sensitive (1 mV/div) 2A63 differential plug-in amplifier with a bandwidth of only 300 kHz, insufficient to reproduce the true shape of superimposed Trichel-pulses.

The oscilloscopic measurements were complemented in some experiments
by more precise measurements of the average value (using DC micro-
voltmeters GM 6020 or HP 419A) and AC r.m.s. value (using AC-coupled
true r.m.s. voltmeter HP 3400 of 10 M Hz bandwidth). The cross-
correlation of the results provided a suitable method for checking the
consistency of oscilloscopic data, i.e. the pulse shape, repetition
rate, and DC pedestal, obtained in separate observations.

(c) The third basic type of measurements, illustrated in Fig. 3.4,
is peculiar to the corona system with contamination. For comparative
purposes the surface potential of a contaminating layer was measured at
a single radius of approximately 8 mm, which is equal to the central-
disc radius. Similarly as the current density, the surface potential
does not vary more than 10% over the disc radius, with the exception
of back corona conditions. The surface potential was measured with the
Keithley 610 B electrometer in conjunction with Model 6103 A probe,
using the electrometer IX output to plot the surface potential as a
function of the applied corona voltage. The \(10^{12}\)-ohm input resistance
of the electrometer probe required an adequately lower Thevenin
resistance of the equivalent voltage source, i.e. the resistance of
the contaminated corona system as seen from the terminal of the surface
probe. A source resistance of not more than \(10^{10}\) ohms was obtained
with a circular surface probe of 16 mm inner diameter and not more than
17 mm outer diameter. In the axially symmetrical point-to-plane
system, such circular probe follows equipotential lines, providing a
conveniently large area of "contact" with the system, and minimizing
the effect of current drain by the instrument probe. The source-
resistance magnitude was checked by connecting a resistor of \(10^{10}\) ohms
in parallel with the instrument probe, and observing the resultant drop in electrometer reading. A drop of 50% indicates a source resistance of $10^{10}$ ohms.

The effect of surface probes (an arrangement with three concentric electrodes is shown in Fig. 3.4) on current-voltage characteristics and current distribution has been investigated by comparing the corona characteristics obtained with a particular contaminator sample, first without a surface probe and then with the probe attached. As expected, a pencil-trace probe on paper has a negligible effect on corona and paper characteristics, but it is easily eroded by back corona. Presumably the thickness of aluminium-foil (20 µm) and Teledeltos-paper (35 µm) probes was responsible for a distortion in the field pattern causing an increase in the central-disc current of up to 10%, with the total corona current not being significantly affected.

In certain experiments the radial and axial potential distribution was measured with up to four concentric probes, as shown in Fig. 3.4. In these measurements it was essential to observe the potentials simultaneously. Switchboard-type electrostatic voltmeters of class 1.5 and measured resistance of more than $10^{13}$ ohms enabled taking simultaneous, but discrete readings. The plotting arrangement was also utilized for recording the results in subsequent high-voltage sweeps. The potential distribution is not necessarily identical in subsequent sweeps, emphasizing the importance of simultaneous readings. In measuring the axial potential distribution for multiple layers, the presence of probes attached to intermediate layers caused a significant
(up to 20%) reduction in the overall breakdown strength, even with pencil trace probes on paper.

3.3 PROCEDURES

To compare the clean and contaminated-system characteristics for various plate-electrode contaminations and ambient conditions, it was necessary to perform a large number of "typical" experiments. Data collection in a typical experiment followed a procedure providing the consistency in measurements and reducing the probability of error by an overlooked variable.

The following 7 steps characterize a typical experimental procedure.

1) Stability in ambient conditions, particularly in relative humidity, had to be attained before making any electrical measurements.

Ambient conditions in the environmental chamber are controlled by the wet and dry contact thermometers. In addition, an electronic hygrometer (Shaw) was used to monitor the fluctuations in relative humidity, which could not be detected from the slow-responding, low-resolution psychrometric temperature difference.

2) The clean-system current-voltage characteristics were plotted for positive and negative corona, in both cases for the central disc and plate simultaneously, using the measuring system of Fig. 3.2.

3) For negative corona in the clean system, with the measuring arrangement of Fig. 3.3, the Trichel-pulse waveform was photographed for the central-disc and plate currents, at four or five
corona voltages in the range between 12 and 30 kV, where the pulses have a distinct repetition rate.

(4) After inserting the contaminating layer and surface probe, there were three quantities to be plotted as functions of the corona voltage, namely the average plate current $I_1$, central-disc current $I_0$, and contaminator surface potential $V_s$, but only two of them could be recorded simultaneously (circuits of Figures 3.2 and 3.4). They were combined sequentially in such a way as to provide a correlation between characteristics recorded in successive high-voltage sweeps. Usually, the sequence was $I_0$ and $V_s$ first, then $I_0$ and $I_1$, and finally $V_s$ and $I_1$. Without erasing previous traces, each curve was re-traced to make any differences more conspicuous. This step was performed for positive and negative corona, alternatively.

(5) Subsequently, the negative-corona current waveform was recorded for the contaminated system, at the same voltage levels as in step (3) if feasible, depending on the back-corona occurrence. As these waveform measurements complement the average-value results from the preceding step, it was necessary to check the continuity of conditions by monitoring the surface potential.

(6) Steps (4) and (5) were repeated for three to four different thicknesses of the same contaminating material.

(7) Finally, to determine the resistivity of the contaminating material by conventional methods, another pliable electrode
(Teledeltos paper normally) was placed on top of the layer and weighted by a foam-lined brass plate to ensure uniform contact. The power supply was connected to the Teledeltos electrode, and the central-disc current plotted as a function of the applied voltage by using essentially the same circuit as in Fig. 3.2. The breakdown voltage for the layer was also recorded. Because of non-linear characteristics, it was necessary to repeat these measurements for thicknesses used in step (6).

The techniques and procedures used in supplementary experiments (e.g., contaminated point, potential distribution, bilateral contamination) are considered as special cases and described together with the respective results.
Measuring system for
DC current-voltage characteristics

Fig. 3.2
System for current waveform measurements
Fig. 3.4

System for surface potential measurements
4.0 EXPERIMENTAL RESULTS

The measuring systems used for data collection (described in section 3.2) comprised the oscilloscope as a final, or output instrument for most experiments. The oscilloscope display of measured quantities has been recorded photographically. Consequently, this information is presented here in the same form. Diagrams showing the corona-current waveforms, current-voltage characteristics and, for contaminating layers, potential transfer characteristics are tracings from Polaroid photographs. Any alternative form of characteristics, derived by mathematical processing for interpretation purposes, is given together with the originally recorded information.

The results are systematized according to the state of contamination of the corona system, and grouped to show the influence of a particular parameter. Only those combinations showing significantly different results have been selected from the collected data. Appropriate statements are made where such variations do not occur.

Most of the clean-system characteristics presented in section 4.1 have been obtained during comparative measurements of the type described in procedures (section 3.3). These characteristics have been compiled to provide a concise reference, although some of them are shown together with appropriate contaminated-system characteristics in section 4.2 for comparison.

The effects of plate-electrode contamination, considered as most significant, are documented in section 4.2.1. The peculiarities of
point-electrode contamination follow in section 4.2.2. Finally in section 4.2.3, some characteristics resulting from contamination of both electrodes are presented to indicate the predominant mechanism in the combined effect of bilateral contamination.

The data presented in this chapter are accompanied by a discussion correlating the author's results with other sources of information and emphasizing certain aspects pertinent to the models introduced in chapter 5.

4.1 CLEAN POINT-TO-PLANE SYSTEM

For proper understanding and interpretation of changes in corona characteristics caused by contamination, it is essential to define the conditions prior to the insertion of a contaminator. Extrapolating on Loeb's explanations of basic physical processes, it is desired to formulate a model for current conduction mechanism from which the boundary conditions for the contaminator can be derived. The directly recorded and processed data presented in diagrams 4.1 to 4.2 have been selected and arranged accordingly. Table 4.1 provides a key for the clean-system data, giving the diagram location according to the functional form and operating conditions.

The gaseous medium in all experiments was air at atmospheric pressure, temperature between 25°C and 90°C, and relative humidity between 10% and 90%. The applied voltage was limited to 30 kV. No artificial source of triggering electrons was used.

The particular point-to-plane geometry (0.9 mm diameter point and
produced a clearly defined mode or regime of corona discharge for each polarity, which can be classified in Loeb's terminology as

(a) steady positive corona, and
(b) Trichel-pulse negative corona, respectively.

According to Bandel's data [16] for positive point under similar conditions, a pulsed discharge occurs in two voltage regions, first at onset, followed immediately by steady corona, and then at voltages above 30 kV as pre-breakdown streamers. In experiments performed by the author, onset conditions were obscured by triggering uncertainties, and some positive-corona current pulsation, about 1% of that for negative corona Trichel pulses, was observed at voltages between 25 kV and 30 kV, possibly due to a streamer formation. As the sparkover voltage for a 4 cm gap and 1 mm diameter point, under clean conditions, is in excess of 50 kV [2], the maximum available voltage of 30 kV was too low to develop either positive streamers or steady, continuous negative-corona. In absence of ultraviolet or gamma-ray triggering, the onset voltage for both coronas showed some statistical distribution in repeated measurements under apparently identical conditions, with a spread of about ±1 kV. However, the onset voltages as indicated by the recorded current-voltage curves are between 7 kV and 9 kV, with higher values for negative corona. These figures are in agreement with the results of more precise measurements by other observers [2] on similar clean systems. Moreover, the statistical uncertainty in simultaneous occurrence of the initiating electrons and necessary field strength to
produce an avalanche (a requirement formulated by the Townsend integral), is probably the main reason for a spread in the repetition period of Trichel pulses, indicated in figure 4.14. Notably, the observed spread was regularly much wider with a newly polished point than after a prolonged operation, when the electron tip became eroded by sputtering.

Perhaps the most significant information obtained from the measurements is the composition of negative corona current. One half of the average negative-corona current flows as steady DC current, described here as Trichel-pulse pedestal. The other half is contributed by superimposed Trichel pulses. This conclusion follows from (a) the measured pulse pedestal $I_p$, and (b) the charge in a single pulse $Q_p$ averaged over the pulse repetition period $T_p$. When compared with separately measured average current $I$, the relationship can be expressed as

$$I = I_p + \frac{Q_p}{T_p} = I_p + \frac{1}{T_p} \int_0^{T_p} i_p(t) dt$$

Eq. 4.1

and

$$\frac{Q_p}{T_p} = Q_p \cdot f_p = I_p = \frac{I}{2}$$

This peculiar current composition, consistent with Loeb's explanations of basic processes, has been observed by the author and independently by Foggo and Whitcombe [17]. They have used an integrating circuit to measure the charge flow from a negative, grounded point. The integrator output waveform showed steps, corresponding to Trichel pulses, with ramps inbetween contributing equal charge increments,
and indicating a steady current flow.

These negative-corona current-waveform peculiarities have been identified by the author in separate observations of the Trichel-pulse shape (yielding $Q_p$) and its pedestal ($I_p$), because the available instrumentation did not provide both the necessary bandwidth and sensitivity with DC coupling simultaneously. To accommodate the most significant part of the Trichel-pulse frequency spectrum [18], an amplifier bandwidth of more than 5 M Hz is required. The pulse waveforms shown in figures 4.9, 4.10, and 4.20 were measured with a 10 M Hz bandwidth, determined by the 3A6 plug-in amplifier in the measuring system of figure 3.3, which provides a maximum sensitivity of 10 mV/div with DC coupling and 100 µV/div with AC-coupled 1121 preamplifier. To observe a DC bias of the current waveform, i.e. the pulse pedestal, it was necessary to use a more sensitive (1 mV/div) DC-coupled 2A63 differential plug-in amplifier with a bandwidth of only 300 k Hz. The response of this measuring arrangement is reproduced in figure 4.11 (for variable gap width) together with respective ground levels to show the steady pedestal current $I_p$, but the superimposed pulses are relatively attenuated, due to the limited bandwidth, and useless for quantitative considerations of the current composition. In figure 4.12, the central-disc current waveform (measured with DC coupling, 1 mV/div sensitivity and 300 k Hz bandwidth) is compared with the pulse baseline measured with AC coupling, 100 µV/div sensitivity, and 10 M Hz bandwidth, to confirm that current between the pulses becomes steady even when observed with the highest available resolution. It shows
also that the low-level pulse-tail duration approaches the repetition period at higher voltages.

The area of Trichel-pulses recorded with 10 M Hz bandwidth, although varying with operating conditions and statistically, corresponds typically to a charge of about 200 pC for the plate-electrode current. This is in agreement with data given by F. H. Kreuger [19] for a similar corona system.

A linear relationship between the average current \( I \) and Trichel-pulse repetition frequency \( f_p \), shown in derived figures 4.13, 4.17 and 4.21, implies a constant charge \( Q_p \) created per avalanche. However, this linearity is not inherently related to the observed composition of negative corona current, because an average current \( I = 2 Q_p f_p \) can be obtained with any combination of \( Q_p \) and \( f_p \), provided that their product remains constant. An abrupt change of that combination has been observed by the author in some experiments, and attributed to the point surface conditions.

Amin [15] has explained that the number of negative ions \( Q_p \) required to quench an avalanche will decrease at higher applied voltages, as the ionization region becomes axially elongated and radially constricted. This effect is particularly significant at lower air pressures and smaller point radii. In the results presented here, the effect of such voltage-dependent change in the ionization-region geometry is obscured by a spread in the magnitude of charge \( Q_p \). This spread at a constant voltage is linearly proportional to the statistical variations of the Trichel-pulse repetition period \( T_p \), as indicated in
Such effect is consistent with a flow of constant current $I_p$ between the pulses, because any statistical variation $\Delta T_p$ of an average period $T_p$ produces a proportional variation in the space-charge drain $I_p \cdot \Delta T_p$. Consequently, when a particular ionization process (a Trichel-pulse being its manifestation) is initiated after an interval $T_p + \Delta T_p$, it has to restore the space charge by generating a charge $Q_p + I_p \Delta T_p$, before it is quenched. As the average current remains remarkably constant and reproducible (within 5%) under given operating conditions, the observed spread in pulse repetition frequencies, indicated in figure 4.13 by shaded areas, should be interpreted unilaterally, i.e. as a variation in frequency $f_p$ at a certain average current $I$, rather than vice versa.

Up to this point, the discussion of the negative-corona current properties applied by implication to the total current. Actually, the current waveform and average current were measured in two parts, namely the plate-electrode current (excluding the central disc), constituting about 90% of the total current, and separately the central-disc current. The current distribution and waveforms thus observed provide an additional information about field configurations under different conditions. The negative-corona current waveforms and average currents recorded at four different gap widths are shown in figures 4.9, 4.11 and 4.7 respectively. These measurements, at interelectrode distances less than the standard 4-cm gap, have been performed to enable the identification of contaminated-system characteristics, where an effectively reduced air gap might be a significant factor. The
centrally placed disc electrode is particularly sensitive to phenomena influenced by the axial field component, which is enhanced at reduced interelectrode distances. The total average current and a proportion of it flowing to the central disc increase with decreasing gap width, for positive and negative corona. Simultaneously the Trichel-pulses for central disc increase in magnitude, but the pulse magnitude for surrounding plate decreases, consistently with Amin's arguments that less charge is needed to quench the ionization in an axially more concentrated region. An overall current rise is obtained by a higher repetition rate of avalanches. Also, the spread in repetition frequency is somewhat reduced at smaller interelectrode distances.

Moreover, the field dependence of Trichel-pulses is indicated by the difference in pulse shapes for the two measured currents ($i_{p0}$ for central disc, $i_{p1}$ for plate electrode). Defining the pulse duration as a time interval between the 50% points (i.e., the instantaneous values of a pulsed current $i_p$ equal to 50% of its amplitude), the central-disc current pulses $i_{p0}$ have generally longer duration than the plate current pulses $i_{p1}$, for all operating conditions used. The $i_{p0}$ pulses exhibit also relatively long low-level tails shown in figure 4.12. The $i_{p1}$ pulses have proportionally similar tails only at smaller gap widths (25-30 mm). Notwithstanding a relatively low level of the $i_{p0}$ pulse tails (less than 5% of the pulse amplitude and falling), the contribution of the tail to a total pulse area is significant, because the tail duration is about 40 times the 50% pulse duration, as evident from data in figures 4.10 and 4.12.
Ignoring the effect of positive ions and considering the Trichel-pulses as a displacement current caused by a simultaneous generation and motion of negative charge carriers in the air gap (an approach further developed in chapter 5), the differences in pulse shapes for $i_{po}$ and $i_{p1}$ can be interpreted in terms of drift velocities for two groups of generated carriers forming $i_{po}$ and $i_{p1}$ respectively. However, Amin has pointed out that the participation of positive ions in the secondary emission of electrons from the point enhances ionization in a narrow axial region, because positive ions are not as widely dispersed as the photons. This is probably the main reason for a larger duration of $i_{po}$ pulses.

In windblown coronas studied by Nygaard [38], a wind blowing in the direction perpendicular to the gap axis contributes to the removal of ions, consequently enhancing the current flow and reducing the frequency of Trichel-pulses (correspondingly with a larger $Q_p$ required for quenching).

The shape of Trichel-pulses did not show any functional changes with temperature in the investigated range from 25°C to 90°C, at less than 10% relative humidity. The pulse repetition frequency increases slightly but steadily with temperature, possibly due to an increase in carrier mobility. The observed waveforms are not shown here, as they are not significantly different from those in figures 4.10, 4.12 and 4.14, but the derived relationship between frequency and average current is given in figure 4.17. Consistently with an increase in average current at a constant pulse area ($Q_p$), the pulse repetition frequency
also increases at higher temperatures. The recorded average currents are shown in figures 4.3 (for positive corona) and 4.15 (for negative corona) at two chosen temperatures, 25°C and 75°C, to show clearly the differences in measured characteristics.

The observed influence of relative humidity increases significantly with temperature, suggesting that the electrical characteristics are affected more directly by the density of "impurities", or the partial water-vapour pressure, rather than by the relative vapour pressure expressed as relative humidity. However, the basic effects of increasing humidity are qualitatively the same at any temperature within the experimental range. Generally, with increasing humidity the average corona currents decrease (more so for negative than for positive corona), the shape of Trichel-pulses remains basically unaltered, and their repetition frequency decreases consistently with average current. Compared with the influence of temperature, these effects are opposite and quantitatively more significant. In addition, a peculiar humidity-dependent instability has been observed at higher temperatures for negative corona and the central-disc current waveform only. To show these effects, the corona characteristics measured at 75°C and various humidity levels are presented here. The recorded current-voltage characteristics (figures 4.5 and 4.18, for positive and negative corona respectively) show that the onset voltage for positive corona increases with humidity. This delayed onset of ionization is associated with an abrupt current rise, followed by a current-voltage curve having an extrapolated origin at the low-humidity
onset voltage. The central-disc Trichel-pulse waveforms in figure 4.20 show the peculiar oscillatory response (dotted curves) superimposed on large pulses, and reaching maximum intensity at higher voltages as the humidity increases.

The superimposed current fluctuations appear as almost sinusoidal oscillations of 20 to 30 MHz. These frequencies are well beyond the 10 MHz bandwidth of the available measuring equipment, so that the observed peculiarity can be regarded only as an indication of certain current instabilities manifested only in the central region of the negative-corona system, and functionally related to humidity.

For the chosen clean system under experimental conditions, the average current-voltage relationships are quadratic for both coronas, fitting the Townsend equation (originally derived for steady discharge in a coaxial system),

\[ I = \text{const} \times V(V-V_c) \quad \text{Eq. 4.2} \]

as proved by the linearity of derived functions \( \frac{I}{V} = f(V-V_c) \), listed in Table 4.1. For a coaxial geometry and positive corona, an approximate analytical expression for the constant in equation 4.2 [20] comprises the carrier drift mobility and factors defined by electrode dimensions. It is reasonable to assume that an equivalent constant for a point-to-plane geometry would be determined by the same quantities. Then, the geometrical factors would account for the slope changes of the functions in figures 4.2 and 4.8, obtained with different gap widths, but not for the difference between positive and negative corona currents. Generally
higher average currents for negative corona could be caused by a higher mobility of negative ions and/or by the negative-corona current composition. The second reason would suggest a current ratio of 2, because the displacement-current component, which does not exist for steady positive corona, constitutes 50% of the average negative-corona current. The ratio of measured average currents is about 1.5. The other possibility of similarly large differences in ion mobilities is not supported by Amin's measurements of almost identical crossing times for positive and negative ions in air at atmospheric pressure, although some of the negative ions (O^- in particular) are known to be faster than the most common O_2^+ ions [21]. Considering that a single mobility figure represents a weighted average mobility of various charge carriers participating in conduction, it is possible that the carrier composition and resulting effective mobility are affected by the humidity, temperature (to a minor extent) and electric field strength [21]. This particularly applies for negative oxygen ions formed by attachment. However, it would be difficult if not impossible to offer an acceptable interpretation of measured V-I characteristics by using a constant in equation 4.2 determined by mobility and electrode geometry only. In a more adequate approximation derived in section 5.1, this constant is determined by the space-charge region rather than electrode geometry.

In correlation to the subsequently presented contaminated-system characteristics, the experimental data collected under clean conditions characterize a fundamental corona-discharge mode for each polarity, which is regarded as a reference in studying different modes obtained with
# TABLE 4.1

## GLOSSARY OF TERMS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>average corona current measured in two parts (Fig. 3-2), as</td>
</tr>
<tr>
<td>I_1</td>
<td>average corona current flowing to the plate electrode, excluding the central disc, and</td>
</tr>
<tr>
<td>I_0</td>
<td>average corona current for the central disc;</td>
</tr>
<tr>
<td>i_p(t)</td>
<td>AC corona current waveform as determined by an AC-coupled measuring system (Fig. 3-3):</td>
</tr>
<tr>
<td>i_p(t)</td>
<td>for the plate less central disc, and</td>
</tr>
<tr>
<td>i_p(t)</td>
<td>for the central disc;</td>
</tr>
<tr>
<td>i_p(t)</td>
<td>corona current waveforms analogous to i_p(t) and i_p(t) as determined by a DC-coupled measuring system of inadequate bandwidth to show proportional pulse height;</td>
</tr>
<tr>
<td>i_p(t)</td>
<td>pulse repetition frequency</td>
</tr>
<tr>
<td>V</td>
<td>applied voltage</td>
</tr>
<tr>
<td>V_c</td>
<td>applied voltage at corona onset, or starting voltage</td>
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</table>
Clean system characteristics

<table>
<thead>
<tr>
<th>FIGURE NUMBERS for</th>
<th>FUNCTION</th>
<th>DISCRETELY VARIED PARAMETER</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>gap width</td>
</tr>
<tr>
<td>POSITIVE CORONA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>average I-V curves</td>
<td>recorded</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>derived</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>recorded</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>derived</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>current pulse waveforms</td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td>i_p(t) and i_o(t)</td>
<td>4.10</td>
</tr>
<tr>
<td></td>
<td>pulse waveforms with pedestal</td>
<td>4.11</td>
</tr>
<tr>
<td></td>
<td>i_b(t) and i_o(t)</td>
<td>4.12</td>
</tr>
<tr>
<td></td>
<td>pulse repetition frequency</td>
<td>4.13</td>
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<tr>
<td></td>
<td>derived f_p(I)</td>
<td>4.13</td>
</tr>
<tr>
<td></td>
<td>recorded T_p = f(I_p)</td>
<td>4.14</td>
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<tr>
<td>NEGATIVE CORONA</td>
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<td></td>
<td>recorded I_s(V) and I_b(V)</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>derived I/V = f(V-V_c)</td>
<td>4.8</td>
</tr>
</tbody>
</table>

* varied parameter is V
Positive corona, 0.9mm dia point
Temp. 25°C
Rel. humidity 50%
Varied parameter: gap width
L = 25, 30, 35, and 40 mm

Fig. 4.1

Fig. 4.2
Positive corona
0.9mm dia point, 40mm gap
Rel. humidity ≤ 10%
Varied parameter: temperature
T = 25°C and 75°C
Fig. 4.5

Positive corona
0.9mm dia point, 40 mm gap
Temp.: 75°C
Varied parameter: rel. humidity
RH = 10, 30, 50, and 70%

Fig. 4.6
Negative corona, 0.9mm dia point
Temp. 25°C
Rel. humidity 50%
Varied parameter: gap width
L = 25, 30, 35, and 40 mm
Negative corona
0.9 mm point
Temp.: 25°C
Rel. humidity: 50%

40 mm gap width

Fig. 4.9

**Applied voltage** $V = 20\ kV$

$1\ mA/\text{div}$

$0.1\ \mu\text{sec/}\text{div}$

$30$

$35$

$40$

$53\ \mu A/\text{div}$

Fig. 4.10

**applied voltage** $V = 15\ kV$

$1\ mA/\text{div}$

$20$

$25$

$30$

$53\ \mu A/\text{div}$

$0.1\ \mu\text{sec/}\text{div}$
Negative corona
0.9mm dia point
Temp.: 25°C
Rel. humidity: 50%

Fig. 4.11

Fig. 4.12
Negative corona, 0.9 mm point
25°C, 50% RH

Fig. 4.13

Fig. 4.14
Negative corona

0.9mm dia point, 40mm gap
Rel. humidity $\leq 10\%$
Varied parameter: temperature

$T = 25^\circ C$ and $75^\circ C$

Fig. 4.15

$\frac{I}{V}$

$\frac{I_4}{V}$ x 3.6

$\frac{I_o}{V}$ x 0.25

$\mu A/kV$

Fig. 4.16
Negative corona, 0.9 mm point, 40mm gap width

**Fig. 4.17**

- Temperature
  - 25°C
  - 75°C
- Relative humidity ≤ 10%
- $I_1 \times 14.5 \mu A$
- $I_0 \mu A$

**Fig. 4.21**

- Rel. humidity
  - 10%
  - 70%
- Temperature 75°C
- $I_1 \times 14.5 \mu A$
- $I_0 \mu A$
Negative corona
0.9 mm dia point, 40 mm gap
Temp.: 75 °C
Varied parameter: rel. humidity
RH = 10, 30, 50, and 70%
Negative corona, 0.9mm point, 40mm gap width
Temperature 75°C
electrodes covered by layers of porous insulating materials.

4.2 CONTAMINATED POINT-TO-PLANE SYSTEM

Table 4.2 provides a summary of the results presented in this section, according to their functional forms, contaminating materials and operating conditions, giving the corresponding diagram locations.

4.2.1 Plate electrode contamination

The selected experimental results obtained with the contaminated plate electrode are presented in diagrams 4.22 to 4.84.

The most significant aspect of plate contamination is the formation of back corona. The contaminated-plate characteristics are compared with the previously shown (in section 4.1) clean-system characteristics, to identify the operating conditions and specific features in electrical characteristics without back corona (non-interacting mode, unipolar ionization) and with back corona (interacting mode, ambipolar ionization). For the investigated point-to-plane system (0.9 mm diameter point and 40 mm gap width), the average current-voltage and waveform characteristics are shown for three contaminating materials (paper, teflon filter, and fly-ash) at different combinations of temperature and relative humidity.

A particular contaminating layer is characterized by its current-voltage relationship, including the breakdown voltage, as measured under equipotential surface conditions (using a parallel-plate configuration). The contaminator surface, i.e. the contaminator-air boundary in the corona system is not necessarily an equipotential.
However, in the absence of back corona, the current density and potential distribution are sufficiently uniform to allow a comparison of operating points. The surface-potential distribution was measured with a probe arrangement illustrated in figure 3.4, with the smallest probe radius \( r = 8 \text{ mm} \) being equal to the central disc radius. This radial surface-potential distribution provides an indication of current distributions in the non-interacting and interacting modes of operation. In some experiments with multi-layer contaminators, a potential distribution through the contaminator (in the axial direction, normal to its surface) was determined by measuring the interface potentials with probes similar to the surface probe with \( r = 8 \text{ mm} \). This axial potential distribution \( V_d = f(z) \) is indicative of a space-charge distribution within the contaminator.

The contaminating materials used in experiments are of two different types:

(a) The fly-ash (a typical industrial precipitate) and paper (an experimentally convenient substitute for fly-ash), with similarly non-linear and humidity-sensitive current-voltage characteristics, and having an undefined porosity, presumably with a large statistical spread in pore sizes. With fly-ash and paper as plate contaminators, the formation of back corona is conditional and determined mainly by the humidity-sensitive resistivity of these materials.

(b) The Millipore teflon LS and LC filter discs have precisely defined porosities \( (5.0 \pm 1.5 \mu\text{m} \text{ and } 10 \pm 2 \mu\text{m}, \text{ respectively}) \).
and a very high resistivity (> $10^{14}$ ohm-cm) relatively unaffected by humidity. Back corona is unconditionally produced when these teflon filters are used as plate contaminators.

The peculiarities of measured characteristics for the two groups of contaminating materials are discussed in the subsequent sections.

4.2.11 Plate contaminators: paper and fly-ash

The contaminator current-voltage ($I_0$-$V_s$) characteristics, in figures 4.26/36/44/50 for paper and in figure 4.84 for fly-ash, and breakdown voltage $V_{br}$, in figure 4.27 for paper, have been measured by using the parallel-plate method described as step (7) in experimental procedures, section 3.3.

The spread of $V_{br}$ indicated in figure 4.27 is the result of measurements on five samples for each thickness shown. For a particular sample, the applied voltage was repeatedly increased from zero to a breakdown level. The first breakdown occurs regularly at a higher voltage than the subsequent breakdowns, which are normally restricted to a hole produced by the first-breakdown avalanche. Such a hole represents a relatively unobstructed air gap between the electrodes. The breakdown strength of air gaps between parallel electrodes is described by the Paschen Law (the corresponding curve in figure 4.27 is reproduced from the book 'Ionized Gases' by A. Von Engel [22]). W. Böning [10] has verified that this law applies also for the breakdown in voids completely surrounded by an insulator. The original porosity of an insulating material influences the first-
breakdown voltage. For example, the measured first-breakdown voltage, and the spread for subsequent breakdowns, is much closer to the Paschen Law for Kleenex tissue, which is substantially more porous than paper in figure 4.27 (Kleenex tissue as a contaminator was used by the author only in preliminary experiments). The temperature and humidity dependence of $V_{br}$ was obscured by a relatively large spread in measured values of $V_{br}$, although somewhat lower voltages $V_{br}$ have been observed at higher temperatures and/or lower humidities.

No mechanical changes have been observed on paper (or fly-ash) when operated as a plate contaminator, under conditions without back corona. After operating with back corona, a large number of almost round through-holes of various diameters have been found. A microscope was used to inspect and measure these holes. The diameter of holes positively identified as being produced by back corona was at least 10 μm, but the largest diameter was considerably smaller than the hole length (equal to the paper thickness). Many of the bigger holes showed a dark circumference, apparently as a result of burning. Similar, but even larger holes are produced by a spark occurring under conditions without back corona. Contrary to the neatness of such holes, a spark under back-corona conditions produced typically a volcano-shaped mound with a center hole widening towards the plate and simultaneously raising the paper.

The individual operating points (in the corona system) shown together with the contaminator current-voltage characteristics (obtained in parallel-plate configuration) have been determined from the recorded
average current $I_0$ as a function of the applied voltage $V$ (figures 4.22/23/32/33/41/42/47/48 for paper and 4.80/81 for fly-ash) and corresponding surface potential $V_s$ at $r = 8$ mm, also as a function of $V$ (figures 4.28/29/37/38/45/46/51/52 for paper and 4.82/83 for fly-ash).

These experimental results provide sufficient information for identification of the non-interacting and interacting modes of operation, introduced as concepts in section 2.3.

(1) In the non-interacting mode, without back corona

(a) The contaminator is operating below its breakdown voltage (figures 4.26/44 for paper and 4.84 for fly-ash at 50% RH). However, it should be noted that in critical cases, such as for fly-ash at 75°C and 30% RH in figure 4.84, the mode of operation depends on the applied voltage. In this particular case, the interacting mode is approached at $V \approx 28$ kV.

(b) There is a negligible space-charge within the contaminator, as indicated by a linear distribution $V_d = f(z)$ in figure 4.31 for paper. This implies that the current carriers injected at the air-contaminator boundary form a surface charge rather than a space charge.

(c) The surface potential distribution $V_s = f(r)$, as in figure 4.30 for paper, becomes more uniform as the applied voltage $V$ increases, which is consistent with a simultaneous increase in surface charge and surface conductivity (a circuit model for a contaminator operating under such conditions is presented in section 5.2). In comparison with the clean-
system distribution, the plate current is more evenly distributed, as indicated in figures 4.26/44 by a decrease in \( I_0 \) relative to \( I_1 \). This uniformity justifies a comparison of contaminator characteristics measured in the corona system with those obtained in the parallel-plate configuration, with strictly equipotential surfaces.

(d) Consequently, the total current \( I \) (approximately equal to \( I_1 \)) is functionally determined by a voltage drop \( (V-V_s) \) across the air gap, in the same manner as for the clean system. This is verifiable from \( I_1-V \) (e.g. figure 4.42) and corresponding \( V_s-V \) (figure 4.46) characteristics. Illustrating by a numerical example: for \( I_1 = 4 \) div in figure 4.42, the required applied voltage is \( V(o) = 6 \) div in the clean system, and \( V(6) \approx 6.7 \) div with six paper sheets covering the plate. The difference \( V(6) - V(o) \approx 0.7 = 2.8 \) kV is to be compared with the corresponding surface potential \( V_s \) in figure 4.46 for \( V = V(6) = 6.7 \) div, which is \( V_s = 5.2 \) div = 2.6 kV. Hence \( V_s \approx V(6) - V(o) \) within a probable error for the low-resolution reading of \( [V(6)-V(o)] \) in figure 4.42.

(e) A comparison of pulse shapes and repetition frequencies (figures 4.24 and 4.25) confirms that the ionization process is not affected by plate contamination in the non-interacting mode of operation. There is an exception at onset, when the discharge becomes intermittent as the build-up of
voltage across the contaminator reduces the air-gap voltage below its critical value.

(2) In the interacting mode, with back corona

(a) The contaminator is operating in the breakdown region of its current-voltage characteristics (figures 4.36/50 for paper and 4.84 for fly-ash at 10% RH). Visual effects of back corona become distinct only for an operating current well above the pre-breakdown magnitude. The highest indicated operating point at 30% RH in figure 4.84 (a) is an example of such pre-breakdown operation. The luminous region of back corona is distinctly above the contaminator surface and extends further from the surface as the current increases, when also a larger contaminator area becomes affected by back corona. In such cases the measured surface potential (e.g. figures 4.51/52) decreases considerably below the breakdown voltage measured between parallel plates, as indicated by operating points in figure 4.50, and even more conspicuously in figure 4.65 for Millipore teflon discs.

(b) Within the contaminator, the potential distribution is non-linear (figures 4.40/54) and varies with the intensity of back corona. In figure 4.54, for example, more back-corona channels and correspondingly higher current were produced at V = 20 kV in sample (b) than in (a). Characteristically for sample (b), its surface potential is
below the Paschen breakdown level. However, this breakdown level is maintained closer to the plate at $z \approx 100 \mu m$.

(c) The surface-potential distribution (figures 4.39/53 for paper) shows a significant potential depression in the area of an intense back-corona ionization. A field configuration consistent with such distribution is suggested in section 5.3. The intensity of back-corona is also manifested by an increase in average current, exceeding in some cases many times the clean-system current at the same applied voltage (figures 4.32/33/47/48 for paper and 4.80/81 for fly-ash at 10% RH). This current increase depends mostly on non-electrical properties of contaminators, such as porosity and structural stability against deformations by back-corona. For instance, the original porosity and its uniformity determine the number of "weak" spots where breakdown can occur more or less simultaneously, and the structural stability determines the size and number of holes, or unobstructed channels, that can be adequately cleared to provide minimum-energy current paths to the plate electrode. The current-carrying capability of such channels is limited. In a hole which becomes relatively large, the back-corona ionization may cease. Alternatively, a high current density in a channel affects the surrounding material in such a way that, as in the case of paper, it may produce an explosive eruption and sparkover. Such
sparkover in the paper-contaminated system occurred at voltages below 24 kV, which is less than 50% of the clean-system sparkover voltage. Another type of contaminator deformation or damage has been observed in preliminary experiments on MF Millipore (esters of cellulose) SS filters, where back-corona carved radial slots as the luminous channels moved radially outwards.

In the interacting mode, the reproducibility of current-voltage characteristics with paper is poor (for different samples the current may vary by a factor of 2 or more), but it is even worse with fly-ash. In a layer of fly-ash, craters rather than holes are formed by back corona, and the dust is removed from the region initially affected by back corona. As the reproducibility of results with Millipore teflon discs is substantially better, it is permissible to conclude that a consistent structural uniformity is an essential property of contaminators for quantitatively predictable results.

(d) Visual appearance of back corona in the negative-point system differs from that in the positive-point system mainly in the concentration of back-corona luminosity. For negative point, the luminosity is more uniformly distributed over the contaminator surface, with brighter spots developing as the current increases. The concentration of luminosity on a few very bright spots is a peculiarity...
of back corona in the positive-point system. Considering that back corona in the negative-point system is a positive discharge, its appearance is consistent with the positive glow discharge described and interpreted by Hermstein [23]. The specific feature of such glow discharge is its lateral spreading over the electrode surface.

Additional information about the effects of plate contamination is provided by the negative-corona (i.e., for negative point) waveforms shown in figure 4.34. The Trichel-pulse amplitude decreases somewhat with rapidly increasing current (as in figure 3.4 (a) for 2 paper sheets) but much more significant is an abrupt transition from pulsed to continuous discharge (figure 4.34 (c)). This transition is accompanied by a discontinuous increase in current (such discontinuities in clean systems have been studied by Miyoshi and presented by Loeb [2]). A current-voltage relationship in this region is not shown for paper and fly-ash, because of an unstable operation with frequent spark-overs, but it is included in characteristics recorded with Millipore teflon discs as plate contaminators. In this regime of continuous discharge from the point, some large random pulses (figure 4.34 (b)) have been observed. Their presence in the current waveform coincided with appearance of bright back-corona spots on the paper surface. Further observations of current waveforms have been made under more stable operating conditions obtainable with Millipore teflon discs.
4.2.12 Plate contaminants: Millipore LS and LC filter discs

The effect of ambient conditions (relative humidity in particular) on the current-voltage characteristics of Millipore teflon discs (figure 4.65) is too insignificant to influence the operating mode in a corona system. Consequently, this contaminator operates unconditionally in the interacting mode, with back corona. However, relative humidity determines the extent of back-corona development, generally resulting in lower currents at higher humidities.

Specifically for the negative-point system, the continuous discharge occurring at about 20 kV at 10% RH, is suppressed at 70% RH within the range of voltages used in experiments (up to 30 kV). In this continuous-discharge regime, the current-voltages relationship (figures 4.60 and 4.73) becomes almost linear, indicating that such intensified bilateral ionization produces a sufficient space-charge neutrality to eliminate the quenching effect of space-charge and consequently to enable such continuous ionization processes at the point.

The current-voltage characteristics obtained with LC filter discs (10 μm pores) are more reproducible than those for LS discs (5 μm pores). As the size of holes produced by back corona does not differ for the two filter types (mostly small holes of 15 to 30 μm have been observed), obviously it is easier to clear such holes in the LC structure with initially higher porosity. However, the end results are similar (comparing figures 4.55/56/59/60 for LS with 4.67/68/72/73 for LC discs).
For positive point, the concentration of back corona on a few relatively very bright spots is more likely to be maintained by LS rather than LC discs. This is illustrated for a contaminator comprising three LS discs in figure 4.59, where the curves 3 and 3 (b) have been obtained with the same contaminator, except that in case 3 (b) one very bright back-corona spot was formed in the central-disc area, and no such spots existed in case 3. This particular back-corona spot channelled about a half of the total current, which quantitatively remained almost the same as in case 3.

In surface-potential measurements, the appearance of a high-intensity back-corona spot close to a surface-potential probe was associated with a marked decrease in the measured voltage, quantitatively similar to the potential depression measured for an area with a large population of low-luminosity back-corona spots (e.g. as in the colour photograph and figure 4.79). Consequently, the radial potential distribution shown in figures 4.63/64/78/79 is representative only for a contaminator surface with a relatively uniform distribution of back corona. Also, the surface potential $V_s$ of a particular contaminator may reach the breakdown level $V_{br}$ only during the first operation, when the back-corona holes are being formed. For example, in figure 4.77 for three new LC discs, the surface potential $V_s$ recorded during the first sweep of the applied voltage $V$ is indicated by a full line, and $V_s$ in subsequent sweeps by a dashed line.

An additional, secondary discharge spot appeared about 10 mm from the electrode tip, on the negative point at voltages above 24 kV. The
corresponding current waveforms are shown in figure 4.75, where diagrams (a) and (b) represent waveforms associated with the primary ionization spot at the electrode tip, and the (repetitive) pulses in diagram (d) are apparently due to a pulsed discharge at the secondary spot, while the primary-spot discharge is continuous. Characteristically, the amplitude of these pulses increases with voltage, contrary to a decrease in the amplitude of Trichel-pulses from the primary spot (prior to the continuous regime). The repetition frequency of these secondary pulses is low (of the order of magnitude $10^4$ Hz) and obscured by a large spread in periodicity. The origin of simultaneously present long random pulses (figure 4.75 (c)) has not been identified, although their duration indicates a prolonged ionization process consistent with a burst or streamer development at the plate.

For positive point, a glow discharge extending along the point electrode, but separated from the electrode tip by a dark region, was visible at voltages above 24 kV. The current waveforms observed in this case are presented in figures 4.69 and 4.74. Although similar to Trichel-pulses in shape and duration, those pulses shown in figures 4.69 and 4.74 (a) have no distinct periodicity, as indicated by the single-sweep traces in figure 4.74 (b). The ratio of simultaneously occurring $i_1$ and $i_0$ pulses appears to be the same as the ratio of resistances (approximately 10:1) in measuring circuits for $i_1$ and $i_0$ (figure 3.3), suggesting that these pulse might be produced by a voltage difference between the central disc and remaining part of the plate. It is conceivable that back-corona, in this case a negative discharge, operates
in a pulsed (Trichel) regime with no synchronization between the ionization processes at individual spots, consequently inducing random voltage pulses between insulated parts of the plate electrode, with the polarity of measured pulses depending on the position of signal-generating back-corona spots relative to the boundary between the central disc and surround plate. To support this assumption, the total current $i(t)$ was measured with the central disc short-circuited to the surrounding plate. This total-current waveform, shown in figure 4.7 (c), does not contain any negative-going pulses, consistently with the previous assumption.

To summarize, the experimental results obtained with the contaminated plate electrode provide a necessary correlation between the clean-system and contaminator characteristics for determining:

(a) the conditions and operating point in the non-interacting, unipolar-corona mode;

(b) the condition for transition to the interacting ambipolar-corona mode, which basically depends on the contaminator resistivity and its breakdown voltage; and

(c) the operating conditions, stability and probable field-pattern deformation in the interacting mode, depending essentially on non-electrical properties of a contaminator material.

An analysis of these aspects is presented in chapter 5.
4.2.2 POINT ELECTRODE CONTAMINATION

The experimental results obtained with the contaminated point and clean plate electrode are presented in figures 4.85 to 4.101, and listed in Table 4.2.

An insulating material covering the point, provided that it is sufficiently defective (as an insulator) to allow the formation of corona discharge (within the experimental voltage range), affects the ionization region and consequently the regime of corona discharge. In such systems, corona remains unipolar (occurring from the point only), but the resulting characteristics may be substantially different from those for the clean system.

4.2.21 Teflon sleeve, screening effects

To exaggerate the effects obtained with the previously used contaminating materials (paper, Millipore filters, and fly-ash), a teflon sleeve around the point electrode was utilized to screen the electrode tip, as earlier on described in section 3.1. A degree of such screening is arbitrarily expressed in terms of the distance X between the sleeve base and the electrode tip, as indicated in the inset figure 4.86.

The visual forms of coronas developed from the screened point are sketched in figure 4.85. These visual forms, indicative of the field patterns and ionization conditions, show that positive corona under such conditions is much more affected than negative corona, both by the screening and relative humidity. For the illustrated sleeve length
(X = -2.5 mm, i.e. extended over the electrode tip by 2.5 mm towards the plate) and 10% RH, the onset voltage is increased from about 8 kV under clean conditions to 25 kV for positive corona and to 22 kV for negative corona (evident from the corresponding current-voltage characteristics in figures 4.86 and 4.87, respectively). Immediately at onset, the positive discharge at 10% RH attains a form of spray corona with streamers crossing the gap. This regime is stable, without sparkovers, at least up to 28 kV. However, the resulting (total) current does not exceed the clean-system current (figure 4.86). The same screening has a simpler effect on negative corona: the onset voltage is increased, but the usual Trichel-pulse corona is developed subsequently, with the current approaching rapidly the clean-system magnitude (figure 4.87). At a reduced degree of screening (X = 0, and +2.5 mm in figures 4.86 and 4.87), the negative-corona characteristics follow closely the clean-system relationship, except for a higher onset voltage. The positive-corona discharge is still in the pulsed, streamer regime at X = 0, producing persistently sparkovers at about 24 kV, and only at X = +2.5 mm it becomes a steady, continuous corona with nearly clean-system characteristics.

The effect of humidity is also more conspicuous for positive than for negative corona. At X = -2.5 mm (figures 4.88 and 4.89) an increase in humidity reduces slightly the onset voltage for both polarities, and again the resulting currents do not exceed the corresponding clean-system magnitudes. This is associated with a suppression of streamer length for positive corona and a constriction of the luminous region
for negative corona, as illustrated in figure 4.85 for 50% RH. At $X = 0$ (figures 4.90 and 4.91), the onset voltage increases with humidity similarly as under clean conditions, and the average current-voltage relationships at 30% and 50% RH follow approximately the clean-system characteristics (e.g. comparing figures 4.5 and 4.90). Nevertheless, the current waveforms (figures 4.92 and 4.93) reveal that the operation of positive corona is in the pulsed regime even at 50% RH.

Generally, for all pulsed discharges (positive and negative) observed at a significant degree of screening (i.e. for $X = 0$ or negative), the periodicity of pulses, if any, is very irregular.

4.2.22 Point contaminants: paper and Millipore LS filter

The current-voltage characteristics, obtained with paper (figures 4.94 to 4.97) and Millipore LS filter (figures 4.98 to 4.101) wrapped around the point, resemble qualitatively and quantitatively the peculiarities recorded with the teflon-sleeve screening at $X \approx 0$. The corresponding visual forms of discharges are also similar. However, the contaminator thickness is not a direct measure of screening, such as the distance $X$ for a solid teflon sleeve, because the size of holes formed by the discharge in a contaminator is not directly related to its thickness. In particular, for a single layer of paper (thickness 70 $\mu$m), a relatively large area of the electrode tip was cleared by the corona discharge, forming a single hole in paper of about 0.4 mm diameter. The resulting characteristics (figures 4.94/95) resemble those obtained with the teflon-sleeve screening at $X = 0$, which is geometrically consistent. The hole or clearing formed in two layers
of paper (thickness 140 \( \mu \text{m} \)) was approximately of the same size (0.4 mm), and the current-voltage characteristics (figures 4.96/97) indicate a considerably higher degree of screening (i.e. \( X < 0 \)), by comparison with the teflon-sleeve effects. However, the ionization-regime geometry may not be the only significant factor influencing these characteristics. For instance, as the observed holes in paper have burnt edges, it is possible that the discharge is also affected by the combustibility of paper.

The effects of point contamination with Millipore LS teflon filters are almost the same as for the teflon sleeve at \( X = 0 \) (comparing figures 4.98/99 with 4.90/91) exhibiting however a peculiar independence on the contaminator thickness. For example, there is no significant difference between the corresponding characteristics for a single layer (figures 4.98/99) and two layers (figures 4.100/101) of Millipore LS covering the point. A different type of clearing formation at the electrode tip is a probable reason for such behaviour. Instead of a large single hole, as in the case of paper covering, a number of small holes have been observed in Millipore LS filters. In the particular single layer (thickness 125 \( \mu \text{m} \)) of figures 4.98/99, six separate holes of about 60 \( \mu \text{m} \) diameter have been found. A new double layer (250 \( \mu \text{m} \) thick) was used to record the characteristics shown in figures 4.100/101. Again separate holes of about 60 \( \mu \text{m} \) have been found subsequently but the number of holes was ten in this case. This increase in the number of holes may explain that the same effective screening is obtained in both cases, producing consequently almost identical
current-voltage characteristics.

The results of a few experiments attempted with the fly-ash-contaminated point can be characterized by the teflon-sleeve screening at \( X \approx 0 \), and they also appeared to be independent of the initial dust thickness (which is understandable considering that the dust particles can be easily removed from a layer of very low cohesion). However, these experiments are not considered as representative because of an unsatisfactory uniformity of the fly-ash coating.

4.2.3 BILATERAL CONTAMINATION

Experiments with bilateral contamination have been conducted with the main purpose to recognize the relative importance of individual, unilateral-contamination effects. The results for two combinations of bilateral contamination, at two levels of relative humidity, are presented as typical:

(a) A single layer of paper (70 \( \mu \text{m} \)) covering the point and two layers (140 \( \mu \text{m} \)) covering the plate, with the recorded characteristics at 10% RH shown in figures 4.102/103, and at 30% RH in figures 4.104/105;

(b) A single layer of Millipore LS (125 \( \mu \text{m} \)) covering both electrodes, with the results at 10% RH in figures 4.106/107, and at 70% RH in figures 4.108/109.

The corresponding characteristics for the clean and unilaterally-contaminated systems are also shown in these diagrams for comparison.
The evidence provided by these comparative measurements on the relative importance of contamination of individual electrodes indicates a definite and consistent pattern, which may be conveniently summarized separately for negative-point and positive-point systems:

(1) For negative point, the point contamination determines a higher onset voltage than in the clean system, but the subsequently developed corona current is predominantly influenced by the plate contamination, particularly if the plate contaminator is operated in the interacting mode, with back corona (such conditions exist for Millipore LS, and paper at 10% RH);

(2) For positive point, the onset voltage in the bilaterally contaminated system is even higher than in the contaminated-point system, and although the current tends to follow the contaminated-plate relationship at a low humidity (figures 4.102 and 4.106), or to approach it at higher humidities (figures 4.104 and 4.108), a spark formation from the contaminated point has an overriding influence.

4.3 GENERAL CONCLUSIONS

Pertinent to the operating modes observed under experimental conditions with the results described in this chapter:

(1) All substantial deviations from the clean-system characteristics (either in magnitude or functional relationship) are associated with the specific corona-discharge modes (or
Two types of operating-mode changes should be distinguished:

(a) change in the system mode, from unipolar to ambipolar ionization, and

(b) at a particular electrode, change from an existing corona-discharge regime to a distinctly different regime.

In an asymmetrical system, like the experimental point-to-plane geometry, the system mode can be changed by the low-stress-electrode (plate) contamination, and not by the high-stress-electrode (point) contamination.

A regime of corona discharge at a particular electrode depends on

(a) the electrode contamination, and/or

(b) the system mode, i.e. the ionization conditions (contamination implied) at the opposite electrode.

The observed negative-corona regimes at the point are:

(a) the Trichel-pulse corona, which occurs under clean and contaminated conditions, and

(b) the steady, continuous negative corona, appearing in the interacting mode of operation at a sufficiently high current, and associated with an intensified back-corona ionization. In this mode of operation, there is a high probability of sparkover, depending
on a structural stability of the plate contaminator. Simultaneous appearance of another discharge spot on the point electrode, operating in the Trichel-pulse regime, is possible.

(6) For positive point, there is a variety of positive-corona regimes fitting into two categories:

(a) Steady, continuous positive discharges from the electrode tip, occurring under clean conditions and in the contaminated-plate system, where also a Hermstein glow may appear along the point electrode in the interacting mode of operation. Compared with the negative-point system in 5(b), a sparkover is less likely to occur in this case, i.e. this system is inherently more stable.

(b) Pulsed positive coronas of different visual forms and current waveforms (burst, streamer) which are primarily determined by the point contamination, but strongly suppressed by relative humidity. To develop the spark regime, there is an optimum degree of point contamination characterized here by the teflon-screen position $X \approx 0$, which also produces such operating conditions.

(7) Back corona in the positive-point system is a negative discharge operating in a pulsed regime similar, if not identical, to the Trichel-pulse corona from a negative point. A continuous regime of this negative back-corona
discharge has not been identified, presumably because the required current density cannot be obtained without evolving the spark regime.

(8) Back corona in the negative-point system is a positive discharge appearing as the Hermstein glow at relatively low currents. At higher currents, a pulsed regime (burst or streamer) is developed simultaneously with a transition to the continuous (negative-corona) regime at the point. Under such high-current conditions, this positive back corona may easily produce a spark, which is consistent with the characteristics of similar corona forms from the contaminated (positive) point.

(9) The lowest sparkover voltages (less than 50% of the clean-system value) have been observed in the following system configurations:

(a) contaminated positive point and clean plate (unipolar ionization, positive corona),

(b) clean negative point and contaminated plate (ambipolar ionization, positive back corona), and

(c) in bilaterally contaminated systems with positive point and a degree of screening characterized by $X \approx 0$, indicating a common, dominant effect of positive (breakdown) streamers.
# TABLE 4.2 Contaminated system characteristics

<table>
<thead>
<tr>
<th>TYPE OF CONTAMINATION</th>
<th>PLATE CONTAMINATION</th>
<th>MILLIPORE TEFON DISCS</th>
<th>FLY-ASH</th>
<th>POINT CONTAMINATION</th>
<th>BILATERAL CONTAMINATION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PAPER</td>
<td>MILLIPORE</td>
<td>FLY-ASH</td>
<td>MILLPORE LS</td>
<td>MILLPORE LS</td>
</tr>
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<td></td>
<td>FORM: 16, 500 RUN; 70 µm</td>
<td>LS pores 50±5 µm</td>
<td>LC pores 10±2 µm</td>
<td>mean particle size = 10 µm</td>
<td>position, mm variable</td>
</tr>
<tr>
<td>OPERATING CONDITIONS</td>
<td>T ºC</td>
<td>25</td>
<td>75</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>RH %</td>
<td>50</td>
<td>40</td>
<td>10</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>back corona</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>corona</td>
<td>4.22</td>
<td>4.32</td>
<td>4.41</td>
<td>4.47</td>
</tr>
<tr>
<td></td>
<td>corona</td>
<td>4.23</td>
<td>4.33</td>
<td>4.42</td>
<td>4.48</td>
</tr>
<tr>
<td></td>
<td>current-pulse</td>
<td>4.24</td>
<td>4.34</td>
<td>4.34</td>
<td>4.34</td>
</tr>
<tr>
<td></td>
<td>waveforms i&lt;sub&gt;c&lt;/sub&gt;_n(t)</td>
<td>4.25</td>
<td>4.35</td>
<td>4.43</td>
<td>4.49</td>
</tr>
<tr>
<td></td>
<td>derived i&lt;sub&gt;c&lt;/sub&gt;_n(t)</td>
<td>4.26</td>
<td>4.36</td>
<td>4.44</td>
<td>4.50</td>
</tr>
<tr>
<td></td>
<td>surface potential V&lt;sub&gt;s&lt;/sub&gt; = f(r)</td>
<td>4.28</td>
<td>4.37</td>
<td>4.45</td>
<td>4.51</td>
</tr>
<tr>
<td></td>
<td>corona</td>
<td>4.29</td>
<td>4.38</td>
<td>4.46</td>
<td>4.52</td>
</tr>
<tr>
<td></td>
<td>potential radial V&lt;sub&gt;s&lt;/sub&gt; = f(r)</td>
<td>4.30</td>
<td>4.39</td>
<td>4.53</td>
<td>4.63</td>
</tr>
<tr>
<td></td>
<td>axial V&lt;sub&gt;s&lt;/sub&gt; = f(z)</td>
<td>4.31</td>
<td>4.40</td>
<td>4.54</td>
<td></td>
</tr>
<tr>
<td></td>
<td>breakdown voltage V&lt;sub&gt;br&lt;/sub&gt; = f(d)</td>
<td>4.27</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**GLOSSARY OF TERMS**

(in addition to those defined in Table 4.1)

- d: contaminator thickness
- r: radius (cylindrical coordinate system)
- V<sub>s</sub>: potential within the plate contaminator
- V<sub>c</sub>: contaminator surface potential
- V<sub>br</sub>: breakdown voltage
**Fig. 4.22**

- **T = 25°C, RH = 50%**
- 0.9mm dia point, 40mm gap
- Contaminator: paper 70 μm
- 1, 2, 4, and 6 sheets

**Fig. 4.23**

- **T = 25°C, RH = 50%**
- 0.9mm dia point, 40mm gap
- Contaminator: paper 70 μm
- 1, 2, 4, and 6 sheets
$V = 25\,\text{kV}$

**Fig. 4.24**

- $T = 25^\circ\text{C}$, RH = 50%
- 0.9 mm dia point, 40 mm gap
- Contaminator: paper
- Negative corona

**Fig. 4.25**

- $f_p$
- $I_f \times 14.5$
- $I_0$, $I_1$

- 140 (2)
- 420 (6)

Paper thickness, $\mu$m (no. of sheets)
Paper characteristics

T = 25°C , RH = 50%
$T = 25^\circ \text{C}, \ \text{RH} = 50\%$

0.9 mm dia point, 40 mm gap

Contaminator: paper 70 μm

1, 2, 4, and 6 sheets
Radial potential distribution

\( T = 25 ^\circ C , \ RH = 50 \% \)

0.9 mm dia point, 40 mm gap
Contaminator: paper

Fig. 4.30
Axial potential distribution
0.9 mm dia point, 40 mm gap
Contaminator: paper

Fig. 4.31
Fig. 4.32

$T = 25 \degree C$, $RH \leq 10 \%$

0.9 mm dia point, 40 mm gap

Contaminator: paper

Fig. 4.33
Trichel pulses

Bandwidth
2 Hz - 10 MHz

Applied voltage $V = 25$ kV

Transition to steady corona

Transition to steady corona

$V = 22$ kV

$V = 23$ kV

Bandwidth
0 - 300 kHz

$T = 25 \, ^{\circ}C$, RH $\leq 10\%$

Contaminator: paper

Fig. 4.34

Negative-corona waveforms
Contaminator: paper

**Fig. 4.35**

- $I_4$, $x\times 14.5$
- $I_0$

- $f_p$
- kHz

- $I_1, I_0$
- 1 2 3 4 5 6

- 0 1 2 3 4 5 6 7 8 μA

- no. of paper sheets thickness 70 μm ea.

- $T = 25^\circ C$, RH $\leq 10\%$

- Operating points
  - o pos. corona
  - o neg. corona

**Fig. 4.36**

- 1.0 μA/div for (a), 5 nA/div for (a), 200 V/div

- $V_S$

- 500 V/div

- 6 paper sheets 70μm each
T = 25°C , RH = 10%
0.9 mm dia point, 40 mm gap
Contaminator: paper

Fig. 4.37

Positive corona

\[ +V_S \]

\[ 500 \text{ V/div} \]

\[ 4 \text{kV/div} \rightarrow +V \]

no. of paper sheets
thickness 70 μm ea.

\[ 6 \]

\[ 4 \]

\[ 2 \]

\[ 1 \]

Fig. 4.38

Negative corona

\[ -V_S \]

\[ 500 \text{ V/div} \]

\[ 4 \text{kV/div} \rightarrow -V \]

no. of paper sheets
70 μm each
Positive and negative corona

\[ T = 25^\circ C \, , \, RH \leq 10 \% \]

Contaminator: paper

---

Fig. 4.39

Applied voltage \( V = 24 \text{ kV} \)

- \( d = 420 \mu m \)
- \( d = 70 \mu m \)

Radial potential distribution

---

Fig. 4.40

Appied voltage \( V = 20 \text{ kV} \)

- \( V = 10 \text{ kV} \)

Paschen law

Axial potential distribution

- Plate
- Paper, thickness \( d = 420 \mu m \)
**Fig. 4.41**

$T = 75^\circ C$, RH = 30%

0.9 mm dia point, 40 mm gap

Contaminator: paper

**Fig. 4.42**
Fig. 4.43

T = 75°C, RH = 30%
Contaminator: paper

Fig. 4.44
T = 75° C, RH = 30 %
0.9mm dia point, 40 mm gap
Contaminator: paper
Fig. 4.47

Positive corona

$I_1$
14.5 μA/div

--- $I_o$
1.0 μA/div

4 kV/div $\rightarrow$ + V

$T = 75^\circ C$, RH ≤ 10 %
0.9 mm dia point, 40 mm gap
Contaminator: paper

Fig. 4.48

Negative corona

$I_1$
14.5 μA/div

--- $I_o$
1.0 μA/div

4 kV/div $\rightarrow$ - V

no. of paper sheets, 70 μm ea.
**Fig. 4.49**

No. of paper sheets, 70μm ea.

- 0 (clean)
- 2
- 6

\[ f_p = 10 \mu A/\text{div} \]

\[ V_s = 500 \text{ V/div} \]

\[ T = 75^\circ C, \text{ RH} \leq 10\% \]

Contaminator: paper

**Fig. 4.50**

Operating points:
- \( \circ \) pos. corona
- \( \bullet \) neg. corona

Paper characteristics:
- 6 paper sheets, 70μm ea.
Fig. 4.51

Positive corona

<table>
<thead>
<tr>
<th>$+V_S$</th>
<th>paper thickness, $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>$500 \text{ V/} \text{div}$</td>
<td>(no. of sheets)</td>
</tr>
<tr>
<td>$420 \text{ (6)}$</td>
<td></td>
</tr>
<tr>
<td>$280 \text{ (4)}$</td>
<td></td>
</tr>
<tr>
<td>$140 \text{ (2)}$</td>
<td></td>
</tr>
</tbody>
</table>

$T = 75^\circ \text{C}, \ \text{RH} \leq 10 \%$

0.9 mm dia point, 40 mm gap

Contaminator: paper

Fig. 4.52

Negative corona

$-V_S$

<table>
<thead>
<tr>
<th>$-V_S$</th>
<th>paper thickness, $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>$500 \text{ V/} \text{div}$</td>
<td>(no. of sheets)</td>
</tr>
<tr>
<td>$140 \text{ (2)}$</td>
<td></td>
</tr>
<tr>
<td>$280 \text{ (4)}$</td>
<td></td>
</tr>
<tr>
<td>$420 \text{ (6)}$</td>
<td></td>
</tr>
</tbody>
</table>

$4 \text{ kV/} \text{div}$

$-V$
Positive and negative corona

\[ T = 75^\circ C, \text{ RH } \leq 10\% \]

Contaminator: paper

---

**Fig. 4.53**

Radial potential distribution

---

**Fig. 4.54**

Axial potential distribution
\( T = 75^\circ C, \ RH = 70\% \)

0.9 mm dia point, 40 mm gap

Contaminator: Millipore LS (teflon) discs

thickness: 125 ± 15 \( \mu \)m

pores: 5 ± 1.5 \( \mu \)m
Fig. 4.57

4 kV/div - - - - -

$T = 75^\circ C$, RH = 70 %
0.9 mm dia point, 40 mm gap

Contaminator: Millipore LS (teflon) discs
- thickness: $125 \pm 15 \, \mu m$
- pores: $5 \pm 1.5 \, \mu m$

Fig. 4.58

500 V/div

4 kV/div - - - - -

+$V_s$

$-V_s$
Contaminator: Millipore LS (teflon) discs

- Thickness: 125 ± 15 μm
- Pores: 5 ± 1.5 μm

$T = 75^\circ C$, RH ≤ 10%.

0.9 mm dia point, 40 mm gap.
**Fig. 4.61**

- $V_s = 4 \text{kV/div}$
- $-V_s$

**Negative corona**

$T = 75^\circ \text{C}, \text{RH} \leq 10\%$

0.9 mm dia point, 40 mm gap

Contaminator: Millipore LS (teflon) discs

- thickness: 125 $\pm$ 15 $\mu$m
- pores: 5 $\pm$ 1.5 $\mu$m

**Fig. 4.62**

- $V_s = 500 \text{V/div}$
- $+V_s$

**Positive corona**

$T = 75^\circ \text{C}, \text{RH} \leq 10\%$

0.9 mm dia point, 40 mm gap

Contaminator: Millipore LS (teflon) discs

- thickness: 125 $\pm$ 15 $\mu$m
- pores: 5 $\pm$ 1.5 $\mu$m
**Fig. 4.63**

3 LS discs  
RH = 70%

**Fig. 4.64**

3 LS discs  
RH ≤ 10%

\[ V_r \]

\[ r \]

\[ kV \]

\[ 0 \quad 8 \quad 16 \quad 24 \quad 32 \quad mm \]

T = 75°C  
0.9 mm dia point, 40 mm gap

Contaminator: Millipore LS (teflon) discs  
thickness: 125 ± 15 μm  
pores: 5 ± 1.5 μm

Radial potential distribution
Characteristics of Millipore LS (teflon)
disc thickness: 125 ± 15 µm
pores: 5 ± 1.5 µm
**Fig. 4.67**

<table>
<thead>
<tr>
<th>T</th>
<th>75°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>RH</td>
<td>70%</td>
</tr>
<tr>
<td>0.9 mm dia point</td>
<td>40 mm gap</td>
</tr>
</tbody>
</table>

**Contaminator:** Millipore LC (teflon) discs,
- Thickness: 125 ± 15 µm
- Pores: 10 ± 2 µm

---

**Fig. 4.68**

**Negative corona**

---

**Positive corona**

14.5 µA/div

1.0 µA/div
\( T = 75^\circ C, \, RH = 70\% \)

Contaminator: Millipore LC discs

Positive-corona waveforms

Fig. 4.69
$T = 75^\circ C$, $RH = 70\%$

0.9 mm dia point, 40 mm gap

Contaminator: Millipore LC (teflon) discs

- thickness: $125 \pm 15 \mu m$
- pores: $10 \pm 2 \mu m$

---

**Fig. 4.70**

**Fig. 4.71**
Fig. 4.72

$T = 75^\circ C$, RH $\leq 10\%$

0.9 mm dia point, 40 mm gap

Contaminator: Millipore LC (teflon) discs

thickness: $125 \pm 15$ $\mu m$

pores: $10 \pm 2$ $\mu m$

Fig. 4.73
\[ T = 75 \, ^\circ \text{C}, \quad \text{RH} \leq 10 \, \% \]

Contaminator: Millipore LC discs

Positive-corona waveforms

Fig. 4.74
Contaminator: Millipore LC discs

Negative-corona waveforms

Fig. 4.75

\[ T = 70^\circ C, \ RH \approx 10\% \]

Contaminator: Millipore LC discs

Negative-corona waveforms
$T = 75^\circ C$, $RH \leq 10\%$

$0.9\text{mm diam point, 40mm gap}$

Contaminator: Millipore LC (teflon) discs

- Thickness: $125 \pm 15\ \mu m$
- Pores: $10 \pm 2\ \mu m$

---

**Fig. 4.76**

- Negative corona
- $4\ kV/\text{div}$
- $500\ V/\text{div}$
- $-V_s$
- $-V$
- No. of discs: 1, 2, 3

---

**Fig. 4.77**

- Positive corona
- $+V_s$
- $500\ V/\text{div}$
- $4\ kV/\text{div}$
- $+V$
- No. of discs: 1, 2, 3
**Fig. 4.78**

- Applied voltage, kV
- 3 LC discs
- RH = 70%

**Fig. 4.79**

- Applied voltage, kV
- 3 LC discs
- RH = 10%

**T = 75 °C**

- 0.9 mm dia point, 40 mm gap

**Contaminator: Millipore LC (teflon) discs**

- Thickness: 125 ± 15 μm
- Pores: 10 ± 2 μm

**Radial potential distribution**
\( T = 75^\circ C \)

0.9 mm dia point, 40 mm gap

Contaminator: fly-ash

layer thickness \( \leq 0.9 \text{ mm} \)

mean particle size \( \leq 10 \mu \text{m} \)
$T = 75^\circ C$

$0.9 \text{ mm dia point, } 40 \text{ mm gap}$

Contaminator: fly-ash

layer thickness $\approx 0.9 \text{ mm}$
mean particle size $\approx 10 \mu m$
Fly-ash characteristics:
layer thickness: 0.9 mm
mean particle size: $\leq 10 \mu m$

$T = 75^\circ C$
Varied parameter: RH
Point electrode screened by a teflon sleeve to simulate contamination

Visual forms of positive and negative corona
Fig. 4.86

$T = 75^\circ C$, $RH \leq 10\%$

0.9 mm dia point, 40 mm gap

Teflon sleeve screening the point

Varied parameter:
Teflon sleeve length

Fig. 4.87
$T = 75^\circ C$

0.9 mm dia point, 40 mm gap

Teflon sleeve screening the point

$X = -2.5 \text{ mm}$

Varied parameter: RH

---

**Fig. 4.88**

**Fig. 4.89**
$T = 75 ^\circ C$

0.9 mm point dia., 40 mm gap

Teflon sleeve screening the point

$X = 0$

Varied parameter: RH
Positive corona

Fig. 4.92

$T = 75 \, ^\circ C$, $RH = 50 \%$

0.9 mm dia point, 40 mm gap

Teflon sleeve screening the point

$X = 0$

Negative corona

Fig. 4.93

$-V = 12 \, kV$

$V = 12 \, kV$

$50 \, \mu A/\text{div}$

$1 \, mA/\text{div}$

$0.1 \mu \text{sec/\text{div}}$
\( T = 75^\circ C \)

0.9 mm dia point, 40 mm gap

Point contaminator:
- paper, single layer

Varied parameter: RH

--- End of Document ---
Fig. 4.96

T = 75 °C
0.9 mm dia point, 40 mm gap
Point contaminator: paper, double layer
Varied parameter: RH

Fig. 4.97
$I_1$ vs $I_0$

- $I_1$: 14.5 μA/div
- $I_0$: 1.0 μA/div

**Fig. 4.98**

- Positive corona
- Clean, 10% RH
- 10% RH
- Clean, 50% RH

**T = 75°C**

- 0.9 mm dia point, 40 mm gap
- Point contaminator: Millipore LS, single layer
- Varied parameter: RH

---

$I_1$ vs $I_0$

- $I_1$: 14.5 μA/div
- $I_0$: 1.0 μA/div

**Fig. 4.99**

- Negative corona
- Clean
- 50% RH
- 10% RH
**Figure 4.100**

- **I**
  - 14.5 μA/div
  - Positive corona
  - clean, 10% RH
  - 50% RH

- **I<sub>0</sub>**
  - 1.0 μA/div

- **T = 75°C**
- 0.9 mm dia point, 40 mm gap
- Point contaminator: Millipore LS, double layer
- Varied parameter: RH

**Figure 4.101**

- **I**
  - 14.5 μA/div
  - Negative corona
  - clean
  - 50% RH
  - 10%

- **I<sub>0</sub>**
  - 1.0 μA/div

- **4 kV/div**
- + V

- **4 kV/div**
- - V
T = 75 °C, RH ≤ 10%
0.9 mm dia point, 40 mm gap

Bilateral contamination
Contaminator: paper 70 µm
point: single layer
plate: double layer
Fig. 4.104

$T = 75^\circ C, \ RH = 30\%$

0.9 mm dia point, 40 mm gap

Bilateral contamination

Contaminator: paper 70 $\mu m$

point: single layer

plate: double layer

--- $I_1$

14.5 $\mu A$/div

--- $I_0$

1.0 $\mu A$/div

Positive corona

contaminated point only

clean

contaminated plate only

--- $I_1$

14.5 $\mu A$/div

--- $I_0$

1.0 $\mu A$/div

Fig. 4.105

Negative corona

going away

contaminated plate only

contaminated point only

plate only

clean

--- $I_1$

14.5 $\mu A$/div

--- $I_0$

1.0 $\mu A$/div

4 kV/div

- $V$

4 kV/div

$+ V$
T = 75° C, RH ≤ 10%
0.9 mm dia point, 40 mm gap
Bilateral contamination
Contaminator: Millipore LS
point: single layer
plate: single layer
T = 75°C, RH = 70%
0.9mm dia point, 40mm gap

Bilateral contamination
Contaminator: Millipore LS
Point: single layer
Plate: single layer
5.0 INTERPRETATION

Consistently with the approach concepts, this chapter is subdivided into sections presenting separate theoretical considerations for

(a) the gaseous medium under clean-electrode conditions, in section 5.1,

(b) the porous insulating solid, in section 5.2, and

(c) the composite system comprising both media (a) and (b), in section 5.3

The models and formulations introduced in sections 5.1 and 5.2, to describe the current-conduction properties of the two media individually, are applied in section 5.3 to characterize the composite-system operation in two basically different modes, non-interacting and interacting.

In interpreting the specific experimental results, an attempt has been made to formulate basic characteristics in terms of more generally applicable lumped parameters. This aim was stimulated by the fact that the investigated corona systems as technical devices lack the parametric formulation of their characteristics, which, by comparison, is commonly used for semiconductor devices. Consequently, an analysis of conduction processes and field conditions is performed to justify a synthesis of more generalized models representing overall characteristics.
5.1.0 Clean-system characteristics

A semi-quantitative analysis of clean-system characteristics, primarily for the range of conditions used in these experiments, is conveniently resolved into separate formulations for the current-conduction processes occurring in distinct time intervals and/or distinct regions of the interelectrode space.

Under experimental conditions, the time-dependent processes are peculiar to negative corona only, producing a repetitive current waveform with two distinct time intervals described here as:

(a) the ionization period $T_i$, characterized by the generation of positive and negative charge carriers, of which only negative carriers remain in the interelectrode space at the end of this period;

(b) the transport period $T_t$, characterized by the motion of negative charge carriers without simultaneous generation. The repetition period of Trichel-pulses is $T_p = T_i + T_t \approx T_t$.

However, the formulation for the transport of carriers without generation equally applies for positive corona, outside its (steady) ionization region.

In the interelectrode space, three regions with specific processes and rather arbitrarily defined boundaries are distinguished.

(1) the ionization region, characterized by plasma conditions with overall charge neutrality during ionization (continuous for positive corona), and no space charge during the
transport period for negative corona; ionization does not occur in other regions;

(2) the accumulation or buffer region (relevant for negative corona only, under experimental conditions) adjacent to the ionization region, and characterized by a high density of negative carriers generated during an ionization period and accumulated in this region; the accumulation of space charge causes the quenching of the ionization process by reducing the field strength and voltage drop across the ionization region; subsequently, during the transport period the space charge accumulated in this region is fully or partly transferred into the next region, so that the accumulation region acts as a buffer between the ionization region and

(3) the transport region, which is characterized by steady conditions not only for positive corona, but also for negative corona at high repetition frequencies of avalanches (such as the distinct repetition frequencies of Trichel pulses observed, i.e. > 20 k Hz) when the buffer region provides a continuous supply of charge carriers.

Without underestimating the complexity of processes involved (ionization in particular), simplifications are necessarily introduced in describing only the most significant electrical effects rather than analysing such processes in detail.
5.1.1 Ionization period - Trichel-pulse shape

The frequency spectrum of Trichel-pulses has been measured by W. Heintz [18], who has also found that a consistent expression for the current is of the form

\[ i_p(t) = B t^{-3/2} \exp \left[ -\frac{\tau}{t} - \beta t \right] \] Eq. 5.1.1

Heintz has interpreted this current waveform as a diffusion current of negative carriers. This concept is incompatible with the coincidence of Trichel-pulses and ionizing avalanches (manifested by luminosity and measured by Amin). As the ionization process is restricted to a relatively small region at the point, it should be emphasized that the current pulse simultaneously observed at the plate electrode can only be a displacement current, because the time required for generated negative charge carriers to cross the transport region by drift and/or diffusion (few milliseconds according to Amin's measurements) is at least 1000 times longer than the Trichel-pulse duration (about \(10^{-7}\) sec). The implied independence of this current on carrier transport conditions is confirmed by the author's comparative measurements of contaminated-system characteristics, showing an unaltered shape of individual pulses irrespectively of the plate contamination with insulating layers, porous and non-porous, provided that the discharge remains in the pulsed mode.

Nevertheless, in the author's opinion it is justified to describe the ionization process by a continuity equation for negative carriers in the buffer region, where the density of positive carriers is
negligible (which cannot be said for the ionization region) and the negative-charge accumulation is a direct result of the ionization process, so that the generation rate is also the injection rate of negative carriers into the buffer region.

The following semi-quantitative analysis shows that, by restricting the applicability of continuity equation to the buffer region and defining the current as a displacement current, the resulting functional form for the Trichel-pulse current $i_p(t)$ is the same as in equation 5.1.1.

The continuity equation is

$$\frac{\partial n}{\partial t} = |\alpha \vec{v} n| + \frac{1}{q} \nabla \cdot \vec{J} = Eq. 5.1.2$$

$$= |\alpha \vec{v} n| + \frac{1}{q} \nabla \cdot (q \mu_n n \vec{E} + q D_n \nabla n)$$

where $n$ is the density of an average type of negative carriers, $\alpha$ is the first Townsend coefficient (representing also secondary effects), $\vec{V} = -\mu_n \vec{E}$ is the drift velocity and $D_n$ is the diffusion constant for average negative carriers. The origin of the coordinate system is placed concentrically with the hemispherical tip of the point electrode, with the positive $z$-direction axially towards the plate. An ionization process is initiated at $t = 0$.

In order to obtain an analytical solution, it is convenient to apply the average-value approximations used by Heintz. These approximations are
(a) \( v = v_z = \text{const.} \), and
\[
E = E_z = \text{const.}, \text{ characterizing the resultant average movement of carriers,}
\]
(b) \( \alpha = \text{const} \), which implies that the ionization conditions are arbitrarily defined.

In addition, the accumulation region which is also the applicability region for equation 5.1.2, is approximated here by a spherical shell of an average radius \( r_A \). In the chosen Cartesian coordinate system, this is expressed as
\[
(c) \quad x^2 + y^2 + z^2 \approx r_A^2.
\]

The shape of a corona discharge (or an ionization region) is only partly determined by the point-electrode geometry, as evident from its visual appearance recorded by Trichel [24], Kip [25], Wagner [26] and many other authors.

Consequently, the expression (c) should be also regarded as an average-value approximation.

Using approximations (a) and (b), the following simplified form of equation 5.1.2 is obtained:
\[
\frac{\partial n}{\partial t} = \alpha v_z n + D_n \nabla^2 n - v_z \frac{\partial n}{\partial z} \quad \text{Eq. 5.1.3}
\]

The solution of this approximate continuity equation, with \( K \) as an arbitrary constant, is
\[ n(x,y,z,t) = K t \frac{3}{2} \exp \left[ -\frac{x^2 + y^2 + (z - v_z t)}{4 D_n t} + \alpha v_z t \right] \]

\[ = K t \frac{3}{2} \exp \left[ -\frac{x^2 + y^2 + z^2}{4 D_n t} - \left( \frac{v_z^2}{4 D_n} - \alpha v_z \right) t + \frac{z v_z}{2 D_n} \right] \]

Eq. 5.1.4 (a)

By introducing the approximation (c), a function of time for the average carrier density arriving into the accumulation region is obtained:

\[ n(t, r_A) = K^1 t^{3/2} \exp \left[ -\frac{t}{\tau} - \beta t \right] \]

Eq. 5.1.4 (b)

The constants are \( \tau = r_A^2/4 D_n \), \( \beta = (v_z^2/4 D_n) - \alpha v_z \), and \( K^1 = K \exp \left( r_A v_z/2 D_n \right) \).

The charge generated by an avalanche and injected into the buffer region is

\[ Q_p = q A_A \int_{v_z}^{T_i} n(t, r_A) dt \]

Eq. 5.1.5

where \( A_A \) is an effective area of the spherical buffer region.

The current observed at the plate electrode is determined by the rate of change of the total space charge \( Q_p + Q_t \) (where \( Q_t \) is the space charge in the transport region). The plate-electrode current is

\[ i_p(t) = \frac{\partial Q_p(t)}{\partial t} + \frac{\partial Q_t(t)}{\partial t} \]

Eq. 5.1.6

The second term in equation 5.1.6 represents the ion removal at the plate and/or drift movement of ions in the transport region. These processes are much slower (as indicated by the crossing times of ions).
than the ionization process, justifying the approximation

\[ i_p(t) \approx \frac{\partial q_p(t)}{\partial t} = q A_A v_z n(t, r_A) \]

Eqn. 5.1.7.

\[ = q A_A v_z K^1 t^{-3/2} \exp \left[ \frac{-\tau}{t} - \beta t \right] \]

which applies only for the ionization period \( T_{i1} \), and it is of identical functional form as equation 5.1.1.

**Discussion**

The continuity of current flow in a loop closed through the external circuitry and power supply is clearly expressed by equation 5.1.7, namely that the current formed by the negative carriers injected into the buffer region continues to flow in the external circuit as an induced displacement current.

As a numerical illustration, the fitting values \( \tau \approx 10^{-8} \text{ sec} \) and \( \beta \approx 5 \times 10^6 \text{ sec}^{-1} \) found by Heintz for a system with 0.06 mm point diameter and 20 mm gap width, also apply to the \( i_p(t) \) waveform measured by the author at 25 mm gap width and 0.9 mm point diameter (figure 4.9).

It should be noted that the contribution of diffusion, although negligible in the direction of a strong axial (z-direction) electric field, is significant for the lateral dispersion of carriers and consequent decrease in carrier density. A negligible diffusion component of the current flowing towards the plate can be confirmed by a simple consideration for the orders of magnitude. Under experimental conditions used, the order of magnitude for the applied voltage is
$10^4$ V, and for the voltage drop across the buffer region at least $10^2$ V (estimated from the potential distribution without space charge, as calculated by Loeb, Parker, Dodd and English [14], for an assumed buffer region one point radius wide at a distance from the point surface of minimum 5 point radii). Even if the density of injected carriers $n$ falls to zero (i.e. $\Delta n/n \approx 1$) within the buffer-region width $\Delta z$, the ratio of diffusion and drift currents

$$\frac{D_n \Delta n/\Delta z}{\mu_n E_z n} = \frac{(kT/q)(\Delta n/n)}{E_z \Delta z} \approx \frac{kT/q}{10^2} = \frac{T}{1.16 \times 10^6}$$

would be equal to unity for an improbably high carrier temperature $T$ of about $10^6$ °K.

To understand the difference between Trichel pulses recorded for the central disc, $i_{p_0}$ (Table 4.1), and the remaining part of the plate electrode, $i_{p_1}$, it is necessary to consider a deviation from average conditions (which are implied in eq. 5.1.7 and applicable to $i_{p_1}$) as appropriate for the central region and current $i_{p_0}$. In equation 5.1.7 the magnitudes of $v_z$ and $\alpha$ affect particularly the time constant

$$\frac{1}{\beta} = \left[ (v_z^2/4 D_n) - \alpha v_z \right]^{-1},$$

which determines the trailing edge of a current pulse $i_p$. It has been pointed out in section 4.1, that $i_{p_0}$ pulses have a longer duration than $i_{p_1}$ pulses. More specifically, the fall time of $i_{p_0}$ is longer. The observed rise times do not differ, although this is possibly due to the rise-time limitations of the measuring circuit used. However, the rise-time determining constant $\tau = r^2_A/4 D_n$ in equation 5.1.7 is also independent of $v_z$ and $\alpha$.

Considering that the maximum field strength for a point-to-plane
geometry occurs in its axis of symmetry, the appropriate values of $E_z$ and $v_z = \mu_n E_z$ must be larger for $i_{p0}$ than for $i_{p1}$. A higher value of $\alpha$ in the central region is also consistent with a higher field strength. Defining $\alpha$ in equation 5.2 as a composite ionization coefficient representing also secondary effects, its effective value for the central region is enhanced by taking into account the secondary emission of electrons from the point due to positive ion bombardment. (Amin has emphasized that this effect is particularly significant in the central region.) Consequently, a proportionally larger increase in $\alpha$ than in $v_z$ can be expected for the central region, resulting in a larger time constant $\frac{1}{\beta}$ and slower decay of $i_{p0}$ pulses in comparison with $i_{p1}$ pulses.

5.1.2 Transport period

To formulate the transport of charge carriers it is necessary to define (a) a field pattern which determines the drift of carriers and (b) those conditions for ionization which determine the duration $T_t$ between two avalanches for negative corona, and influence the potential distribution both for positive and negative corona.

To achieve the generality of analytical solutions, which are not obtainable from field equations point-to-plane geometry, the following method is applied. A definite field pattern in the point-to-plane corona system is assumed and an arbitrary flux tube from the relevant part of the system (i.e., from a relatively restricted zone where the corona processes - ionization and transport - take place) is chosen to be analysed. Using a suitable conformal transformation such a flux
A flux tube can be transformed into a regular prism, with its bases corresponding to the electrode boundaries of the original flux tube, and the distance from one of the bases becoming the only spatial variable. To realize such conformal transformation, it would be necessary to approximate the actual field configuration by an orthogonal three-dimensional system with rotational symmetry and separability of variables, enabling a conformal transformation into the Cartesian one-dimensional model by known methods [27]. (As the choice of such systems is limited, perhaps the best fitting would be obtained by a spheroidal system with hyperboloids as equipotentials.) The transport and ionization conditions are analysed and formulated in this one-dimensional model. The results for terminal current-voltage characteristics are applied to the original point-to-plane system, without performing the conformal transformation, by introducing suitable lumped parameters independent of geometrical transformations. As these solutions apply to any relevant flux tube of the original point-to-plane geometry, the average values of lumped parameters may be used to characterize the whole system.

For negative corona, the transport conditions depend essentially on the total space-charge modulation, expressed as a ratio
\[ \frac{Q_p}{(Q_p + Q_t)} = \frac{1}{1 + \frac{Q_t}{Q_p}} \]
where \( Q_p \) is the charge removed during the transport period \( T_t \) and \( Q_p + Q_t \) is the total space charge at the beginning of this period. At onset the modulation is 100\% (i.e., \( Q_t = 0 \)), and approaches zero with increasing frequency of Trichel pulses (i.e., \( Q_p << Q_t \)) at higher applied voltages.
Using the one-dimensional model, the transport of carriers is analysed for the two extremes of space-charge modulation. The conditions at onset or 100% modulation are specific for negative corona, while the low modulation conditions are common for positive corona and negative corona at voltages considerably above onset, at high repetition frequencies of Trichel pulses.

(A) Conditions at onset - 100% space charge modulation

In a one-dimensional representation, as suggested above, the space charge and field distribution in a flux tube are shown in figure 5.1.

Before the first avalanche occurs the applied voltage must reach a critical onset level \( V = V_c \), producing a uniform field \( E_c = V_c / Z_L \) in this model. The actual potential distribution in point-to-plane configuration, calculated by Loeb et al [14] and indicated for various stages of ionization in a number of diagrams [2], forms a high-field region at the point. The necessary condition for ionization, expressed by the Townsend criterion \( \gamma \exp \int \alpha \, dz = 1 \), is satisfied in this region when \( V = V_c \). An avalanche can start as soon as the triggering electrons become available. This high field region, described here as the ionization region, does not extend more than 5 point radii from the point surface. Characteristically, this is also a region where approximately half of the applied voltage is dropped under space-charge-free conditions. Quoting the results obtained by Loeb et al [14], the calculated axial distance from the point for 50% voltage drop is 3 point radii, compared with a distance of 4 point radii measured in an electrolytic tank model.
Consequently, in the one-dimensional model, a critical field strength at the "point" can be specified as

\[ E_{p \, \text{crit}} = E_c = \frac{V}{Z} \approx \frac{V}{2Z_{10}} \]  

Eq. 5.1.8

where \( Z_{10} \approx \frac{Z}{2} \) is the conformally transformed boundary between ionization and buffer regions, and \( Z_{L} \) is the distance between "point" and "plate" boundaries (in figure 5.1, \( Z_{10} \) is arbitrarily placed for graphical convenience).

Subsequently, during the first avalanche a negative charge \( Q_A \) (a fraction of the generated charge \( Q_p \) contained within the particular flux tube) is injected into the buffer region \( W_0 = Z_{20} - Z_{10} \), and an equal positive charge is removed from the ionization region into the "point" (assuming negligible recombination). The ionization ceases as the field \( E_p \) drops to an extinction level \( E_{p \, \text{ext}} \).

At the beginning of the following transport period, \( t = 0 \) and only the charge \( Q_A \) with an average density of its carriers \( n_0 \) forms a relatively narrow space charge layer \( W_0 \ll Z_L \).

In considering the movement of this space charge layer and corresponding "plate" current density \( J_L \), the effect of diffusion is ignored. To justify this approximation, similarly as in section 5.1.1, it is appropriate to assess the ratio of the diffusion transit time in the one-dimensional model, approximately \( (Z_{L} - Z_{20})^2/D_n \), and the drift transit time, approximately \( 2(Z_{L} - Z_{20})^2/\mu_n V_c \) for a small field distortion by the space charge and a voltage across the transport region about
$V_c/2$. Their ratio, $q V_c/2kT$, is of the order of magnitude $10^7/T$, which indicates that the carrier movement by diffusion is relatively very slow for all reasonable carrier temperatures.

In the one-dimensional model, within the space-charge layer of uniform carrier density $n$ there is a constant field gradient

$$\nabla^2 V = \frac{dE}{dZ} = \frac{qn}{\epsilon}$$

Eq. 5.1.9

Since there is no recombination, the difference $E_A$ between field strength at the leading edge $E_L$ (in this model, equal to the field at the "plate") and trailing edge $E_P$ (equal to the field at the "point"),

$$E_A = E_L - E_P = \frac{q n_0 w_0}{\epsilon}$$

Eq. 5.1.10

is constant for any position of the space-charge layer before it reaches the "plate". However, the space-charge widens as it traverses the gap, because the leading-edge drift velocity is

$$\mu n E_L = \frac{dZ_2}{dt}$$

Eq. 5.1.11

and the trailing-edge velocity is lower

$$\mu n E_P = \mu n (E_L-E_A) = \frac{dZ_1}{dt}$$

Eq. 5.1.12

The time variation of the layer width $w = z_2-z_1$ is readily obtained from equations 5.1.11 and 5.1.12 by integration, with the result

$$w = w_0 + \mu n E_A t$$

Eq. 5.1.13

The average density of carriers decreases correspondingly, i.e.

$$n = \frac{n_0 w_0}{w}$$
The displacement current density at the electrodes can be determined by calculating the time dependence of $E_L$ or $E_P$:

$$J(t) = \frac{\partial D}{\partial t} = \varepsilon \frac{\partial E_L}{\partial t} = \varepsilon \frac{\partial E_P}{\partial t} \quad \text{Eq. 5.1.14}$$

The condition that the potential difference between electrodes is equal to the applied voltage $V_C$, is expressed as

$$V_C = E_C Z_L = (E_L - E_A)Z_1 + \frac{E_A}{2}(Z_2 - Z_1) + E_L(Z_L - Z_2)$$

or

$$E_C Z_L = -\frac{E_A}{2}(Z_1 + Z_2) + E_L Z_L \quad \text{Eq. 5.1.15}$$

A differential equation for $E_L$ as a function of time is obtained by differentiating equation 5.1.15 and substituting equations 5.1.11 and 5.1.12:

$$E_A \frac{\partial}{\partial t} (Z_1 + Z_2) = \frac{E_A}{2} \mu_n \left(2E_L - E_A\right) = Z_L \frac{\partial E_L}{\partial t} \quad \text{Eq. 5.1.16}$$

With the boundary condition at $t = 0$, $E_{L0} \approx E_C + \frac{E_A}{2}$ because $Z_{10} \approx Z_L/2$ and $Z_{10} + Z_{20} \approx Z_L$, equation 5.1.16 has the solution

$$E_L = \frac{E_A}{2} + E_C \exp \left[\mu_n \frac{E_A}{Z_L} t\right]$$

$$= \frac{E_A}{2} + E_C \exp \left[\frac{E_A}{E_C} \frac{t}{T}\right]$$

where $T = Z_L/\mu_n E_C$ is a carrier crossing time at onset, for the full interelectrode distance and negligible space-charge effect.

An expression for the "plate" current density is obtained by
substituting equation 5.1.17 into 5.1.14

\[ J_L = \epsilon \mu n \frac{E_A}{Z_L} E_C \exp \left( \frac{\mu n}{Z_L} E_A t \right) \]

Eq. 5.1.18

\[ = \epsilon \frac{E_A}{T} \exp \left( \frac{E_A}{E_C} \frac{t}{T} \right) \]

For small space-charge distortion, i.e. \( E_A \ll E_C \) (compatible with operating conditions used in experiments), the field strength \( E_L \) is approximately

\[ E_L \approx E_A/2 + E_C \left( 1 + \frac{E_A}{E_C} \frac{t}{T} \right) \]

Eq. 5.1.19

\[ = E_C + E_A \left( 0.5 + \frac{t}{T} \right) \]

The corresponding current density is

\[ J_L \approx \epsilon \frac{E_A}{T} \left( 1 + \frac{E_A}{E_C} \frac{t}{T} \right) = \epsilon \frac{E_A}{T} \]

Eq. 5.1.20

and the time required for the leading edge \( Z_L \) to reach the "plate" is

\[ T_1 \approx \frac{Z_L - Z_20}{\mu E_C} \approx \frac{2(Z_L/2)^2}{\mu V_C} = \frac{T}{2} \]

Eq. 5.1.21

During this transit interval, the "plate" current density is defined by equations 5.1.18 or 5.1.20.

The transport of carriers is completed in the subsequent time interval \( T_2 = T_t - T_1 \), when the initially injected carriers are collected by the "plate". During this clearing interval, the space-charge layer \( W_2 = Z_L - Z_{12} \) shrinks at the rate
At the same time, the density of carriers $n$ decreases at a rate determined by the continuity equation

$$- \frac{\partial n}{\partial t} = \frac{n \mu (E_n - E_p)}{w_2} = \frac{q \mu n^2}{\epsilon}$$

Eq. 5.1.23

where $E_n - E_p = E_{A2} = \frac{q n w_2}{\epsilon}$. With the boundary condition $n = n_{T_1}$ at $t = t_1$, the solution of equation 5.1.23 is

$$n = \frac{n_{T_1}}{1 + n_{T_1} \frac{q \mu n}{\epsilon} (t - T_1)}$$

Eq. 5.1.24

From equation 5.1.15, for $Z_2 = Z_L$ and $Z_L - Z_1 = w_2$, the "point" field strength is

$$E_p = E_L - E_{A2} = E_C - E_{A2} \frac{w_2}{2Z_L} = E_C - \frac{q n w_2}{2 \epsilon Z_L}.$$  

Eq. 5.1.25

This field strength reaches again the critical value for ionization $E_p \text{crit} = E_C$ when $w = 0$, i.e. at $t = T_t$. Simultaneously the "plate" field $E_L$ decreases to $E_C$ from its maximum, approx. $E_C + E_A$ at $t = T_1 \approx T/2$.

Solutions for the time variation of $w_2$, current $J_L = q \mu n E_L$, and total transport time $T_t$ are obtainable from equations 5.1.23,25,24 by numerical methods. However, the relationships are simplified with the previously used assumption $E_A \ll E_C$, and consequently $n \approx n_{T_1} \approx n_0$ and $w_{T_1} = w_0$. 
Equations 5.1.25 and 5.1.23 are simplified to

\[
\frac{E_p}{E_c} = E_c \left(1 - \frac{w_2}{2Z_L} \frac{E_{A2}}{E_c}\right) \approx E_c
\]
as both \( w_2/2Z_L \ll 1 \) and \( E_{A2}/E_c \ll 1 \), and

\[
\frac{\partial w_2}{\partial t} \approx -\mu E_c = -\frac{Z_L}{T},
\]

with the result

\[
w_2 = w_0 - Z_L \frac{t-T_1}{T} \quad \text{Eq. 5.1.26}
\]

Then the transport period \( T_t \) is determined from the condition \( w_2 = 0 \) at \( t = T_t \),

\[
T_t \approx T_1 + \frac{w_0}{Z_L} T = T_1(1 + 2 \frac{w_0}{Z_L}) \quad \text{Eq. 5.1.27}
\]

For a narrow space-charge layer \( w_0 \ll Z_L \), as initially assumed, the transport period is determined by the drift transit time of carriers. Consequently, the expected repetition period of Trichel-pulses is

\[
T_p = T_1 + T_t \approx T_1 \approx \frac{2(Z_L - Z_{20})^2}{\mu_n V_c} \quad \text{Eq. 5.1.28}
\]

**Discussion**

Although at onset no distinct periodicity has been observed in experiments, the calculated period from equation 5.1.28 for typical experimental conditions (transforming to point-to-plane geometry \( Z_L - Z_{20} \approx L = 40 \text{ mm}, V = 8 \text{ kV measured, and } \mu_n \approx 3 \text{ cm}^2/\text{V sec} as a known value [2][22] \) is \( T_t \approx 4/3 \text{ m sec} \), which is in agreement with Amin's
measurements of ion transit times (about 2 m sec, under similar experimental conditions).

Over a period $T_p$, the total charge flow per unit area of the "plate" is $2q n_0 w_0$, i.e., twice the negative charge created by an avalanche, consistent with the generation of an equal number of positive and negative carriers. The charge-flow distribution is

(a) for the ionization period, $q n_0 w_0/2$ (implied by the boundary condition for equation 5.1.16),

(b) for the transport period, subdivided into transit interval, $q n_0 w_0/2$ (from equation 5.1.20), and clearing interval, $q n_0 w_0$ (from equation 5.1.25).

Therefore, the average "plate" current density

$$J_{L \text{ av}} = \frac{2q n_0 w_0}{T_p}$$

describes basically the same relationship observed above onset at distinct repetition frequencies (equation 4.1).

Contrary, the current composition implicitly described by equations 5.1.7, 5.1.17 and 5.1.25, is different from that observed above onset. Assuming that the experimental conditions at onset are adequately characterized by $E_A << E_c$ and $w_0 << Z_L$, the pulse pedestal current density $J_L$ predicted by equation 5.1.20 is only $J_{L \text{ av}}/4$, and a pulse produced by the space-charge removal ($T_1 < t < T_L$) is merged with the following ionization-period pulse (provided that there is no triggering delay), forming an apparently large Trichel-pulse contributing
\[ J_L \text{ av}. \] With unsteady conditions at onset, the author's measurements do not provide quantitative evidence for comparison, except that generally large Trichel-pulses have been observed at onset.

At smaller interelectrode distances and significant space-charge distortion of the field \( E_L \), certain current peaking would occur at \( t = T_1 \). This effect is a possible explanation for a secondary peak, occurring a few microseconds after the initial Trichel-pulse, observed by Sawa, Shinohara and Ieda \([28]\) in experiments with small gaps (1 to 2 mm).

(B) **Conditions above onset - negligible space-charge modulation**

Under experimental conditions used by the author, the repetition frequency of Trichel-pulses becomes distinct at an average plate current \( > 10 \mu\text{A} \) with a corresponding frequency \( \geq 30 \text{ kHz} \) (e.g., figure 4.13). This occurs at an applied voltage of \( (1.5 \text{ to } 2) \times V_c \). All waveform measurements, with results presented in section 4.1, have been performed at applied voltages above \( 1.5 V_c \). For this range of voltages the repetition period \( T_p \), compared with the ion transit time \( T_1 \), is

\[ T_p < 10 T_1 \approx 10 T_p, \text{ onset.} \]

Conditions in the ionization region, described in the one-dimensional model, are considered to be the same as at onset, i.e., that an avalanche starts when the field strength reaches \( E_{p \text{ crit}} \) (equation 5.1.8) and is quenched by the generated negative space charge, which reduces the field strength to an extinction level \( E_{p \text{ ext}} \). The next avalanche starts when this charge is transferred from its initial position,
arbitrarily described as a buffer region, into the transport region and an equal charge removed at the "plate", resulting in an increase of $E_{p}$ to the critical value $E_{p}^\text{crit}$. In the transport region there is a space charge formed by carriers generated in many previous avalanches, because the transit time is much longer than the repetition frequency of avalanches.

The one-dimensional description of space-charge and field conditions above onset is illustrated in figure 5.2. The distribution of space charge for $V = V_1$, slightly above onset, is indicated as discrete with individual space-charge layers of increasing width and correspondingly lower density as they approach the "plate". In this case, the space-charge modulation is still significant. As the applied voltage increases and the carrier injection rate $f_p = \frac{1}{T_p}$ becomes much higher than $\frac{1}{T_1}$, a continuous space-charge distribution is approached. Also, the diffusion of individual ion groups definitely contributes to the formation of a continuous distribution. For steady positive corona, the continuity of space charge is inherent. In figure 5.2, such continuous distribution is shown at a voltage $V_2 > 1.5 V_C$.

For a continuous injection of carriers, the one-dimensional formulation of conditions in the space-charge region is

$$J = J_L = q \mu_n n E$$

and

$$\frac{dE}{dz} = \frac{J}{\varepsilon \mu_n E}$$

Eq. 5.1.29
The initial condition for equation 5.1.29 is $E = E_p \text{crit} \approx E_c$ at $Z = Z_1$, which is true for steady positive corona at all times, but for negative corona only at $t = T_t$ and $Z = Z_{11}$, i.e. for a minimum width of the space-charge region in figure 5.2 for which the supply of carriers is regarded as continuous. However, a large space charge in the transport region ($Q_t > Q_p$) causes also $E_p << E_L$ and consequently, by comparing equations 5.1.22 and 23, $\frac{w}{n} \frac{\partial n}{\partial t} \gg \frac{\partial W}{\partial t} = -\frac{\partial Z_1}{\partial t}$.

This relationship implies that for a low space-charge modulation, the width of the space-charge region (comprising both the buffer and transport regions) is almost constant.

Integration of equation 5.1.29 yields

$$E^2 - E_{p \text{crit}}^2 = \frac{2J}{\epsilon \mu} (Z-Z_1). \quad \text{Eq. 5.1.30}$$

Introducing new variables $E_{\text{eff}}^2 = E^2 - E_{p \text{crit}}^2 \approx E^2 - E_c^2$ and $w = Z - Z_1$, the effective field strength is

$$E_{\text{eff}} = \sqrt{\frac{2J}{\epsilon \mu_n} w}$$

and the corresponding effective voltage

$$V_{\text{eff}} = \int_0^{W} E_{\text{eff}} \; dW = \frac{2}{3} \sqrt{\frac{2J}{\epsilon \mu_n}} W_L \quad \text{Eq. 5.1.31}$$

where $W_L = Z_L - Z_1$ is the space-charge width.

The resulting current-voltage relationship

$$J_L = \frac{9}{8} \epsilon \mu \frac{V_{\text{eff}}^2}{W_L^3}, \quad \text{where } \mu = \mu_n \text{ for negative ions} \quad \text{Eq. 5.1.32(a)}$$

and $\mu = \mu_p$ for positive ions,
describes the rate of charge-carrier removal at the "plate", and represents (a) the average current for positive corona and (b) the pedestal current only for negative corona. The continuity of current flow is maintained at the "point" (a) for positive corona, by a flow of electrons generated in the ionization region, and (b) for negative corona, as a displacement current

\[ J_p = \varepsilon \frac{\partial E_p}{\partial t} = \varepsilon \frac{\partial}{\partial t} \left( E_{p \text{ ext}} + \frac{J_{L \text{ t}}}{\varepsilon} \right) = J_L. \]

The charge removed at the "plate" during a transport period \( T_t \) equals the charge injected into the buffer region during an ionization period \( T_i \ll T_t \), i.e.

\[ \varepsilon (E_{p \text{ crit}} - E_{p \text{ ext}}) = J_L T_t, \]

indicating a current composition as experimentally observed (equation 4.1), with an average current density for negative corona.

\[ J_{L \text{ av}} = \frac{\varepsilon (E_{p \text{ crit}} - E_{p \text{ ext}}) + J_L T_t}{T_p} \approx 2 J_L = \frac{18}{8} \varepsilon \mu_n \frac{V^2}{W^3_{eff}}. \]

Eq. 5.1.32 (b)

These one-dimensional formulas (equations 5.32 (a) and (b)) express that the average current-voltage relationship is quadratic for any unipolar corona system, provided that the discharge mode is as assumed, i.e. with an ionization region substantially shorter than the inter-electrode distance, so that the space charge in the transport region determines the overall current-voltage relationship. The width \( W_L \) of the space-charge region depends on, but is not fully determined by, the
electrode geometry, being influenced also by the gas pressure and composition, electric field strength and polarity. Comparing the average current-voltage characteristics in a particular system, it should be noted that $W_L$ need not be the same. For example, relative to negative Trichel-pulse discharge, positive streamers represent an elongated ionization region with correspondingly shorter $W_L$.

The results obtained here apply through an appropriate conformal transformation to any flux tube of the actual field pattern where the discharge region is included. To demonstrate the compatibility of these expressions with the measured point-to-plane characteristics above onset, equations 5.1.32 (a) and (b) are to be extended to describe the total current. In the following section an approximate generalization is obtained by using capacitance and average interelectrode distance as lumped parameters, invariant in conformal transformations.

5.1.3 Lumped parameter formulation

For a "plate" area $\Delta A$ in the one-dimensional model of a flux tube, its average positive and negative corona currents, $\Delta I_+$ and $\Delta I_-$ respectively, follow from equations 5.1.32 (a) and (b):

$$\Delta I_+ = \frac{9}{8} \epsilon \mu_p \frac{V^2_{\text{eff}}}{W_L^3} \Delta A \quad (a)$$

and

$$\Delta I_- = \frac{18}{8} \epsilon \mu_n \frac{V^2_{\text{eff}}}{W_L^3} \Delta A \quad (b)$$

Eq. 5.1.33

To formulate the terminal current-voltage characteristics for point-to-plane configuration, it is necessary to find a relationship
between $V_{\text{eff}}$ and applied voltage $V$, i.e. to evaluate the defining integral (equation 5.1.31)

$$V_{\text{eff}} = \int_0^{W_L} E_{\text{eff}} \, dW = \int_0^{W_L} \sqrt{(E-E_{p \text{ crit}})(E+E_{p \text{ crit}})} \, dW,$$

Eq. 5.1.34

and also, it is convenient to recognize that

$$\epsilon \Delta A/W_L = \Delta C_W = \frac{\partial}{\partial W_L} (\Delta Q_W)/\partial V_W \quad \text{Eq. 5.1.35}$$

is the space-charge-region capacitance for a particular flux tube. As a ratio of charge and voltage, capacitance does not vary with conformal transformations.

An equipotential boundary between the ionization and buffer regions on one side, and the plate electrode on the other side of the space charge region become terminals of this circuit element.

With the previously used approximations $W_L \approx Z_L/2$ and $E_{p \text{ crit}} = E_c = V_c/Z_L$, the integral of equation 5.1.34 can be evaluated in terms of average fields

$$(E - E_{p \text{ crit}})_{av} \approx \frac{V - V_c/2}{Z_L/2} - \frac{V_c}{Z_L} = 2 \frac{V - V_c}{Z_L} \quad \text{and}$$

$$(E + E_{p \text{ crit}})_{av} \approx 2 \frac{V}{Z_L} \quad \text{so that}$$

$$V_{\text{eff}} = W_L \sqrt{(E-E_{p \text{ crit}})_{av} \times (E+E_{p \text{ crit}})_{av}} \approx W_L \sqrt{\frac{4}{Z_L^2}} \, V(V-V_c).$$

Eq. 5.1.36
Considering that a measured current distribution for the point-to-plane system [13] indicates an average flux tube length $L_{av}$ not much larger than the gap width $L$, a transformation $Z_L \rightarrow L_{av} \geq L$ is consistent with the limited precision of formulations used here.

Then, substituting into equations 5.1.33 the ratio $\frac{v_0^2}{W_L^2}$ from equation 5.1.36 and capacitance $\Delta C_w$ defined in equation 5.1.35, the average terminal current $I = \Sigma \Delta I$ is geometrically determined by the total space-charge-region capacitance $C_w = \Sigma \Delta C_w$ and average current-path length $L_{av} \geq L$, namely

$$I_t = \frac{9}{2} \frac{C_w}{L_{av}^2} \mu_p (V-V_c) \text{ for positive corona, and (a)}$$

Eq. 5.1.37

$$I_\ell = 9 \frac{C_w}{L_{av}^2} \mu_n (V-V_c) \text{ for negative corona, (b)}$$

which is in accordance with the experimentally found relationship (eq. 4.2) between current and voltage.

Discussion

In this form the validity of equations 5.1.37 is not restricted to the investigated point-to-plane system. For example, applying equation 5.1.37 (a) to a coaxial configuration and ignoring the ionization-region volume (which is one of the assumptions used in deriving the Townsend equation in coaxial geometry, e.g. [20]), the capacitance is $C_w \approx 2 \pi \epsilon l / 2 \ln (r_2 / r_1)$ and the current-path length is $L = L_{av} = r_2 - r_1 \approx r_2$, where $r_1$ and $r_2 \gg r_1$ are the inner and outer cylinder radii respectively, and $l$ is the cylinder length. The result
\[ I_+ = \frac{9\pi\varepsilon_0\mu_n}{r_2^2 r_1^2 \ln(r_2/r_1)} V(V-V_c) \]
differs from the classical Townsend equation only in the numerical coefficient 9 instead of 8. The theoretical ratio of average currents for negative and positive corona is 2, provided that \( \mu, L_{av}, C_w \) and \( V_c \) are equal in both cases. The assumption for equal effective mobilities \( \mu_p = \mu_n \) is supported by Amin's measurements of ion crossing times, but the measured onset voltage \( V_c \) is higher for negative corona than for positive corona. Avoiding the differences in \( V_c \), it is convenient to compare the ratios \( I/[V(V-V_c)] \) which are also the slopes of functions \( I/V = f(V-V_c) \) derived from experimental results (and listed in Table 4.1). For the range of experimental conditions used, the measured ratios \( I/[V(V-V_c)] \) for negative corona are about 50\% higher than for positive corona. As the current distribution does not differ significantly (indicated by the relative magnitude of measured currents \( I_1 \) and \( I_0 \)), equations 5.1.37 provide a feasible explanation that the experimentally found ratio 1.5, instead of 2, is due to a 10\% wider space-charge region for negative corona. This conclusion follows from the ratio of equations 5.1.37 (b) and (a) for a Cartesian model:

\[
2 \frac{C_w}{L_{av-}} \frac{L_{av+}^2}{C_w} \approx 2 \frac{L_{av+}^3}{L_{w-}^3} = 1.5
\]

and consequently \( L_{av-} = 1.10 L_{av+} \).

A 10\% difference in the space-charge-region width means a much more substantial difference in the ionization-region width. Suggesting such differences is not against experimental evidence provided by
other manifestations of the ionization region, in particular the 
Lichtenberg figures studied by Nasser and Loeb [2].

To check quantitatively the credibility of equations 5.1.37, a 
known value for mobility (3 cm²/V sec) was used to calculate the 
fitting magnitude of $C_w$ for typical measured characteristics. Then, 
the ionization-region width was assessed from $C_w$ and compared with the 
original assumption for such region to be a few point radii wide. 
Specifically for the negative-corona current measured at 25°C, 50% RH, 
0.9 mm dia point and 40 mm gap (figures 4.7 and 4.8), the calculated 
capacitance is $C_w = 0.3\, \text{pF}$. Assuming a spherical ionization region 
with outer radius $r_i$, concentric with the hemispherical electrode 
tip, the capacitance to plate is approximately $C_w = 4\, \pi \varepsilon r_i \, [27]$ 
and consequently $r_i = 2.7\, \text{mm}$ or the ionization-region width of about 
5 point radii. However, by using in calculations the gap width $L$ 
instead of a larger average distance $L_{\text{av}}$, the capacitance $C_w$ is under­
estimated, but this is at least partly compensated by the assumption 
for a spherical ionization region. The actual form of this region 
becomes more important at smaller interelectrode distances, particularly 
for the current distribution between the central disc ($I_0$) and 
remaining part of the plate ($I_1$). Under such condition, an elongated 
ionization region increases the partial capacitance $C_{w_0}$ to the central 
disc and correspondingly the current $I_0$.

The dependence of measured corona characteristics on relative 
humidity is presumably a combined effect of reduced effective mobility 
and also reduced ionization-region width due to the heavy, slow moving
water ions (having a mobility of about \( \frac{1}{4} \) the mobility of \( \text{O}_2 \) ions in air [22]) or perhaps even droplets enhancing the space charge formed by oxygen ions.

Another consistency test for the lumped-parameter model is the following consideration for potential distribution associated with the pulsed operation of negative corona. The conditions for inception and extinction of a particular avalanche have been formulated in terms of the voltage drop across the ionization region. The difference \( \Delta V_i \) between the inception and extinction voltages across the region, at a constant applied voltage, results from a potential perturbation caused by the generated charge \( Q_p \). At \( t = T_1 \), voltage across the space-charge region is increased by \( \Delta V_i = Q_p / C_w \) and the ionization-region voltage reduced by the same amount. In the previous numerical example, where \( C_w = 0.3 \text{ F} \) and measured average charge \( Q_p = 220 \text{ pC} \) (section 4.1), the calculated voltage difference is \( \Delta V_i \approx 700 \text{ V} \). As the recorded onset voltage is \( V_c = 8 \text{ kV} \), the ionization-region voltage varies expectedly between the inception level of about 4 kV and extinction level of 3.3 kV. Although a direct experimental evidence to confirm these figures is lacking, the ratio of inception and extinction voltages of 1.2 is at least compatible with the characteristics of cold-cathode gas-filled electronic devices operated in series with a current-limiting resistor (a discharge tube being similar to the ionization region and a resistor to the transport region).
Symbolic representation

As a supplement to the analytical results obtained from the spatial systematization of conduction processes, it is appropriate to represent a clean unipolar corona system by three circuit elements symbolizing the ionization, buffer and transport regions. This lumped-element representation is illustrated in figure 5.3 by means of suitable symbols and corresponding piecewise-linear potential distributions for positive and negative corona. The chosen symbols are intended to indicate the current-conduction mechanisms in the three regions more specifically than signified by a combination of conventional circuit elements. However, the parameters used to characterize these elements are conventional capacitances and (non-linear) conductances. In particular,

(a) The ionization region is described as a gating element with two distinct conduction states, "on" and "off". Due to the plasma conditions there is a negligible space charge in the "on" state, which is characterized by a conductance $G_i$. The relative magnitude of the conductance $G_i$ and "holding" current $I_i \text{ min} \leq G_i V_i$ determine the stability in the "on" state. The holding current for a gating element representing steady positive corona is small enough to be sustained in equilibrium with the transport rate, i.e. $I_i \text{ min} \leq G_t V_t$. For a negative-corona gate with $G_i \gg G_t$, the operation is necessarily intermittent unless the applied voltage is high enough to produce $V_t \gg V_i$. Under experimental conditions
used by the author, $V_i$ and $V_t$ are of the same order of magnitude. Then, during an "on" (i.e., ionization) period the gate current is approximately $i_i = G_i V_{ic} \exp\left(-\frac{G_i t}{C_w}\right)$, where $C_w = C_t C_b/(C_t + C_b)$ and $V_{ic}$ is the breakover gate voltage. From the previous definition of critical conditions (equation 5.1.8), this breakover voltage is $V_{ic} \approx V_c/2$. The current $i_i$ flows until the voltage across the gate drops to $V_{i\min} = V_{i\text{ext}}$. The negative stored charge in $C_w$ increases by the amount $Q_p = C_w (V_{ic} - V_{i\text{ext}})$ which is injected into the buffer element, forming simultaneously a displacement current pulse in the external circuit.

(b) Although the buffer and transport regions above onset are just parts of the space-charge region, they are symbolized separately to indicate the time-varying charge stored in the buffer element. The same symbolic form is used both for negative and positive corona, to suit the description of streamer discharges as well. The peculiarities of these elements are (1) that the charge they store also determines their conductance, and (2) that the relaxation of this stored charge is necessarily associated with a current in the external circuit (consistently with the assumption that there is no recombination). Consequently the conductance is voltage dependent and for both elements together is

$$G_w = \text{const} \times C_w (V-V_i).$$
This conductance determines the average current above onset, which is, for applied voltages $V$ considerably higher than $V_i$,

$$I = G_w(V-V_i) \approx \text{const} \times C_w V^2 \left(1-2 \frac{V_i}{V}\right). \quad \text{Eq. 5.1.38}$$

Assuming $V_i \approx V_c/2$ and allowing for different values of the constant, as appropriate for positive and negative corona, this expression becomes homologous with equations 5.1.37, although it describes only the space-charge transport current.

The relaxation time constant for the stored charge $Q_w = C_w(V-V_i)$ is $T_w = Q_w/I$. Specifically for negative-corona representation, the gate remains inoperative over a period of time $T_t$ such that $Q_p/T_t = Q_w/T_w$, provided that $T_t \ll T_w$. The periodicity of gate operation is $T_p = T_i + T_t \approx T_t$ and the average terminal current comprises the current $Q_p/T_i$ charging $C_w$ and relaxation current $Q_w/T_w$, i.e.,

$$I = \frac{1}{T_p} \left(\frac{Q_p}{T_i} + \frac{Q_w}{T_w} T_t\right) \approx 2 \frac{Q_p}{T_p} = 2 I \quad \text{Eq. 5.1.39}$$

This lumped-element representation of corona systems is applied in chapter 6 as a basis for the design of an analog electronic circuit using solid-state devices to simulate the operation of individual lumped elements and their interactions as they occur in clean and contaminated corona systems.

Conclusion

The convenience in interpretation obtained by the temporal and spatial systematization of corona processes is not restricted to clean systems only. With such systematization, it is easier to anticipate
One-dimensional model

Fig. 5.1

conditions at onset

conditions above onset

Fig. 5.2

Fig. 5.3

Lumped element representation

conditions above onset
the effects produced by a contaminating layer covering one of the electrodes. For instance, an insulating layer covering the plate occupies a part of the transport region. The capacitance $C_w$ may not be significantly changed, but a total transport time will be increased if the layer conductivity is smaller than that of the transport region. In such a case the displacement current $Q_p/T_i$ or individual Trichel-pulses will not be affected, but the average current will drop. On the other side, a layer covering the point occupies the clean-system ionization region and its effect will primarily depend on its ability to suppress or spatially restrict the ionization. Therefore, the lumped-element representation is suitably expanded in section 5.3 to describe also the characteristics of contaminated corona systems.

5.2 CONTAMINATOR CHARACTERISTICS

The interpretation of contaminator characteristics presented in this section attempts to formulate those common properties of otherwise dissimilar substances (fly-ash, paper, teflon) which are relevant for their performance as contaminators in corona systems.

Certain similarities in measured electrical characteristics of contaminator materials are regarded as a result of common structural properties, in particular,

(a) the contaminator substances used in experiments are amorphous or polycrystalline insulators rather than crystals,

and (b) the layers of such insulators are inhomogeneous, with structural discontinuities due to the particulate (as fly-ash) or fibrous (as paper and teflon filters) structure and
inclusions of voids or pores.

It is convenient to use an approximation in describing the structure of such insulating layers as an agglomerate of homogeneous particles (or fibres) with a uniform (statistical) distribution of their sizes and contact boundaries. Consequently, an analysis of measured current-voltage characteristics should take into account both the current-conduction properties of homogeneous particles (or fibres) and contacts between them.

In formulating the current-conduction mechanisms in an amorphous but homogeneous insulator, it is suitable to apply the electron energy band concept. D. R. Lamb [29] has shown that the energy spectrum of electrons in amorphous or polycrystalline substances has a band structure in exactly the same manner as a crystal, although with possibly significant quantitative differences (e.g., amorphous semiconductors have their intrinsic conductivity even when containing the impurities which act as donors or acceptors in crystals of the same chemical composition). The current conduction mechanisms in thick and thin homogeneous insulating layers have been extensively studied, notably by Lampert [30], Tredgold [31], Lamb [29], and Gross [32] (bibliographical review). Generally, space-charge-limited currents are usual in thick layers, but Schottky emission or tunnelling may dominate in thin films [33]. Moreover, in an insulator, characterized by a wide energy gap between the conduction and valence bands, a discrete or continuous trap distribution within the energy gap is the rule rather than the exception [29][32]. As the density of
free carriers is usually much smaller than that of (deep) traps, such traps may dominate the characteristics of a space-charge region which is produced either by the (low-level) carrier injection from an external source or by the proximity of another solid with a different work function. The effect of traps is to reduce the width of such space-charge regions. However, this effect becomes less significant in accumulation layers, where the ratio of free and trapped carriers is increased by injection of excess carriers. Consequently, such (surface) accumulation layers have a higher conductivity than the bulk. The space-charge-layer width is relevant for the potential distribution in a homogeneous material, and it is appropriate to consider its magnitude in comparison with the contaminator thickness. Many, Goldstein and Grover [34] have analysed the potential distribution in surface-space-charge layers for discrete and continuous trap distributions and showed that a particularly simple solution is obtained for a continuous and uniform trap distribution, resulting in approximately exponential distribution of potential (similarly as for an intrinsic semiconductor) with a characteristic or effective Debye length

\[ L_t = \sqrt{\frac{\varepsilon \varepsilon_0 kT}{q^2(kTN_t)}} \]  

where \( kTN_t \) is the volume density of traps in an energy interval \( kT \), and the densities of free carriers are neglected.

Assuming that such conditions are representative for high-resistivity insulators, a numerical value of \( L_t \) may be estimated by assuming further
a total trap density of about $10^{21}$ m$^{-3}$ (a magnitude usual for insulators [29]) is uniformly distributed over an energy gap of less than 10 eV, and the relative permittivity is $\varepsilon_r \leq 5$. At room temperature, with $kT \approx 0.025$ eV, the orders of magnitude are for $kT N_t \approx 10^{19}$ m$^{-3}$, and for the effective Debye length $L_t \approx 10^{-6}$ m. The width of a space-charge layer as estimated by this method, would be much smaller than the typical experimental contaminator thickness of $10^{-4}$ m, but not small enough to justify an assumption for a linear potential distribution within an average homogeneous region of $10^{-5}$ m (taking the size of average fly-ash particles as typical).

Nevertheless, the inhomogeneity of contaminators is at least an equally significant property influencing the current-voltage characteristics. The contact energy barriers between homogeneous regions establish a staircase-type distribution of the applied voltage, and usually determine a linear (average) potential distribution over a statistically representative distance with many such barriers. This is in agreement with the measured (linear) potential distribution within a contaminator operating in the non-interacting mode, without back corona (figure 4.31). The characteristics of contacts between insulator particles have been studied by K. McLean [35], who has found the evidence for Schottky-emission enhanced current flow through such contacts.

Models describing the most significant current-conduction mechanisms in a contaminator are presented in subsequent sections for two different surface conditions:
(1) contaminator with equipotential parallel surfaces, as used in experiments with parallel-plate electrodes to measure the current-voltage characteristics and breakdown voltage of contaminator materials; and

(2) contaminator with one non-equipotential surface, representative for operation with corona current injection in the non-interacting mode.

The current conduction through a contaminator operating in the interacting mode is predominantly a gaseous process (back corona), actually bypassing the solid, which only provides a necessary (breakdown) condition to establish such corona-system mode.

3.2.1 Parallel equipotential surfaces

(A) Current-voltage characteristics, excluding breakdown

A lumped one-dimensional model representing a particulate or fibrous insulating layer placed between two (guarded) parallel electrodes is shown in figure 5.4 (a). In this model, describing average structural conditions in the direction of an applied field, solid is separated from pores and lumped into a slotted block of cross-sectional area $A$ which is smaller than the electrode area $A_e$. The ratio $k = A/A_e$ is a measure of porosity or compaction (as applicable for fly-ash layers). Regular discontinuities in this solid block represent the distributed contacts between particles or fibres, with an effective distance $l$ between the contacts in the field direction. An effective contact area $A_c = A_{c1} + A_{c2} < A$ is subdivided into two parts, $A_{c1}$
and $A_{c_2}$, to describe the mechanisms of current transfer between the homogeneous regions in this model:

1. the contact area $A_{c_1}$, with a negligible structural discontinuity between adjacent homogeneous regions, is assumed to have ohmic characteristics;

2. Schottky emission becomes effective in the contact area $A_{c_2}$ when the ohmic current $I_{c_0}$ flowing through the constriction area $A_{c_1}$ produces a sufficiently high voltage drop $V_2$ across an average distance $a$ (of the order of magnitude $10^{-8}$ m) to establish the emission current $I_{ce}$ comparable with or exceeding $I_{c_0}$;

3. there is no significant current transfer over a much wider gap $a'$, but the surface current $I_{cs}$ at the contact may not be negligible.

The effect of space charge in homogeneous regions is ignored, and the current $I_b$ flowing through the bulk of these regions is assumed to follow Ohm law. Consequently, the bulk is characterized by a linear parameter, its intrinsic conductivity

$$\sigma_b = \kappa \exp (-q E_G/2kT).$$

In addition, adsorbed gases or vapours may produce a significantly high surface conductivity $\sigma_{s'}$, and thereby increase the apparent conductivity $\sigma$ of homogeneous regions. The surface current $I_s$ is not necessarily equal to the contact surface current $I_{cs}$.

Accordingly, a non-linear current-voltage relationship of
contaminator layers is attributed to the contact characteristics. These characteristics are dominated by insulator-to-insulator contacts, because in this model there are only two metal-to-insulator and many insulator-to-insulator contacts. This predominant role of contacts between particles in current conduction through layers of dust has been verified by K. McLean [35] and the emission mechanism between particles has been previously suggested by Tassicker, Herceg and McLean [36].

These current-conduction processes, for the structural model of figure 5.4 (a), are formulated by means of the corresponding energy-level diagram shown in figure 5.4 (b) which implies the assumption of an approximately one-dimensional field pattern with equipotentials for \( z = \text{const} \). The total DC current \( I = I_s + I_b = I_{c_o} + I_{ce} + I_{cs} \) flowing between the electrodes produces a voltage drop \( V_1 \) across each homogeneous region of a width \( \ell \), with an approximately linear current-voltage relationship

\[
I = I_s + I_b = \sigma_{ls} \frac{A}{\ell^2} V_1 + \sigma_b \frac{A}{\ell} V_1 \approx \sigma \frac{A}{\ell} V_1 \quad \text{Eq. 5.2.2}
\]

where \( \sigma_{ls} \) is the surface conductance defined conventionally as a conductance per square area of the surface parallel to the direction of current flow, and such surface area for one homogeneous region is \( A_\ell \). As a simplification, the apparent bulk conductance \( \sigma \) is used to describe both current paths.

The same total current \( I \approx I_{c_o} + I_{ce} \) produces a voltage drop \( V_2 \) across each contact region of width \( a \), with a linear relationship for the ohmic contact current \( I_{c_o} \).
\[ I_{co} = \sigma \frac{A_{ci}}{a} V_2 \]  
Eq. 5.2.3

and a non-linear relationship, as derived in [36], for the emission current \( I_{ce} \),

\[ I_{ce} = 2 J_0 A_{c2} \sinh \left( \frac{qV_2}{2kT} \right) \]  
Eq. 5.2.4

where \( J_0 = \text{const} \times T^2 \times \exp \left[ -\frac{q(E_G/2 + \phi_c)}{kT} \right] \) is the density of an emission current from both surfaces across the energy barrier \( \phi_c \) at \( V_2 = 0 \). With an applied field, i.e. for \( V_2 > 0 \), the energy barrier becomes asymmetrical as indicated in figure 5.4 (b), enhancing the emission from one surface and suppressing it from the other, and resulting in the field-enhanced current \( I_{ce} \).

A voltage \( V_s \) applied between the electrodes produces an average field strength

\[ F_{av} = \frac{V_s}{d} = \frac{V_1 + V_2}{\ell + a} \]  
Eq. 5.2.5

Substituting \( V_1 \approx \frac{Ie}{\sigma A} \) from eq. 5.2.2, the "contact voltage" \( V_2 \) is approximately

\[ V_2 \approx F_{av} (\ell + a) - \frac{Ie}{\sigma A} = \frac{V_s}{d} (\ell + a) - \frac{Ie k}{\sigma A} \]  
Eq. 5.2.6

and the resulting current-voltage relationship is, in an implicit form,

\[ I \approx I_{co} + I_{ce} = \sigma \frac{A_{ci}}{a} \left\{ \frac{V_s}{d} (\ell + a) - \frac{Ie k}{\sigma A} \right\} + 
+ 2 J_0 A_{c2} \sinh \left\{ \frac{a}{2kT} \left[ \frac{V_s}{d} (\ell + a) - \frac{Ie k}{\sigma A} \right] \right\} \]  
Eq. 5.2.7

The applicability of this relationship has been demonstrated in the previously mentioned report [36], where only the emission term of
equation 5.2.7 was derived and numerical values of appropriate parameters were calculated, fitting experimental results for a particular fly-ash in a temperature range from 100°C to 200°C. The fly-ash characteristics presented in figure 4.84 are very similar, indicating a predominant influence of Schottky emission between particles. However, for materials of substantially lower bulk conductivity \( \sigma_b \approx \sigma \), the emission term in eq. 5.2.7 is also lower, due to a larger energy gap \( E_g \), which also reduces the emission current density \( J_0 \). In a contaminator layer consisting of fused particles or fibres, the effective contact area \( A_{c1} \) with ohmic characteristics may be relatively large, resulting in an approximately linear current-voltage relationship. An example of such structure is Millipore teflon filter, although its characteristics shown in figure 4.65 have been recorded with an insufficient instrument sensitivity to indicate any current below breakdown except at 70% RH, where the additional effects of humidity have to be considered.

(B) **Humidity effects**

S. Masuda [37] has interpreted the effects of humidity in layers of dust by means of a model which does not include the emission process between particles. In Masuda's model, the (ohmic) contact areas and/or surface conductivity of particles increase with humidity, due to a film of adsorbed water vapour, enhanced by capillary condensation at the contacts. This explanation appears to be compatible with the current-voltage characteristics of Millipore filters (figure 4.65), where an average value of the fluctuating current \( I_0 \) increases linearly
with voltage, which is consistent with a predominant role of rather noisy surface conduction. On the contrary, the highly humidity-sensitive fly-ash characteristics (figure 4.84) retain their non-linearity indicative of a continuing influence of Schottky emission in a wide range of humidities. A reasonable deduction is that humidity in this case directly affects the emission current. Such strong influence of adsorbed water vapour on emission current is consistent with a known effect of water vapour on semiconductor surfaces, namely that the adsorbed water vapour, as an electropositive gas, introduces donor states at the surface and reduces the work function \([34]\). Consequently, in the energy-level diagram of figure 5.4 (b), a direct effect of a reduced work function \(W\) is a lower energy barrier \(\phi_{co} = W - \phi'\), where \(\phi'\) is in the first approximation only a function of the gap width \(a\). The current density \(J_0\) and nett emission current \(I_{ce}\) increase correspondingly with a reduced \(\phi_{co}\). Therefore, it is permissible to conclude that in contaminator layers such as fly-ash, with predominantly Schottky-emission characteristics, the main effect of humidity is in lowering the Schottky barriers, rather than increasing the area of ohmic contacts or providing a surface current path.

(C) Breakdown characteristics

It should be emphasized that the current-conduction processes assumed in eq. 5.2.7 are pertinent only to the operating conditions considerably below breakdown. For the model structure in figure 5.4 (a) it is probable that a breakdown would occur in air, along the surface of the solid block rather than through the insulator bulk. Consequently
the Paschen Law for an air gap \( d \) between parallel electrodes is appropriate to describe the dielectric breakdown strength of this contaminator model. The measured breakdown voltages (figure 4.27 for paper, and 4.66 for Millipore LS) are generally higher, approaching the Paschen Law only in repeated breakdowns, after a hole has been formed in the sample. However, similar holes are formed in these materials when operated as contaminants in the interacting mode (with back corona). Therefore, the Paschen breakdown is considered as representative for contaminants operating continuously under breakdown conditions, such as in the interacting corona-discharge mode.

A linear approximation for the breakdown voltage \( V_{br} \) as a function of contaminator thickness \( d \), according to the Paschen curve shown in figure 4.27 (and 4.66), is

\[
V_{br} \approx (6 \times 10^5 d + 300) \text{ volts} \quad \text{Eq. 5.2.8}
\]

where \( d \) is expressed in meters and the range of applicability is for \( d \) from 50 to 500 \( \mu \text{m} \).

A rapid increase in current as the applied voltage \( V_s \) approaches \( V_{br} \) (a conspicuous example is fly-ash at 30\% RH in figure 4.84) may be described as a current-carrier multiplication process preceding an avalanche. Accordingly, a multiplication factor \( M \) is defined as a ratio of the actual current \( I_M \) and current \( I \) extrapolated from the low-voltage region (e.g. using equation 5.2.7).

\[
I_M = MI,
\]

and a voltage dependence of \( M \) may be obtained by expressing \( M \) in terms
of a probability $P$ that a given carrier will produce another carrier during its transit time between electrodes, i.e.

$$M = \frac{1}{1-P}.$$ 

A voltage dependence of $P$ in the form

$$P = \left(\frac{V_s}{V_{br}}\right)^m,$$

where $m$ is an adjustable index depending on material constants and geometrical factors, gives a reasonable fit for experimental data and satisfies basic conditions that $P = 0$ when $V_s = 0$, and $P \rightarrow 1$ when $V_s \rightarrow V_{br}$. However, it is only an assumption that the current increases due to a carrier multiplication process, so that the resulting relationship

$$I_M = MI = \frac{I}{1-\left(\frac{V_s}{V_{br}}\right)^m} \quad \text{Eq. 5.2.9}$$

is regarded only as a fitting formulation for the observed non-linearities in current-voltage characteristics close to breakdown.

### 5.2.2 One non-equipotential surface

An analysis of current conduction through a plate contaminator operated in the non-interacting mode differs from the previous analysis, for a layer between parallel metal electrodes, in the specific formulation of surface conditions at the contaminator-air boundary, where corona current is injected into the plate contaminator.

It is assumed that the injected current carriers form an accumulation layer of negligible depth in comparison with the contaminator
thickness, i.e. that a surface charge is formed rather than a space charge. This assumption is supported by the measured (linear) potential distribution within contaminator layers operating under non-interacting conditions (figure 4.31), and partly justifiable by the estimated order of magnitude of the effective Debye length \( L_d \) (eq. 5.2.1) which, admittedly, is not necessarily an adequate measure for the depth of accumulation layers, as mentioned before.

The excess carriers in a surface accumulation layer produce a conductivity \( \sigma_s \), parallel to the surface, which is higher than that of a parallel layer of comparable thickness in the underlying material (described subsequently as bulk). The total charge per unit surface area, comprising trapped and free carriers, is equal to the flux density \( D = \varepsilon r \varepsilon_0 F_{av} = \varepsilon r \varepsilon_0 V_s/d \), so that the surface conductivity \( \sigma_s \) may be expressed as a conductance per unit surface area

\[
\sigma_s = \mu_{eff} \varepsilon r \varepsilon_0 V_s/d \tag{5.2.10}
\]

where an effective mobility \( \mu_{eff} \) is used to account for the fact that free carriers constitute only a certain proportion of the total surface charge. Generally, \( \mu_{eff} \) is a function of \( V_s \), which, together with the ratio of free and trapped carriers varies with the injection rate. In the investigated point-to-plane system, \( V_s \) is also a function of radius \( r \) (using a cylindrical coordinate system), because of a radial variation of the corona (injection)current density. This radial current distribution is influenced by plate contamination, because a field component parallel to the surface is a necessary consequence of the
non-uniform injection current distribution. The radially varying surface potential is simultaneously determined by the current distribution and bulk characteristics (section 5.2.1 and eq. 5.2.7).

It is convenient to discuss the consequences of interaction between the surface and bulk conduction mechanisms by using a lumped-element circuit representation shown in figure 5.5. (b). In this model, the bulk resistances $R_{bn}$, where $n = 0, 1, 2 \ldots k$, are determined by the current-voltage relationship in eq. 5.2.7 applied to a cylindrically sectionalized contaminator. In parallel with $R_{bn}$ are corresponding capacitances $C_{bn}$. The surface resistances $R_{sn}$, accordingly with eq. 5.2.10, may be expressed for small contaminator sections as

$$R_{sn} = \frac{l}{K_n V_{sn}} \tag{Eq. 5.2.11}$$

where the coefficient $K_n$ is a function of material properties and geometrical factors. Capacitances in parallel with $R_{sn}$ are omitted, consistently with the assumption of a negligible accumulation-layer thickness. In figure 5.5. (b), the directions of indicated DC element currents are consistent with an injection current

$$I_i = \sum_{n=0}^{k} I_{in}$$

which monotonically decreases with radius $r$.

Assuming that the injection-current distribution is invariant, i.e. that the currents $I_{in}$ are supplied by constant-current sources, the nodal equations for $n = 0$ and $n = 1$ are
The most significant effect of surface conductivity, an equalization of surface potential may be expressed by comparing the surface voltages $I_{io} R_{b0}$ and $I_{i1} R_{b1}$ for $R_s \to \infty$ (negligible surface conductance) with actual surface voltages $V_{so}$ and $V_{s1}$. From equations 5.2.11 and 5.2.12, the ratio of their differences is

$$\frac{1}{B_{01}} = \frac{I_{io} R_{b0} - I_{i1} R_{b1}}{V_{so} - V_{s1}} = 1 + (R_{b0} + R_{b1})K_0 V_{so} - \frac{V_{s1} - V_{s2}}{V_{so} - V_{s1}} R_{b1} K_1 V_{s1}$$

Eq. 5.2.13

An approximation for the equalization factor $B_{01}$,

$$B_{01} \approx \frac{1}{1 + R_{b0} K_0 V_{so}}$$

Eq. 5.2.14

applies for small and approximately equal potential differences, i.e. $(V_{s1} - V_{s2}) \approx (V_{so} - V_{s1})$, and also $K_0 \approx K_1$. This expression shows that a radial decrease in surface potential predicted by the clean-system current distribution only (i.e., without considering the effect of surface conductivity) is in fact reduced proportionally with the bulk resistance $R_b$ and surface potential $V_s$. Such influence of surface conductivity is exhibited, at least qualitatively, in
experimental data for surface-potential distribution of paper in figures 4.30, where the bulk resistance is obviously higher for $d = 420 \mu m$ (figure 4.30 (b)) than for $d = 70 \mu m$ (figure 4.30 (a)).

Simultaneously with the surface-potential equalization, the bulk-current distribution $I_{bn} = f(r)$ becomes more uniform than the injection-current distribution $I_{in} = f(r)$. This uniformity of $I_{bn}$ is further improved by the non-linearity of bulk resistances $R_{bn}$, which is for all contaminators such that $R_{bn}$ decreases with an increasing surface potential $V_{sn}$.

Moreover, the injection current distribution is actually not invariant, because the radial field component at the air-contaminator boundary affects also the field pattern in air and consequently the ion movement in the transport region of the point-to-contaminator air gap. In comparison with the clean-system current distribution, the contaminated-plate system has a more uniform current density in air (in the non-interacting mode). This is illustrated qualitatively in figure 5.5 (c) showing the clean-system current density $J_c$, contaminated-system injection-current density $J_i$, hypothetical potential $V_{bs}$ resulting from $J_c$ and non-linear bulk resistivity $\rho_b$, and finally the surface potential $V_s$ produced by the combined effect of surface and non-linear bulk conductances.

To describe the relative magnitudes of measured currents $I_0$ (central disc) and $I_1$ (surrounding plate), for example in figures 4.22 and 4.23, it is suitable to use a simplified version of the contaminator
model in figure 5.5 (b). This simplified model has only two independent junctions, \( n = 0 \) and \( n = 1 \), and three elements relevant for DC conditions, the resistances \( R_{bo} \), \( R_s \), and \( R_{b1} \ll R_{bo} \) (because of a relatively small central-disc area). Then, the bulk currents \( I_{bo} \) and \( I_{b1} \) represent the measured currents \( I_0 \) and \( I \), respectively.

In this large-section model, the surface resistance \( R_s \) is more appropriately characterized as varying with an average surface potential \( (V_{so} + V_{s1})/2 \) rather than \( V_{so} \) only. Therefore \( R_s \approx 1/K(V_{so} + V_{s1}) \).

As an approximation, the injection currents \( I_{i0} \) and \( I_{i1} \) are identified with the (measured) clean-system currents \( I_{oc} \) and \( I_{1c} \). Then, from model equations for this simplified model (eq. 5.2.12 with the current \( I_{s1} = (V_{s1} - V_{2s})/R_{s1} \) omitted), the ratios of contaminated-plate and clean-system currents are, approximately,

\[
\frac{I_{1}}{I_{1c}} \approx 1 \quad \text{and} \quad \text{Eq. 5.2.15}
\]

\[
\frac{I_{0}}{I_{oc}} \approx \frac{1}{1 + R_{bo} K V_{so} [1 - (V_{s1}/V_{so})^2]} \quad \text{Eq. 5.2.16}
\]

\[
\approx \frac{1}{1 + R_{bo} K V_{so}}
\]

in the non-interacting mode.

In figures 4.22 and 4.23, taken as representative for non-interacting mode operation, the difference between \( I_1 \) currents measured under clean and contaminated conditions is small, particularly for thin contaminator layers, but \( I_0 \) decreases significantly with contaminator
thickness (i.e., with increasing $R_b$), which is consistent with equations 5.2.15/16. However, the dependence of $I_0/I_{oc}$ on $V_{so}$ is not obvious from experimental results, partly because $V_s$ does not change rapidly with current after an initial rise (as in figures 4.28/29), which is due to a non-linear bulk resistivity.
accumulation layer

(b) electron energy-level diagram
for current path B-B in (a)

Fig. 5.4 Contaminator with parallel equipotential surfaces

Fig. 5.5 Contaminator with one non-equipotential surface
5.3 CONTAMINATED SYSTEM CHARACTERISTICS

Although the approach concepts (section 2.3) of a contaminated system as a two-media (air and contaminator) system operating in two alternative modes (interacting and non-interacting), have been verified in section 4.2.1 from experimental data, it is necessary to elaborate the description of these operating modes by

(a) correlating them with the corona-discharge regimes, which actually dominate the system characteristics (conclusions in section 4.3),

(b) formulating criteria for mode transitions, with a particular emphasis on back corona, and

(c) developing pertinent models, based on the previously presented clean-system and contaminator models.

5.3.1 Non-interacting mode

This mode of operation, characterized by the fundamental clean-system corona regime, is obtained basically in a contaminated-plate system with positive or negative clean point, but also in contaminated-point and bilaterally contaminated systems with negative point only, as summarized in section 4.3.

Nevertheless, certain interaction between the two media in a contaminated-plate system does exist even in this mode, as discussed already in section 5.2.2, but it affects only the field pattern and current distribution in the contaminator and transport region of the air gap, and not the ionization regime. Consequently, the models and
results presented in section 5.1 for the clean system are applicable to the air gap of a contaminated system, provided that the air-contaminator boundary is regarded as approximately equipotential. The surface-potential equalization (eq. 5.2.14) definitely supports such approximation, particularly at relatively high applied voltages \((V > 2 V_c)\) and correspondingly improved uniformity of surface potential (e.g., figure 4.30). Under such operating conditions, the contaminator surface resistance \(R_s\) is considerably smaller than its bulk resistance \(R_b\), for any relevant section of the contaminator.

Accordingly, the lumped element models for the clean system and contaminator may be combined to represent a contaminated-plate system as shown in figure 5.6 (a). In this model, the space-charge-region capacitance \(C_w\) is somewhat larger than that of the clean system, because the transport-region capacitance \(C_t\) increases with a radial spreading of the field pattern. However, the corresponding conductance \(G_w\), determined by the ratio \(C_w/L_{av}^2\) (comparing equations 5.1.37 and 5.1.38), does not change significantly, because the capacitance \(C_w\) and average current-path length \(L_{av}\) increase simultaneously. Consequently, the DC current \(I\) is determined by the voltage drop \([(V-V_s) - V_i]\) across the space-charge region in the same manner as in the clean system. To formulate this current-voltage relationship, the voltage drop across the air gap \((V-V_s)\) is appropriately substituted for \(V\) in equations 5.1.38 and 5.1.37, obtaining

\[
I = G_w [(V-V_s) - V_i] \approx \text{const} \times (V-V_s)[(V-V_s) - V_c] \quad \text{Eq. 5.3.1.}
\]
Experimental data for the non-interacting mode have been previously discussed in section 4.1.11, and their consistency illustrated by a numerical example, which also demonstrates the applicability of equation 5.3.1.

The surface potential $V_s$, implicitly assumed as known in equation 5.3.1, can be determined by solving simultaneously equations 5.1.37 and 5.2.7 (or 5.2.9 when $V_s$ approaches $V_{br}$). A graphical method for obtaining such solution is shown in figure 5.6 (b) for two alternative contaminators, (1) and (2), having the same breakdown voltage $V_{br}$ but different (non-linear) resistivities. The essential condition for operation in the non-interacting mode, $V_s < V_{br}$, is easily satisfied with contaminator (1), but for contaminator (2) the mode of operation depends on the applied voltage. As illustrated for this contaminator, a solution with $V_s < V_{br}$ is obtained for an applied voltage $V'$, but such solution is not possible at a higher applied voltage $V$.

To calculate the operating point for a contaminated-plate system (i.e., to determine $I$ and $V_s$ for a given $V$) from known characteristics for the clean system and contaminator individually, it is necessary to determine quantitatively an effective (equipotential) area $A_{eff}$ of the contaminator surface (in equation 5.2.7, $A_{c1}$ and $A_{c2}$ are directly proportional to $A_{eff}$), with assumably uniform distribution of the total injection current $I$. A particular difficulty arises from the fact that this area is a function of the surface voltage $V_s$, due to its influence on the pattern of current distribution. However,
if an effective area $A_{o\text{ eff}}$ is determined (experimentally) for the
clean system, such that

$$A_{o\text{ eff}} = \frac{I_c}{J_{oc}}$$

where $I_c$ is the total clean-system current and $J_{oc}$ is the current
density in a representative plate region (e.g., homologous with the
central-disc probe in the experimental jig), and further, the effective
contaminator area $A_{eff}$ is expressed similarly as

$$A_{eff} = \frac{I}{J},$$

the ratio of effective areas, for equal currents $I_c = I$, is

$$\frac{A_{o\text{ eff}}}{A_{eff}} = \frac{J_{oc}}{J_{oc}}.$$

The ratio $J_{oc}/J_{oc}$ is essentially the current equalization factor
formulated in eq. 5.2.16, giving an expression for the voltage
dependence of $A_{eff}$:

$$A_{eff} = A_{o\text{ eff}} \frac{J_{oc}}{J_{oc}} \approx A_{o\text{ eff}} (1 + R_{bo} \frac{KV_s}{C_c}) \quad \text{Eq. 5.3.2}$$

In addition to the average (DC) operating conditions, it is
important to consider the AC performance of the model in figure 5.6 (a)
when representing a system with negative point and Trichel-pulse
corona. The high-resistivity contaminants used in experiments
are characterized by a time constant $R_c C_c \gg T_p$, the repetition period
of Trichel-pulses. Also, for relatively thin contaminants $C_c \gg C_w$.
Consequently, there is a negligible voltage drop across $(R_c || C_c)$ and
the surface potential $V_s$ is virtually a steady DC voltage. As the ionization process, described in section 5.1.1, is not affected by plate contamination in the non-interacting mode, the displacement current $i_p(t) = \frac{\partial Q_p}{\partial t}$ (eq. 5.1.7) remains the same as in the clean system. This applies for any section of the contaminated plate (because of a negligible AC voltage drop across the contaminator), explaining the experimental observations (figure 4.24) that there is no significant difference in $i_{p0}(t)$ and $i_{p1}(t)$ waveforms under clean and contaminated-plate conditions. Also, the relationship between the average total current $I$ (approximately equal to the measured current $I_1$) and Trichel-pulse repetition frequency $f_p$ (eq. 5.1.39 or 4.1) is necessarily preserved, as indicated in figure 4.25 by the derived $f_p(I_1)$ functions. However, such invariant relationships do not apply for the central-disc current $I_0$ (or for a current in any radially limited section of the plate), because the space-charge removal from the transport region in air is affected by plate contamination, resulting in a diversion of conduction current (versus displacement current) and consequently exhibiting a different pedestal in waveforms of such limited-area currents. In figure 4.25, the slope of $f_p(I_0)$ for the contaminated system differs from that for the clean system, correspondingly with a reduced (DC) pedestal current.

The lumped-element model in figure 5.6 (a) is also suitable to represent a bilaterally contaminated system operating in the non-interacting mode. In such systems with negative point, the clean-system corona regime is preserved, but the ionization and transport
conditions are changed quantitatively, requiring a different set of parameters \( (V_i, C_i, G_i, G_w, \text{ and } C_w) \). Contrary, for a bilaterally contaminated system with positive point, the combination of lumped elements in figure 5.6 (a) may not be pertinent. For example, a probable corona regime is streamer corona (instead of a steady discharge in the clean system), possibly with streamers crossing the air gap, in which case the air gap should be represented by an ionization-region element only.

Problems in characterizing the influence of point contamination in effecting a corona-regime change are discussed in subsequent sections, together with other aspects of interacting-mode operation.

5.3.2 Criterion for the onset of back corona

The onset of back corona signifies a transition from the non-interacting to interacting mode of operation in a contaminated plate system. This transition is caused by the plate contaminator and it occurs when the contaminator surface potential \( V_s \) reaches a breakdown magnitude for the contaminator, i.e., when

\[
V_s \geq V_{br}
\]

Eq. 5.3.3

where \( V_{br} \) is the Paschen breakdown voltage expressed in equation 5.2.8 for contaminators used in experiments. A transition in the opposite direction, from the interacting to non-interacting mode, may exhibit a hysteresis effect due to the mechanical deformations of a contaminator operating in the interacting mode. Hence, such reverse transition may occur for \( V_s \leq V_{br} \).
The low current (onset) operating points in figures 4.36/50/65, for contaminators operating in the interacting mode, prove the criterion expressed in eq. 5.3.3.

A probability for the onset of back corona is usually described in terms of a critical contaminator resistivity. Its magnitude is known to be in the range $10^{10}$ to $10^{11}$ ohm cm for industrial electrostatic precipitators [1][4].

To find an expression for the critical resistivity $\rho_{\text{crit}}$, and to calculate its magnitude for the investigated point-to-plane system, the relationship $V_s = F_{av} \times d = \rho J d$ and $V_{br}$ from eq. 5.2.8 are substituted in eq. 5.3.3, with $\rho = \rho_{\text{crit}}$ when $V_s = V_{br}$, obtaining

$$\rho_{\text{crit}} J d = 6 \times 10^6 d + 300$$

or

$$\rho_{\text{crit}} = \frac{6 \times 10^6 + 300}{J} \quad \text{Eq. 5.3.4}$$

where the contaminator thickness $d$ is expressed in meters and the current density $J$ in A/m$^2$. Under experimental conditions, a typical current density $J = I_0/(2 \text{ cm}^2)$, where 2 cm$^2$ is the area of the central disc probe, is $J \approx 10^{-2}$ A/m$^2$ in the non-interacting mode and conditionally at the onset of back corona. Using $d = 3 \times 10^{-4}$ m as a typical contaminator thickness, the critical resistivity is

$$\rho_{\text{crit}} \approx 7 \times 10^8 \ \Omega \cdot m = 7 \times 10^{10} \ \Omega \text{ cm},$$

showing the same order of magnitude as known values for electrostatic precipitators. This agreement is understandable, because the collecting plate current densities in electrostatic precipitators and in the
experimental system, intended as a simulator, are of the same order of magnitude.

However, the expression for $\rho_{\text{crit}}$ in eq. 5.3.4 is only a linear approximation for the criterion in eq. 5.3.3, and the magnitude of $\rho_{\text{crit}}$ depends essentially on an estimated current density at the onset of back corona. For instance, the relevant current density for contaminators of very high resistivity (like Millipore teflon discs, described in section 4.2.12 as producing back corona unconditionally) is a minimum current density $J_{\text{min}}$ obtainable in a particular system without an intermittent corona discharge. Accordingly, estimating $J_{\text{min}} \approx 5 \times 10^{-4} \text{A/m}^2$ for the experimental system, a conditional back-corona onset may be expected for contaminator resistivities up to $10^{12} \Omega \text{cm}$. For contaminator resistivities $\rho > 10^{12} \Omega \text{cm}$, this corona system will operate unconditionally, at any steady current density $J$, in the interacting mode.

Further, the contaminator resistivity is a non-linear parameter and the value of $\rho_{\text{crit}}$ is appropriate only for an operating point at $V_s \to V_{\text{br}}$. In conventional measurements of resistivity, a voltage $V_s \ll V_{\text{br}}$ is applied across a sample, and the measured resistivity may be perhaps by an order of magnitude higher than that at $V_s \to V_{\text{br}}$. However, by using a low-voltage resistivity value to estimate a probability of back-corona occurrence, only an overestimate can be made.

Another aspect of approximations inherent to eq. 5.3.4 is a deceiving indication that thin contaminators are less likely to produce
back corona than thick ones. For example, the previously calculated $\rho_{\text{crit}} = 7 \times 10^{10} \Omega \text{ cm}$, for $d = 3 \times 10^{-4} \text{ m}$, becomes $\rho_{\text{crit}} \approx 1.6 \times 10^{11} \Omega \text{ cm}$ for $d \approx 3 \times 10^{-5} \text{ m}$. Actually, considering conditions preceding the onset of back corona, the total corona current increases and becomes less uniformly distributed as the contaminator thickness decreases (because of smaller $V_s$ and $R_b$, eq. 5.2.16), so that the current density $J$ in the critical central region may increase faster than the term $(6 \times 10^6 + 300/d)$ in equation 5.3.4. This is one of the reasons that back corona is easier to develop with relatively thin contaminators, as shown in experimental results (figures 4.32 and 4.33).

5.3.3 Interacting mode and corona regimes

Accordingly with the distinctions made in conclusions on experimental results, section 4.3, and previously used terminology,

(a) the interacting mode signifies only operation with bilateral ionization (i.e., with back corona), peculiar to systems with plate contamination, and

(b) other forms of interaction between current-conduction mechanisms in the air gap and contaminator are denoted by the resulting non-fundamental corona-discharge regimes at a particular electrode.

To describe the corona-system characteristics in the interacting mode, with transition criteria already formulated in section 5.3.2, a lumped-element representation is developed also for this case. However, an analytical evaluation of operating conditions from the known clean-system and contaminator characteristics, similarly as for the non-
interacting mode, is not feasible because the current-conduction processes are dominated in this mode by non-electrical properties of contaminators. Such properties determine, for instance, the number and current carrying capability of back-corona channels (including spark development), the mechanical stability of contaminators (particularly important for layers of dust), and also the shape and size of clearings in contaminators covering the point, which may determine a particular corona regime. Although the experimental results show certain similarities between effects produced by different contaminators (enabling, for example, the effects of point contamination to be characterized by the teflon-sleeve screening), most of the relevant non-electrical properties are specific to a particular contaminator material. A study of such properties, that would provide sufficient information for a quantitative analysis of composite characteristics in the interacting mode, is considered to be beyond the scope of this thesis.

Nevertheless, the lumped-element models in figures 5.7 (b) and (c) provide a parametric description of the interacting-mode characteristics shown in figure 5.7 (a), which is based on the recorded characteristics in figure 4.60 and 4.73 for a negative-point system. This system has been chosen for discussion as generally representative as a contaminated system operating in the interacting mode and changing corona regimes during operation. By comparison, the corresponding positive-corona characteristics (fig. 4.59) are simpler, without discontinuities peculiar to regime changes.
The model in figure 5.7 (b) is intended to represent the system performance for applied voltages $V < V_A$. At $V_A$, the corona regime is changed and the current increases discontinuously. In this model, as compared with the non-interacting-mode model in figure 5.6 (a), an additional ionization-region element in parallel with $R_c$ and $C_c$ represents the back-corona ionization process. The total DC current consists of the back-corona current $I_{bc}$ and the contaminator (bulk) current $I_b$. The contaminator surface voltage $V_s$ is approximately equal to the back-corona ionization voltage $V_{i2}$, which is compatible with a positive Hermstein glow being restricted to the contaminator surface. The Trichel-pulse regime at the (negative) point is indicated by $I < I_{i1 \text{ min}}$ where $I_{i1 \text{ min}}$ is the gate "holding" current, as previously described in section 5.1.3.

A discontinuous increase in current at $V = V_A$ is associated with a (simultaneous) transition of Trichel-pulse corona at the point to steady negative corona, and from Hermstein glow at the plate to burst or streamer back corona, as concluded from experimental observations of current waveforms. These new corona regimes produce a visually intensified back corona and substantially different conditions for current conduction, with the most significant consequences being:

(a) $I \approx I_{bc}$,

(b) $V_s < V_{i2}$, because the back corona ionization region extends considerably above the contaminator surface, and

(c) an overall space-charge neutrality in the air gap, as discussed subsequently.
A suitable lumped-element representation for this intensified back-corona regime, i.e. for $V > V_A$, is shown in figure 5.7 (c).

These models and the processes they represent are discussed in the following paragraphs, for characteristic voltage ranges ($V < V_A$) and ($V > V_A$) separately.

Case 1 : $V < V_A$, model in figure 5.7 (b)

It is assumed that the current $I_b$ is produced by those carriers generated in the ionization region at the point, as in the non-interacting mode, and the current $I_{bc}$ is a composite result of ionization processes at both electrodes. Accordingly, the back-corona current $I_{bc}$ is conducted by ambipolar carriers in ducts or regions (their number and distinctiveness depending on actual distribution of back-corona spots) with reduced space-charge density and approaching quasi-neutrality at higher currents.

This assumption is consistent with a field configuration in air as sketched in figure 5.8 (a), where the indicated back-corona channel may alternatively represent a cluster of such channels. The corresponding surface-potential distribution $V_s = f(r)$ shown in figure 5.8 (b) is consistent with measured distributions for contaminators operating in the interacting mode (e.g. figures 4.78/79). This field pattern demonstrates that quasi-neutral conditions, created by ambipolar carriers, may prevail in the air gap if back corona spreads over a proportionally large area of the contaminated plate (which is contrary to an
interpretation by Lowe, Dalmon, and Hignett [8]). In a diagram \( V_s = f(r) \), as in figure 5.8 (b), the width and depth of a potential valley are indicative, respectively, of a contaminator area affected by (intense) back-corona and a current density in that area, but it does not mean that there is no back-corona elsewhere.

To formulate a current-voltage relationship for the lumped-parameter model, the back-corona ducts are lumped into a single (arbitrarily defined) duct characterized by quasi-neutral conditions and a conductance \( G_{wb} \). The remaining relevant part of the air gap is described as a parallel space-charge duct with a conductance \( G_{ws} \). Consequently, the total conductance of the nominal space-charge region in air is

\[
G_{wc} = G_{ws} + G_{wb} \quad \text{Eq. 5.3.5}
\]

and the corresponding current is

\[
I = \left( G_{ws} + G_{wb} \right) \left( V_{\text{ii}} - V_s \right) = I_b + I_{bc} \quad \text{Eq. 5.3.6}
\]

Also, the contaminator bulk current \( I_b \) is identified with a current in the space-charge duct. A current-voltage relationship for this current is of the same form as for the non-interacting-mode current in equation 5.3.1, i.e.

\[
I_b = G_{ws} \left( V_{\text{ii}} - V_s \right) \approx \text{const} \times \left( V - V_s \right) \left( V - V_s - V_c \right) \quad \text{Eq. 5.3.7}
\]
The back-corona current $I_{bc}$ flowing through the quasi-neutral duct is expressed as

$$I_{bc} = G_{wb} \left( V - V_s - V_{i1} \right) = G_{o} \left( \frac{I_{bc}}{I_{c\ell}} \right) \left( V - V_s - V_{i1} \right)$$  \hspace{1cm} \text{Eq. 5.3.8}$$

where the conductance

$$G_{wb} = G_{o} \left( \frac{I_{bc}}{I_{c\ell}} \right)$$  \hspace{1cm} \text{Eq. 5.3.9}$$
is formulated as a product of the parameter $G_{o}$ representing a minimum or primary conductance for a back-corona duct of given geometry, and the current-carrier multiplication factor $I_{bc}/I_{c\ell}$. Such formulation is consistent with the fact that back-corona is not a self-sustained process. Back corona depends essentially on the supply of carriers generated at the point, and these primary carriers are regarded as multiplied by carrier-pair generation in the back-corona ionization region.

The ratio $I_{bc}/I_{c\ell}$ compares the resulting and primary carrier densities in terms of the resulting back-corona current $I_{bc}$ and a clean-system current $I_{c\ell}$ that would flow in the same duct at a particular applied voltage. Obviously, $I_{c\ell}$ is a fictitious current because of different field patterns under respective conditions. Although the multiplication factor $I_{bc}/I_{c\ell}$ may not vary significantly with voltage in the discussed voltage range ($V < V_A$), with persistent corona regimes, the parameter $G_{o}$ depends on voltage and contaminator properties determining the extent of back-corona development, i.e. the number and size of back-corona ducts represented by the lumped parameter $G_{o}$.
For instance, experimental data show that a contaminator with larger pores and uniform porosity (comparing the results for Millipore LC and LS filters) will have more places suitable for the formation of back-corona channels, but the size of holes produced by back-corona in teflon filters is generally smaller than in paper of comparable thickness and mean porosity. Also, the current-carrying capability of back-corona channels decreases with contaminator thickness, but it is higher for chemically inert teflon than for paper. Furthermore, in teflon filters the number of holes rather than their size increases with voltage, contrary to the appearance of larger holes with burnt edges in paper.

To summarize, in the interacting mode and $V < V_A$, the prevailing effect of back corona is partial space-charge neutralization, which progresses toward quasi-neutrality as the applied voltage increases. A current increase resulting from the reduced space-charge limitations is described in this model by the lumped conductance $G_w$, which generally increases with voltage, but its functional relationship with non-electrical properties of contaminators is not formulated.

Another manifestation of a reduced space charge is observed in the current waveform (as in figure 4.34 (a)), which displays only Trichel-pulses because back-corona is a steady discharge. The amplitude of these pulses decreases with voltage, compatibly with an elongated ionization region resulting from a
partial neutralization of space charge in the buffer region. In the clean system, an enhanced space-charge removal at smaller interelectrode distances produces similar results (figure 4.14).

Case 2 : \( V > V_{\text{A}}' \), model in figure 5.8 (c)

The new corona regimes occurring at \( V \geq V_{\text{A}} \) are probably initiated at the point by a sufficiently reduced space charge in the buffer region to allow initially a prolonged ionization (as in figure 4.75 (b)) with a corresponding increase in production of negative carriers. These carriers stimulate carrier-pair generation in the back-corona ionization region. The resulting positive ions move towards the point and further reduce the space charge. These processes can be described in analogous terms as a response of a non-linear closed-loop system with positive feedback. Consequently, at \( V = V_{\text{A}} \) there is an abrupt increase in current, which settles to a stable value when an overall space-charge neutrality is achieved.

The previously described consequences of operation at \( V > V_{\text{A}} \) are represented in the corresponding model by

(a) omitting \( R_c \) and \( C_c \) as irrelevant, because \( I \approx I_{bc} \) (however, \( C_{bc}' \) appropriately includes \( C_b \)),

(b) indicating larger and approximately equal ionization voltages \( V_{i_1} \approx V_{i_2} \approx V_c \), consistently with spatially extended ionization regions, and
(c) modifying suitably the transport-region symbol to indicate an approximately equal density of positive and negative ions.

Accordingly, the transport-region conductance is

\[ G'_w = G'_o \frac{I}{I_{cl}} \approx \text{const} \]  \hspace{1cm} \text{Eq. 5.3.10}

because \( G'_o \) has reached its maximum in \( G'_o \) by representing the whole current field, and the multiplication factor \( I/I_{cl} \) is presumably only a slow-varying function of voltage. Consequently, the current-voltage relationship is approximately linear.

\[ I \approx G'_w (V - 2V_c) \]  \hspace{1cm} \text{Eq. 5.3.11}

which is in agreement with the recorded characteristics and an extrapolated onset voltage of about \( 2V_c \), as shown in figure 5.7 (a).

Stability of operation for voltages \( V > V_A \) depends again on specific contaminator properties, e.g., the discussed characteristics have been recorded under stable conditions obtainable with teflon contaminators (figures 4.60 and 4.73), but with paper and particularly fly-ash, the operating point for \( V = V_A \) may be reached but not exceeded without a high probability of sparking.
5.3.4 Effects of bilateral contamination

The models in figures 5.7 (b) and (c) can be also applied for bilaterally contaminated systems by providing an appropriate set of lumped parameters, such that particular corona regimes are adequately described. In addition to the interacting mode operation, the current voltage characteristics are dominated by the positive-corona regimes, as concluded from experimental data in section 4.3. Distinguishing further, the transition to a non-fundamental positive corona regime at the point, as produced by point contamination, has more significant consequences than a regime change in positive back-corona (in a negative-point system). Conveniently, the effects of point contamination may be characterized by the position of a teflon sleeve, which screens the point and produces virtually identical effects as point contaminators (section 4.2.21). Such characterization avoids the difficulty of describing a particular corona regime (with corresponding parameters $V_i$, $G_i$, and $C_i$) in terms of indefinite contaminator properties.

At applied voltages below the onset voltage $V_c$, a contaminating layer covering the point reduces the field strength in air close to the point and, compared with the clean system conditions, a higher voltage $V_c$ is needed to start a corona process, proportionally with an equivalent degree of teflon sleeve screening. After corona onset, the ionization region is partly surrounded by the contaminator (or sleeve), which beyond its physical boundaries increases the field strength far from the point (in comparison with the clean system field pattern) and produces an elongation of the ionization region, as indicated by visual
corona forms shown in figure 4.85. The ionization-region size is also influenced by relative humidity, or gas composition in general. The corresponding lumped parameters $G_i$ and $C_i$ are smaller and $V_i$ larger than those for the clean system. A pulsating ionization process is, in this representation, a consequence of reduced conductance $G_i$, such that $I_i \min > G_i V_i$. For positive corona this means a non-fundamental (streamer) regime, while the negative-corona Trichel-pulse regime is not essentially affected. As the space-charge-region conductance $G_w$ increases simultaneously with the ionization-region elongation for geometrical reasons, the ionization region may grow to reach the plate, which is consistent with the observed length of positive streamers (figure 4.85). A magnitude of $G_i$ determines whether this regime will remain stable or a further transition to the spark regime will occur.

For a high degree of screening, which implies that a significant part of the ionization region is surrounded by the point contaminator (or sleeve), $G_i$ is small enough to maintain a stable streamer regime even with streamers long enough to cross the air gap, i.e. $I_i \min < G_i V_i$ even when $V_i \to V$ and $G_i V_i \approx I$ (as for $X = -2.5$ mm in figure 4.85). By reducing the degree of screening, $G_i$ may increase sufficiently to evolve the spark regime, i.e. $I_i \min = G_i V_i$ when $V_i \to V$, as for $X = 0$ which is also representative for thin ($< 0.5$ mm) point contaminants used in experiments).

In describing the characteristics of bilaterally contaminated systems, these effects of point contamination have to be considered simultaneously with conditions pertinent to a particular operating
mode. A mechanism providing the highest overall conductance dominates the system performance. This obviously applies for voltages above the onset voltage $V_c$, which is exclusively influenced by point contamination.

Accordingly, the performance of a bilaterally contaminated system with negative point is dominated by back corona, effected by plate contamination. This includes the high-yield continuous regime at the point, which is induced by back corona at higher voltages and cannot be achieved by point contamination. The experimental results shown in figures 4.107 and 4.109 are typical examples of such performance.

In bilaterally contaminated systems with positive point, back corona is not necessarily the most effective current-conduction mechanism. Its effectiveness in reducing the space-charge in the transport region (with a corresponding increase in $G_w$) should be compared with the transport-region shortening (also increasing $G_w$) which occurs simultaneously with a growing length of positive streamers, as effected by point contamination. The experimental results in figures 4.102 and 4.106 are consistent with a predominant influence of back-corona at lower voltages and relatively short streamers, followed at higher voltages by the predominence of long streamers, as they become the most efficient current-conduction mechanism to maximize the conductance in such systems.

5.3.5 Significance for electrostatic precipitators

To investigate the effects of contamination, the point-to-plane configuration has been chosen by the author as a most informative corona
system and also representative for other asymmetrical systems, such as used in electrostatic precipitators (sections 2.4 and 3.1). This representativeness applies (a) for ionization processes (negative corona, usually) occurring at the high-stress, discharge electrodes spontaneously (on plain wires) or at the pre-determined places (on electrodes with spikes), and (b) for transport or carriers, both in the non-interacting and interacting modes of operation.

In a negative-corona precipitator system under clean conditions, corona ionization at discrete points on the high-stress electrodes (wires) is identifiable visually and by a non-homogeneous current distribution at the low-stress, collecting electrodes [12]. The ionization and transport processes for individual discharge spots in such systems are considered by the author to be adequately characterized by equivalent point-to-plane systems.

However, to describe the overall average performance of a system with long discharge electrodes (wires), it is not sufficient to represent such systems as a parallel combination of independent point-to-plane units. It is necessary to take into account also the interaction and current sharing between units, particularly under contaminated conditions.

Certain interaction between units can be envisaged even under clean conditions. A particular ionization spot and its current field, as a corona-discharge unit, is constricted by adjacent units (similar constriction is produced in a point-to-plane system by the point contamination). Also, the number of such units for a given system depends on the applied voltage and contamination. Under clean conditions,
as a result of larger number of units with elongated ionization regions, the average system current may increase faster than predicted by a quadratic current-voltage relationship (such as eq. 5.1.37), based on constant (low-voltage) geometrical factors. This is consistent with known electrical characteristics of precipitator systems (e.g., [1]).

However, the changes in these clean-system characteristics, resulting from bilateral contamination by a precipitate, are much more significant for technical purposes. The response of individual corona-discharge units is considered to be essentially the same as in the investigated point-to-plane system (e.g., as in figure 4.103 for the interacting mode, and in figure 4.105 for the non-interacting mode). In addition, the overall system performance is influenced by a reduced number of corona-discharge units (in comparison with the number of such units under clean conditions at the same applied voltage), resulting from the contamination of high-stress, discharge electrodes. This contamination disturbs the clean-system current distribution between interacting units, by suppressing or completely eliminating conduction in some units. In the system characteristics, such reduced number of corona-discharge spots only enhances the basic response of individual units, tending to localize the current flow.

Consequently, for electrical characteristics and performance of precipitators, the technically significant aspects of contamination can be summarized as follows:

1. Back corona, produced by the collecting-electrode contamination (conditions: section 5.3.2) is associated
with partial neutralization of space charge (section 5.3.3), consequently impeding the particle-charging mechanism, and it is accompanied by forces (section 4.2.11) contributing to the re-entrainment of already collected particles.

In the interacting mode of operation, but with a low density of back-corona channels of relatively low ionization efficiency (as in figure 4.33 for 6 layers of paper), the total system current does not exceed the clean-system current. Nevertheless, even in such a case the current distribution may be highly non-homogeneous, with a large proportion of the total current conducted by the back-corona channels, which also increases the probability of sparking.

(2) In the non-interacting mode, the discharge-electrode contamination is more effective in suppressing the total current than the collecting-electrode contamination (as in figure 4.105). In the lumped-parameter description, this is due to the low-conductance ionization regions produced by the discharge-electrode contamination. The simultaneous elongation of these ionization regions and constriction of corresponding current fields stimulates the formation of breakdown streamers, but more so for positive corona (figures 4.94/96) than for negative corona (figures 4.95/97). Also, the suppression of some corona-discharge units (in comparison with clean-system conditions) can be described as a reduction in the effective length of discharge electrodes.
A high density of airborne particles contributes further to the current suppression without improving the homogeneity of current distribution (similarly to the humidity effect in figures 4.94 to 4.97).

(3) In the interacting mode, the discharge-electrode contamination enhances the non-homogeneity of current distribution even for individual units (as indicated in figure 4.103 by a large increase in $I_0$ relative to $I_1$), but with much more significant localization of current flow in large systems. Such localization of current flow improves the space-charge neutralization inherent to the interacting-mode operation, and reduces the sparkover voltage.

Alternatively, the discharge-electrode contamination may stimulate the formation of back corona in critical cases, by increasing the current density (although the total current remains smaller than in the clean system). For positive corona, the discharge-electrode contamination is the most significant factor in producing the streamer regime and sparkover at relatively low voltages (as in figure 4.102).
Fig. 5.6 Contaminated system non-interacting mode

Fig. 5.7 Contaminated system interacting mode

Fig. 5.8 Contaminator with back corona
6.0 CORONA ESCAPEMENT ANALOG

The design idea of an electronic (solid state) analog circuit has been developed simultaneously with the formulation of lumped elements representing corona systems. Moreover, finding a fitting analog circuit helped the author to clarify the concepts of lumped-element representation of corona system, because a similarity was sought both in functioning of parts and in overall response of the analog. This circuit and its response is presented here to emphasize the lumped-element representation of corona systems in analogue terms.

6.1 Lumped-element analogs

An analog realization of lumped elements for a contaminated corona system is shown in figure 6.1 (b), in correlation with the lumped elements in figure 6.1.(a), as introduced in section 5.1.3 (figure 5.3) and expanded in section 5.3.3 (figure 5.7). The design philosophy and operation of individual sections are discussed subsequently.

Ionization-region analog

In this circuit, R1 and C1 correspond to the lumped parameters \( G_{11} \) and \( C_{11} \) for a particular corona regime with a relatively stable ionization-region geometry, as determined by the geometry of point electrode and its contaminator. Such stable conditions are peculiar to the negative Trichel-pulse and steady positive corona regimes. Also, these linear circuit elements may be considered as an average-value approximation for non-linear, voltage-dependent parameters appropriate for positive streamer corona.
The breakover voltage $V_B$ of a four-layer diode $D_1$, chosen as a suitable gating element for a Trichel-pulse-corona analog, corresponds to the ionization voltage $V_{i1}$ and it is also equal to the "onset" voltage $V_c$ of the analog, which does not represent the electrostatic field configuration below onset (i.e., for $V < V_B$ the diode resistance is much higher than the combined resistance of other sections, resulting in $V_3 \approx 0$). A 4E20 diode with $V_B \approx 20$ V and a maximum applied voltage $V_{\text{max}}$ of about 70 V (as limited by voltage ratings of other semiconductor devices in the circuit) provides a relative range of applied voltages $V_{\text{max}}/V_c = V_{\text{max}}/V_B \approx 70/20$, similarly as in the experimental point-to-plane system where $V_{\text{max}}/V_c = 30/8$ is typical.

A Zener diode, instead of the four-layer diode, would be appropriate in a steady-positive-corona analog.

**Buffer-region analog**

A linear approximation used in this section, with $R_2$ in parallel with $C_2$ representing $G_b$ and $C_b$ respectively, is justified by a relative magnitude of $G_b$, such that $G_b \gg G_t$ (and the transport-region conductance $G_t$ appropriately represented by a non-linear circuit), consistently with a higher density of current carriers in the buffer region particularly under conditions with a small space-charge modulation (section 5.1.2).

An undesirable consequence of using (unavoidably) separate circuit elements $R_2$ and $C_2$ as analogies for $G_b$ and $C_b$, is the relaxation time constant $R_2C_2$ which is not implied by the lumped element they represent.
As previously defined in section 5.1.3, the buffer-region and transport-region elements can be relaxed only through an external circuit, which is not a property of parallel RC circuits (alternatively, a series connection would not provide the essential DC current path). Also, by separating the displacement current (via C) from the drift current (via R), the analog can be regarded as a two-part network representing an essentially two-terminal element. Consequently, a relevant analogy of the corona current is the sum of currents through R and C, i.e. only a terminal current of the analog.

Transport-region analog

The transport-region conductance $G_t$, approximately equal to the total space-charge-region conductance $G_w$, is a linear function of voltage across it, as expressed in eq. 5.1.38. Such response and certain similarity in conduction processes, involving voltage-dependent densities of current carriers, is obtained with an N-channel depletion-type MOS FET (T1). This transistor is biased at cutoff by a variable voltage source $V_{G_1}$. A suitable proportion of the "transport-region" voltage $(V_2-V_1)$, applied through R3 and P1 (consuming a negligible current), partly compensates the bias voltage $V_{G_1}$ and consequently increases the channel conductance. The choice of a 3N 139 transistor was determined by its availability and suitability of drain current vs. gate-to-source voltage characteristics for obtaining the desired linearity of channel conductance vs. $(V_2-V_1)$.

Alternatively, an enhancement-type MOS FET can be used, having perhaps a more straightforward analogy in voltage dependence of MOS FET -
channel and transport-region conductances.

**Plate contaminator and back-corona analog**

To represent the non-linear contaminator characteristics, the same circuit configuration is used as in the transport-region analog. In a way, the plate contaminator is only another transport-region with different transport characteristics. The high-transconductance characteristics of a 3N 128 MOS FET (T2) were found more fitting than those of 3N 139 to simulate the characteristics of typical contaminators. With a suitable adjustment of $P_2$ and $V_{G_2}$, this circuit produces current-voltage relationships resembling those of paper and fly-ash at different humidities.

A contaminator breakdown voltage (depending on its thickness) is determined in this analog by a suitable Zener diode $D_3$. Consequently, the simulated criterion for the onset of back-corona is $(V_1 - V_0) = V_z$, where $V_z$ is the Zener voltage of $D_3$. A carrier multiplication process attributed to back-corona, as discussed in section 5.3.3, is simulated by a n-p-n transistor $T_3$, its forward current transfer ratio $\beta$ being analogous to the current-carrier multiplication factor in eq. 5.3.9. To control an effective magnitude of such multiplication, actually depending on the number and effectiveness of back-corona channels in a contaminator, a part of the current trough $R_6$ is shunted via $R_7$ and $D_2$, thereby reducing the transistor $T_2$ base current $I_B$ which is "multiplied" to produce $I_E \approx I_C \approx \beta I_B$, where $I_E$ and $I_C$ are the transistor emitter and collector currents, respectively. Diode $D_2$ in the shunt path matches the characteristics of the emitter junction of $T_3$. The collector
circuit of T3, with $R_8$ connected to the ionization-region analog, represents the lumped, quasi-neutral back-corona channel characterized in section 5.3.3 by a linear conductance $G_{wb}$. Consequently, the collector current $I_C \approx I_E$ is analogous to the back-corona current $I_{bc}$, and appropriately dependent on the resistance ($R_2$), breakdown voltage ($D_3$) and other (non-electrical) properties ($R_7$) of a plate contaminator.

6.2 Results

A typical response of the analog is presented in figures 6.1 (c) to (f), under conditions simulating the clean-system, non-interacting and interacting modes of operation. To record the results, the same techniques were used as in the corona-system measurements.

In figure 6.1 (c), the average current-voltage relationship (1), for a simulated clean system, is obtained by reducing $V_{G_2}$ to zero, which produces a negligible channel resistance of about 300 $\Omega$, i.e. the "contaminator" is virtually short-circuited.

Contaminators of different resistivities but the same breakdown voltage (i.e., of the same thickness as implied by a constant $V_z = 6.8$ V) are simulated by a suitable adjustment of $V_{G_2}$, as specified in figure 6.1. By changing $D_3$, a different contaminator thickness can be also simulated. Consequently, by changing the "contaminator" resistance, typical non-interacting-mode (2) and interacting-mode (3) and (4), characteristics are obtained. The vertical and horizontal CRO sensitivities have been selected so that the display of these characteristics emphasizes their similarity with experimental results.
for corona systems (e.g., figures 4.23/33/60/81).

The corresponding "surface" potentials \( V_1 - V_0 = f(V) \), shown in figure 6.1 (d), are comparable with the recorded \( V_s = f(V) \) in figures 4.29/38/83.

The current waveforms presented in figure 6.1 (e) are, on a different time scale, typical for the Trichel-pulse regime, including a corona-regime change to steady conditions occurring in the simulated interacting mode (4) at \( V \approx 45 \) V, which corresponds to \( V_A \) in figure 5.7 (a). This transition is also discontinuous, because an increase in the average current \( I \) as it reaches a holding level for \( D_1 \) \( (I_h \approx 1.5 \text{ mA}) \) is further "multiplied" by \( T_3 \). The current-voltage relationship (4) for \( V > 45 \) V (not displayed in figure 6.1 (c), but similar to that in figure 5.7 (a) for \( V > V_A \)) becomes linear and determined by \( R_8 \) as \( T_3 \) approaches saturation. This is consistent with the interpretation in section 5.3.3 that an overall space-charge neutrality produces a linear transport-region conductance \( G'_{wc} \) (eq. 5.3.10).

Furthermore, the analog enables observations of those quantities that are not easily measurable in the corona system, such as the spatial distribution of an applied voltage. The waveforms of "boundary" voltages \( V_3, V_2, \) and \( V_1 \) for the simulated buffer, transport, and contaminator regions respectively, are presented in figure 6.1 (f) for an applied voltage \( V = 40 \) V (the corresponding current waveforms are shown in diagram (e)). As implied in the formulation of lumped parameters (section 5.1.3 and figure 5.3), only \( V_3 \) varies with time.
Fig. 6.1 Corona escapement analog
REFERENCES


