Laboratory investigations of pulsed RF plasmas relevant to CW arc pluming at high-power aerials. Pt. 1: Critical breakdown under pulsed RF conditions


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Abstract: The mechanisms responsible for the development of electrical discharges at high-power aerial arrays under RF conditions have been investigated in the laboratory using pulsed discharge techniques. Both uniform and nonuniform electric field conditions have been studied, the former to investigate the influence of such parameters as humidity and environmental conditions, the latter to establish more precisely the role of sharp points and the consequent localised distortion of electric fields. The dramatic effects observed under actual operating conditions could be explained in terms of the influence of small protuberances at the corona shields, and highlights the possibly important environmental consequence of large insect populations in the vicinity of such aerial arrays.

1 Introduction

An extensive series of investigations has been in progress in these laboratories [1, 2] into the mechanisms by which electrical discharges develop at high-power aerial arrays in the presence of RF fields in the 6–26 MHz range. The investigations were initiated following an intolerably high incidence of 'plume' formation at Telecom Australia's 250 kW transmitter operating at Darwin in the Northern Territory of Australia. This 'plume' took the form of an intense luminous gas discharge from an active radiating part of the aerial and terminated in free air [3].

In this laboratory, limited high-voltage RF facilities confined early studies to relatively small electrode gaps, d, at low pressures, p [1–3]. Both uniform and nonuniform field conditions were investigated. We report here measurements up to large values of pd (> 200 torr cm), corresponding to conditions much closer to those prevailing at the transmitter itself.

RF discharges have considerable theoretical and experimental importance, and represent a large and growing field of interest. At the theoretical level, the detailed distinctions between RF discharges and those occurring under DC conditions or at microwave frequencies are not clearly understood. At the practical level, parasitic discharges give rise to a wide spectrum of RF noise power on high-voltage transmission lines [4–5] which seriously affect radiocommunications. RF plasmas are also used for plasma etching of semiconductors [6], and RF techniques have been used increasingly for plasma heating in fusion-oriented experiments.

The lack of information about the properties of steady-state RF discharges led to studies in air in the frequency range 1–10 MHz and discharge currents ranging from 0.05 to 2 A [7, 8]. Although re-ignition voltages were investigated, the phenomena studied were RF glow and RF arc discharges rather than the earlier corona phases. They were also confined to very small electrode gaps, an extension of these results to practical problems presenting considerable difficulties.

For DC conditions, other investigators, for example Ishiguro and Ushita [9], have noted large reductions in DC voltages due to the influence of protrusions introduced into sphere gaps. For nonuniform RF conditions added complexities arise because of polarity, hysteresis and associated time-dependent effects arising from space-charge accumulations. Consequently, a series of more fundamental studies of the precise mechanism responsible for the development of corona discharges at high voltage has been initiated in these laboratories. The use of highly time-resolved image-intensifier and spectroscopic investigations based on 'snapshot' studies of 10 ns duration will be described elsewhere. The investigations reported here have been undertaken as a first step to improving our understanding of a specific engineering problem.

2 Experimental procedures

2.1 Pulsed RF supplies

Preliminary results reported earlier [3] used a pulsed RF supply in order to achieve high peak powers in short, low duty-cycle (~0.1%) pulses. Unfortunately, although output currents up to 2 A could be supplied, the output voltage was limited to a maximum of 10 kV RMS. This restriction effectively confined observations to subatmospheric pressures. For further laboratory observations into the region of more direct relevance for the high power pluming phenomenon associated with the field transmitters, RF voltage amplitudes ~30 kV RMS were required. In addition, extension of the limited (~10 µs) pulse lengths to the millisecond range was desirable. Such an RF generating power supply was designed and supplied by Telecom Australia. However, in order to study discharge phenomena at these higher power levels, careful attention must be given to the influence of external circuit parameters on the initial, highly transient phases of the RF breakdown events.

In tuning the output tank circuit of the RF generator, it is possible to optimise either the peak amplitude of the RF voltage or the shape of the pulse envelope, but not both
simultaneously. If the tank circuit is tuned to resonance at the RF frequency, a maximum of the RF voltage is obtained, but the shape of the pulse envelope is poor. If, on the other hand, the tank circuit is detuned slightly, a more acceptable pulse envelope is obtained at the expense of peak output voltage. This effect is illustrated in Fig. 1.

![Fig. 1 Pulse shapes for output tank circuit tuned for maximum RF amplitude and optimum RF envelope conditions and pulse lengths of 10, 100 and 300 μs, respectively](image1)

Fig. 1 Pulse shapes for output tank circuit tuned for maximum RF amplitude and optimum RF envelope conditions and pulse lengths of 10, 100 and 300 μs, respectively

a. b Pulse length = 10 μs
Horizontal 5 μs/cm; vertical 0.5 V/cm × 6000
b. c Pulse length = 100 μs
Horizontal 20 μs/cm; vertical 0.5 V/cm × 6000
c. d Pulse length = 300 μs
Horizontal 100 μs/cm; vertical 0.5 V/cm × 6000
da, e and f are tuned for maximum output voltage, i.e. resonant at RF frequency f₀.
b, d and f are tuned for optimum pulse envelope (i.e. f = f₀)

which shows examples of the pulse shapes for tuned and detuned conditions and pulse lengths of 10 μs, 100 μs and 300 μs. As a consequence, if an acceptable pulse envelope for breakdown voltage measurements with a repetition frequency of 50 Hz is required, it is necessary to restrict breakdown potential measurements with the present apparatus to approximately 27 kV peak, the restriction becoming more severe the longer the pulses.

2.2 Amplifier performance with RF ionisation chamber
In coupling the RF power supplies to the ionisation chamber, it was necessary to re-tune the output tank circuit to compensate for the gap and stray capacitance. In the case of the 10 kV supply this was achieved by a variable capacitance in the output tank circuit, which was adjusted as the discharge gap was varied. For the 30 kV supply, the tank circuit inductance was varied by a tap on the output coil. This was optimised for a discharge gap of 15 mm and some detuning tolerated for smaller values of discharge gap.

2.3 RF breakdown potential measurements
Resistive and capacitive dividers were employed for the measurement of voltages up to 10 and 30 kV RMS, respectively. The resistive attenuator (total resistance 10 kΩ) provided a 500:1 division ratio. The capacitive divider, consisting of two series capacitors, 0.01 μF and 1.6 pF, respectively, provided a division ratio of 6000:1 when a test point on the output transmission line was connected via 50 Ω coaxial cable to a CRO with 1 MΩ input. In this arrangement one end of the capacitive divider and one electrode of the discharge gap are at earth potential.

These voltage dividers enable the voltage across the discharge gap just prior to the collapse of applied voltage (resulting from the passage of a discharge) to be observed on an oscilloscope screen. This observed maximum voltage which a given discharge gap can maintain is often regarded as the 'breakdown potential', Vₜ. It is an unsatisfactory definition of a breakdown potential, particularly when dealing with nonuniform fields (see Section 3.2.1). Under such conditions, intermittent sparking occurs at voltages well below that defined above. For our immediate purposes we retain the simplistic definition, quoting RMS values of the breakdown potential so that valid comparisons can be made with earlier uniform-field measurements at low values of pd. Corresponding peak values are also given.

The accuracy of the values of the breakdown voltage is determined by a variety of parameters such as:

(a) the fluctuation of the output voltage
(b) uncertainties in component values of the measuring system including divider ratios, cable capacitance, etc.
(c) the sensitivity of the particular technique adopted as a criterion for observing the breakdown event.

The dominant factor controlling the accuracy in the present experiments is the output voltage fluctuation occurring over the time involved in a measurement at 50 pulses/s. We estimate the accuracy of the values quoted as \( \pm 5\% \).

2.4 Effect of pulse length and pulse shape on breakdown measurements
Some comments are necessary about the effect of pulse shape. Careful measurements with pulses of different lengths but optimum pulse envelopes (see Fig. 1) showed that \((Vₜ)_{\text{RMS}}\) was independent of pulse length. Fig. 2,

![Fig. 2 \((Vₜ)_{\text{RMS}}\) and \((Vₜ)_{\text{pk}}\) as a function of \(p_{20}\),d for different pulse lengths](image2)

\( \bigcirc \) 10 μs, 50 Hz plane-plane electrodes; stainless-steel/copper
\( \triangle \) 100 μs, 50 Hz plane-plane electrodes; stainless-steel/copper

however, shows a decrease in \((Vₜ)_{\text{RMS}}\) for measurements in dry air when the generator was tuned to resonance and the pulse length was increased from 10 to 100 μs. No further decrease occurred when the pulse length was increased to 300 μs. The reasons for the differences appear to be associated with time lag phenomena and can best be appreciated by referring to the pulse shapes of Figs. 1a and b. The effective duration of the 'tuned' pulse (Fig. 1a) at the maximum voltage amplitude is only \( \sim 1 \) μs. For the detuned pulse of Fig. 1b the maximum voltage remains applied for times > 5 μs. Consequently, if a formative time \( \sim 5 \) μs is required to complete the breakdown mechanism, it will not be possible to observe a breakdown event at the threshold voltage when using a pulse shape such as that in Fig. 1a. The gap would need to be overvolted until the time lag diminished to < 1 μs. The time lags associated with this effect are considered to be formative rather than statistical lags and to be determined by the time required for the development of space-charge accumulations. This

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will be discussed in more detail in a subsequent paper. In the following Sections the measurements reported have all been made with flat detuned pulses, where the breakdown potentials were independent of pulse length.

A further observation was that the breakdown potential observed with 10 μs pulses decreased when measured in a gas sample that has previously been subjected to breakdown events with 100 μs pulses. This did not occur with 10 μs pulses after subjecting the gas sample to breakdown events with 10 μs pulses. The decrease is undoubtedly associated with the production of new species such as NO, NO₂ etc. in air discharges. The influence of impurities will be considered further in Section 3.1.4.

2.5 Discharge chamber and vacuum system

For measurements in air, the spark chamber and gas handling manifold were pumped by a mechanical pump via liquid-nitrogen traps. This achieved an ultimate vacuum of a few micrometres of mercury, with a sealed-off rate of rise of pressure of less than 1 μm min⁻¹. For other gases, a 150 1 s⁻¹ oil diffusion pump achieved an ultimate pressure of a few times 10⁻⁵ torr. Background pressures were measured with a Pirani or ionisation gauge. Pressures in excess of 1 torr were read on a Wallace and Tiernan bourdon gauge (Type FA129, 0-800 torr). Reproducibility of breakdown potential measurements was checked by repeated observations on different gas samples. For the uniform-field measurements both electrodes were made of stainless steel unless otherwise stated.

3 Experimental results

3.1 Breakdown potential measurements in uniform-field gaps

Plane-parallel Rogowski-profiled electrodes were used in these experiments. The gap was maintained at 15 mm at which value acceptable output voltage levels at the tuned frequency of 10 MHz were obtained. The large value of the discharge gap capacitance with plane-parallel electrodes imposes the major limitation to extension of the observations to large values of pd. The present measurements were limited to the range pd < 600 torr cm, but this increased the range previously covered [3] by a factor of three. The gap was illuminated from a side window using a Penray UV lamp. This ensured that no excessive statistical time lag effects were present. Measurements were made for laboratory air, dry air and dry nitrogen.

3.1.1 Measurements with 10 μs pulses in dry air

Figs. 3A and B show the comparison of breakdown potential (V₀) measurements at low and high values of p₀d, where the pressure has been quoted for a temperature of 20°C. Fig. 3A shows the values of V₀ of RMS and of (E₀RMS) and Fig. 3B the revised comparison of (E₀RMS)/p₀ as a function of p₀ for DC, RF and microwave breakdown in air. For the latter, comparison measurements [3] at low values of p₀d for a gap separation of 19.5 mm have been included. The new measurements at d = 15 mm are seen to fall on the extension of the smooth curve through the earlier measurements. A comparison of the RF and DC measurements is considered in more detail in Section 3.1.2.

3.1.2 Comparison with DC measurements

All breakdown potentials so far have been quoted as RMS values. This has provided direct comparisons with microwave data as shown in Fig. 3B. For comparisons with DC observations, the more comprehensive set of data now available provides an opportunity to reassess the validity of 50 Hz repetition rate) in the present investigations over the range of p₀d values from 50 to 450 torr cm. These recent RF measurements indicate clearly that, whilst for values of 50 < p₀d < 200 torr cm, neither the RMS nor the peak values agree well with the DC observations, there is a close correlation between the DC and peak RF values at the higher values of p₀d. In the form E₀/p₀ as a function of p₀d shown in Fig. 4B it becomes very clear that, whilst at low values of p₀d there is a close correlation of the DC values with RMS values, at high values of p₀d the correlation strongly favours the peak values of the RF voltage.

The comparison has been carried a stage further in Fig. 3B by adding the values of E₀/p₀ corresponding to peak values of the RF voltage. Once again the change from a
correlation with RMS values at low $p_{20} \cdot d$ to correlation with peak values at high $p_{20} \cdot d$ is seen clearly. The DC and RF peak values of $E_p/p_{20}$ merge at $p_{20} \cdot d$ values ~600 torr cm.

![Graph showing RF breakdown potentials as a function of $p_{20} \cdot d$ in dry air compared with DC measurements](image)

**Fig. 4A** RF breakdown potentials as a function of $p_{20} \cdot d$ in dry air compared with DC measurements

from the electron-neutral collision frequency and the fraction energy loss per collision under breakdown conditions, as discussed earlier [11]. At higher pressures in the present investigation, the energy relaxation time can be shown to become appreciably less than the period of the RF field. The 100% modulation of the mean electron energy that would then occur in the RF electrical field would ensure that the breakdown criterion is satisfied at the peak value of the RF field.

At lower pressures the relaxation time is much longer and would become comparable with the period of the RF field as the pressure falls below 1 torr. Some difficulties might be anticipated, therefore, in attempting to correlate DC breakdown voltages with RMS or peak values of the RF field. However, as will be seen in subsequent investigations reported elsewhere, at the pressures (>25 torr) used in these studies the relaxation time remains always very much less than the period of the 10 MHz RF field, and the difficulties arise essentially because of problems associated with space-charge accumulation rather than with the relaxation process itself.

### 3.1.4 Investigations of gas composition effects

**Changes of gas composition with time:** As noted briefly in Section 2.4 electrical discharge action itself, in gas mixtures, can lead to changes in the observed breakdown potentials. Consequently, some detailed observation of breakdown potentials in uniform fields in a variety of N$_2$-O$_2$ mixtures were undertaken. For reasons outlined in Section 2.4, measurements were confined to 100 μs pulses. A single value of $p_{20} \cdot d = 445$ torr cm was chosen to obtain $(V_0)_{RMS}$ as a function of % O$_2$ in the N$_2$-O$_2$ mixture. No prolonged discharging was allowed to occur. A fresh mixture was investigated in each case and the threshold voltage for the first breakdown event only was recorded. The monotonic change in $V_p$ towards larger values with increase in % O$_2$ in the mixture is shown in Fig. 5A. The time changes in the breakdown potential are shown in Fig. 5B. For these observations the gases N$_2$ and O$_2$ were admitted to the evacuated chamber in the appropriate proportions. $V_p$ was measured immediately and the discharge left on for 30 s before remeasuring $V_p$ within a further period of 5–10 s. The sequence was repeated to yield the results shown by the solid line of Fig. 5B. A reversal of the timing procedures, i.e. a measurement of $V_p$ lasting ~5 s, followed by a rest period of 30 s before remeasuring, led to the results shown by the broken line of Fig. 5B. No such time effects were noted in either pure nitrogen or pure

![Graph showing comparison of RMS and peak values of $E_p/p_{20}$ as a function of $p_{20} \cdot d$ with corresponding DC measurements in dry air (10 μs pulses: 30 Hz repetition frequency)](image)

**Fig. 4B** Comparison of RMS and peak values of $E_p/p_{20}$ as a function of $p_{20} \cdot d$ with corresponding DC measurements in dry air (10 μs pulses: 30 Hz repetition frequency)

![Graph showing breakdown voltage $(V_0)_{RMS}$ as a function of percentage O$_2$ in N$_2$-O$_2$ mixtures for constant $p_{20} \cdot d = 445$ torr cm and 100 μs pulses](image)

**Fig. 5A** Breakdown voltage $(V_0)_{RMS}$ as a function of percentage O$_2$ in N$_2$-O$_2$ mixtures for constant $p_{20} \cdot d = 445$ torr cm and 100 μs pulses

3.1.3 The influence of time constants for momentum and energy relaxation

The transition from ‘RMS’ to ‘peak-value’ correlation with DC breakdown voltages as $p_{20} \cdot d$ is increased from 50 to 540 torr cm can be understood in general terms by consideration of the relevant relaxation time constants for electron momentum and energy [11]. The momentum time constant can be shown to be always very much less than the period of the RF field under the conditions of the present investigations. There will be no significant departure, therefore, from 100% modulation of the electron momentum and the electron drift velocity is in phase with the applied field for all pressures.

The electron energy relaxation time is, however, much larger than the momentum relaxation time. This characteristic time for electron energy relaxation can be estimated

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oxygen. The largest changes in $V_e$ occurred at percentages of $O_2$ between 10 and 20%, i.e. under conditions close to atmospheric. However, under no conditions were the changes greater than 10%, and in many cases were much smaller. Further detailed observations in nonuniform fields will be reported in a further paper.

External gas composition effects: Retaining uniform-field conditions, three common additives, pure water vapour, saline-contaminated water vapour and carbon dioxide, that could possibly influence ‘pluming’ phenomena at a transmitter site, were examined. The additives were introduced by simply allowing the air sample to be investigated to enter the system via an appropriate solution in the case of the water vapour investigations and by admitting the gas at the appropriate pressure in the case of the carbon dioxide.

The influence of water vapour was established by measurements on three different samples of air. The first, admitted to the system via cold traps of liquid nitrogen, is identified as ‘dry air’. The second, admitted directly to the system from the atmosphere without contact with liquid-nitrogen traps, is identified as ‘laboratory air’. The third, bubbled through a bath of water into the discharge chamber, is referred to as ‘moist air’. No attempt was made to measure the humidity levels. These results which cannot be distinctly separated in Fig. 6 are compared with those in CO$_2$ for the same pulse length and gap separation. The small increases ($\geq 1\%$) observed in $V_e$ with increasing humidity were not inconsistent with previous DC observations [12]. Measurements made after bubbling the air sample through a near-saturated solution of salt water were identical with those observed in moist air.

The measurements in pure CO$_2$ were supplemented with a series of observations of $V_e$ versus $\%$ CO$_2$ in either N$_2$ or laboratory air and are shown in Fig. 7. Added to N$_2$, the CO$_2$ impurity led to a large increase in $V_e$ which peaked at about 25% CO$_2$ content with a value some 25% higher than for pure N$_2$ and only some 3% larger than for pure CO$_2$. No such peaks were observed in N$_2$-O$_2$ mixtures.

By contrast, a decrease in $V_e$ occurred when CO$_2$ was added to laboratory air, although its magnitude does not become appreciable until the percentage of CO$_2$ has reached $> 50\%$. Even at close to 70% of CO$_2$ content the reduction amounts to only about 6%.

Qualitatively, these observations can be understood in terms of the relative magnitudes of the effective ionisation coefficients $\lambda' = \lambda - \eta$ for the various mixtures of air and nitrogen with carbon dioxide. Such effective values, $\lambda'$, simply recognise the changes in the net gain of electrons as the balance between ionising ($\lambda$) and attaching ($\eta$) processes varies with the composition of the mixtures. Electron attachment processes have been the subject of more detailed investigations using highly time-resolved techniques, and further discussion of them will be deferred to a subsequent paper. For the present purposes it does not appear that common gas composition effects play any significant role in the observation of ‘pluming’ phenomena at transmitter aerials.

3.2 Breakdown potential measurements in nonuniform field gaps

Nonuniformity was introduced into the electric field by simply introducing a fine needle point through a 1 mm diameter aperture in the upper stainless-steel electrode of the Rogowski-profiled arrangement used in Section 3.1 for the uniform-field observations. By varying the protrusion of the fine needle below the plane surface, it has been possible to increase the degree of nonuniformity in a controlled manner. Although there was very little change in the observed breakdown voltages with change in electrode materials, the highest breakdown voltage was observed.
with a stainless-steel upper electrode and a copper lower electrode. These electrodes were used to provide the optimum conditions for studies of the effect of nonuniformity on the reduction of the breakdown potential. In all other respects the procedures for applying the RF voltages and for minimising time lag effects were identical with the uniform-field studies.

3.2.1 Breakdown criteria in nonuniform fields

In uniform-field breakdown at pulse repetition frequencies of 50 Hz, no evidence appeared of any corona or weakly ionised discharge prior to the appearance of the diffuse or the filamentary glow discharge. Consequently, there was no ambiguity about the critical voltage required to produce the breakdown event. With nonuniform fields, however, stable corona could exist under some circumstances, followed, as the applied voltage increased, by transitions to various other modes of discharge. Different values of critical voltage corresponded to the onset of the different modes, and in some cases no detectable change in the applied voltage accompanied the visual appearance of a plasma. The same three stages in the breakdown mechanism could be distinguished in both air and N₂. For the case of N₂ the following phenomena were observed:

(a) a corona first appears at the needle point when the voltage reaches a critical value, \( V'_c \). This corona is limited in extent, is stable and persists after removal of the external irradiation.

(b) with further increase in voltage the extent of the corona surrounding the needle point changes, the purplish-blue colour of the plasma remains the same but with evidence of a red filamentary channel appearing at the centre. The corona remains stable until, at a voltage \( V'_c \), a transition occurs to a much brighter, whist, more intense discharge that is intermittent.

(c) as the voltage is increased beyond \( V'_c \) the rate of intermittent discharge increases until eventually at a voltage \( V'_{sc} \) it becomes 'continuous', i.e. it occurs at the applied frequency of 50 Hz.

(a) could not be detected by an observable collapse of voltage, whereas (b) and (c) could. Visual observation is therefore necessary for the determination of the onset of corona. Whilst we have employed sophisticated image-intensification techniques in our most recent studies, the measurements reported here relied on the direct visual identification of the corona, taking care to minimise the effects associated with the degree of dark adaptation of the naked eye.

3.2.2 Measurements of breakdown potentials for nonuniform fields

Measurements were made in dry air and dry nitrogen of the potentials \( V'_c \), \( V'_{sc} \), \( V'_{sc} \) as defined in Section 3.2.1. A constant separation of the two Rogowski-profiled electrodes was maintained at 15 mm and an ordinary, commercial steel sewing needle was used to introduce nonuniformity into the electric field. The radius of curvature of the tip of the needle was \( \sim 20 \mu m \). Although this was degraded by erosion after prolonged discharging to between approximately 100 to 400 \( \mu m \), no evidence was found to indicate that during particular sets of measurements the corona voltages were changing rapidly as a consequence of such erosion. Nevertheless, the whole question of the precise influence of the shape of the needle point requires further investigation.

Values of the needle-point protrusion were set at 0, 1, 2, 3 and 4 mm, respectively, for \( p_{20} d \) values in the range 200–1000 torr cm. The observations reported here were confined to either 10 or 100 \( \mu s \) pulses at repetition frequencies of 50 Hz. The value of electrode separation used for the parameter \( p_{20} d \) has been taken as \( d' = d - x \), where \( x \) is the value of the needle-point protrusion (see Figs. 8A and B), i.e. we plot \( V'_c \) as a function of \( p_{20} d' \).

A comparison of the critical voltages \( V'_{sc} \) for \( x = 0 \) in dry air and nitrogen and for \( V'_{sc} \) for \( x = 3 \) mm (pulse length = 10 \( \mu s \)) is shown in Fig. 8A. Also included are \( V'_{sc} \) for dry nitrogen with \( x = 3 \) mm.

![Fig. 8A Comparison of critical voltages \( V'_{sc} \) for \( x = 0 \) in dry air and nitrogen and for \( V'_{sc} \) for \( x = 3 \) mm (pulse length = 10 \( \mu s \)). Also included is \( V'_{sc} \) for dry nitrogen with \( x = 3 \) mm.](image-url)
19.5 kV RMS, whereas for $x = 4$ mm the corresponding $V_e$ was only 4.7 kV RMS.

Fig. 8B compares values of $V_I$ for dry air and dry nitrogen with $x = 2$ mm observed with 100 $\mu$s pulses. Also shown are the values of $V_{e2}$ for $x = 0$ and $V_{e2}$ for $x = 2$ mm in dry nitrogen.

One final comment needs to be made about the initial breakdown values $V_e$ plotted in Figs. 8A and B. Visual observation shows that the 'coronal' plasma is limited in extent to the region surrounding the needle point. Consequently, the value of $d'$ used in the Figures should refer not to the whole gap but only to that part of the gap converted into the stable corona. If we assume that the voltage $V_e$ is only sufficient to maintain a discharge at the value of $p_{20}d'$ represented by the $V_{e2}$ versus $p_{20}d'$ curve, it is possible to predict the extent of the visual corona that would be observed. For example, at the value of $(V_{e2})_{N_2}$ corresponding to $p_{20}d' = 980$ torr cm in Fig. 8A, the $p_{20}d'$ value of the same voltage of the $(V_{e2})_{N_2}$ curve for $x = 3$ mm is $\approx 350$ torr cm. For the same pressure, therefore, this applied voltage would only sustain a corona over a proportion (350 $\times$ 980) of the region beyond the needle point. With $d' = 1.2$ cm the extent of the corona would then be only $\approx 0.4$ cm. This would increase by a factor $\approx 2$ for the corresponding situation at $p_{20}d' = 380$ torr cm on the $(V_{e2})_{N_2}$ curve. This leads to the prediction that the extent of the corona observed at threshold $V_e$ should be greater, the lower the value of $p_{20}d'$, and that no corona breakdown event should be observable provided the value of $p_{20}d'$ is increased sufficiently at any given value of $x$. This is indeed consistent with the visual observations, and will be considered in greater detail in a further paper dealing with investigations using image-intensification techniques coupled with analysis of the spectral emissions by means of an optical multichannel analyser. For the present purposes we simply note (Fig. 9) the variation of the axial length $L$ of the corona in air as a function of pressure for three different constant voltages applied to parallel plates separated by $d = 15$ mm. A tuned 10 $\mu$s RF pulse of frequency 10 MHz and a repetition rate of 50 Hz was used, and the values of $L$ determined from image-intensified photographs obtained by the techniques described previously [13]. The light output was recorded over a period of 500 ns (gating pulse length of the image converter) at the peak of the 10 $\mu$s tuned pulse. For these experiments the radius of curvature of the needle point $r$ was 20 $\mu$m and protruded a distance of $x = 2$ mm below the upper plate for each of the three experiments. Clearly, with increasing pressure, a stage is reached at which the corona 'spot' remains extremely small before developing directly into a filamentary channel, which then becomes the first visual evidence of the breakdown event.

4 Discussion

The investigations reported here direct attention to several important matters related to the evidence [3] that plumes have been observed at the Darwin site in the presence of maximum voltage gradients in the range of only 2.3 to 6.4 kV (peak) cm$^{-1}$. Now that we have identified visually the early initial corona breakdown event, it can be seen from Figs. 8A and B that the voltage gradient required to initiate this basic breakdown phenomenon is indeed within this range of values. Consequently, the existence of such adverse conditions of voltage gradient could itself be responsible for the formation of the initial plasma, from which the more intense pluming phenomenon could develop.

Probably of more significance, however, is the fact that these relatively low voltage gradients can be established by sharp points protruding only small distances from the normal boundary surfaces. In the presence of large insect populations there would seem to be ample opportunity for such adverse conditions to be established by these natural causes, leading to the formation of extensive amounts of weakly ionised 'coronal' plasmas on the aerial arrays.

One final comment is necessary concerning the question of whether the 'pluming' phenomena are controlled by RMS or peak values of the applied voltage amplitude. The visual observations of the corona show no extensive penetration beyond the vicinity of the needle point. The value of $d'$ appropriate to the early stages of any 'pluming' phenomenon may therefore be very much less than values linked to the gap geometry of our experiments. This means that the pd values for the onset of plume formation, especially under atmospheric pressure conditions, would be very low. The 'small-volume' breakdown in these circumstances would be controlled by quasi-RMS voltage levels.

In extending the present investigation it is essential to establish the relevance of these particular laboratory experiments to the problems existing at the transmitter aerial. For this purpose further studies have been made with toroidal and spherical electrode geometries that are more appropriate to the transmitter aerial design. These are reported in Part 2 of this paper [14].

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6 References


Fig. 9 Corona axial length as a function of pressure for constant applied voltages using the geometry shown

- 96 kV
- 10.8 kV
- 11.6 kV (pk)