LABORATORY STUDIES OF CORONA CURRENT EMISSIONS FROM BLUNT, SHARP AND MULTIPOINTED AIR TERMINALS

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Abstract: This paper presents the results obtained from a systematic series of laboratory experiments investigating the corona current emission characteristics of blunt, sharp and multipointed air terminals. A number of aspects are considered, including the effect on corona emission of changing the distance between the terminal and overhead screen, the difference in corona current emission parameters between all of the main air terminal types, and empirical relationships describing the variation of these parameters for one set of air terminals as a function of their height above the ground.

1. Introduction

In recent times, there has been a growing acceptance of the theory that minimising the pre-stroke space charge accumulation around an air terminal will enhance its ability to initiate and sustain an upward leader (e.g., see [1], [2], [3], [4], [5]). Hence, one parameter for assessing the performance of an air terminal is its corona emission or "point discharge" current under a static electric field, corresponding to the thunderstorm conditions prior to the approach a lightning downward leader. Remarkably, very few in-depth laboratory experiments have been carried out with the aim of quantifying this phenomenon under controlled conditions. The work of Kip [6] is often cited in the literature. Yet, this classic work was performed on a small scale (point-to-plane gaps of centimetres) and no-one appears to have attempted to solve the problem of scaling the laboratory data to the field in which the air terminals are put to their ultimate test.

During 1997, corona current measurements on a selection of blunt, sharp and multipointed air terminals were carried out using high voltage facilities located at Telstra Research Laboratories in Australia and Mississippi State University in the United States (hereafter abbreviated TRL and MSU respectively). The main aims of these experiments were to: (a) investigate the "laboratory factor" in air terminal testing, namely, for a given electric field intensity, the variation in results with the changes in the air gap (the distance between the terminal and the overhead screen); (b) provide a quantitative assessment of the differences in corona emission characteristics in a selected set of air terminals, and (c) obtain a scaling relationship describing the corona current characteristics of a new prototype family of ellipsoidal, "corona reducing and triggering" (CRT) air terminals, as a function of their height above the ground.

2. Experimental Method

The experiments were carried out using a horizontal, conductive, overhead screen of dimension 3.5 x 5 m, hoisted to heights of up to 8 metres, with applied negative potentials up to 450 kV. Stress relief in the form of conductive tubing, 30 cm in diameter, was used around the edges of the screen.

Atmospheric conditions were monitored throughout the experiments. However, corrections to the data were not required because the variations in humidity, pressure etc. were only small, giving less than 2% error in the results.

A vibrating capacitor electric field sensor was used to "calibrate" the electric field between the overhead screen and ground. This was necessary because the field magnitude is not simply the ratio of the screen potential to the separation. The field is modified by factors such as the finite size of the overhead screen and the laboratory walls. An additional benefit of such a calibration procedure is that results obtained in different laboratories can be standardised.

The static electric field resulting from a wide range of negative DC potentials applied to the overhead screen was measured at ground level using the sensor for plate heights from 2 to 8 m in 1 m steps. These distances bracketed the minimum and maximum separations that were to be used for any of the measurements. Bench tests showed that the sensor produces an output voltage in volts which is approximately 1/11th of the applied electric field in kV/m.

Figure 1 displays a typical set of electric field calibration curves. It is quite obvious from these plots that the experimentally determined electric field strength is less than the "simple-minded" *V*/*d* value. Applying a line-of-best-fit to each plot, we obtain calibration factors α, where *E*(measured) = α(*V/d*), in the range 0.66 to 0.83, depending on the height of the screen above the ground.

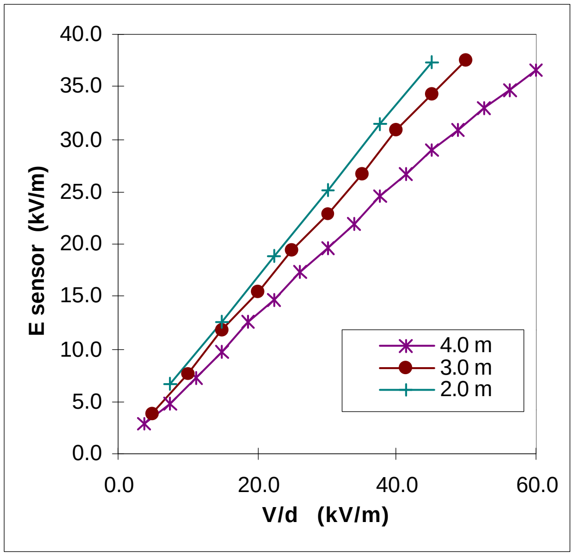

Figure 1: Typical electric field calibration curves.

The corona current measurements were made by grounding the air terminals through a 1 MΩ resistor so that each volt across the resistor corresponded to 1 μA of point discharge current. The potential on the overhead screen was increased in steps on 10 kV and the potential difference recorded for each configuration of air terminal.

The following air terminals were tested:

- a Franklin rod with a conical tip and hemispherical capping of radius ~1 mm
- three ellipsoidal CRT air terminals which, under dynamic conditions, operate on a "capacitive coupling" principle, i.e., each has an electrically floating metallic dome and flat tip ~3 mm in diameter, with a grounded, centrally protruding conducting rod ~25 mm in diameter; the three dome sizes (diameters) were 350, 500 and 700 mm; the central rod and tip was adjustable so that it could be set to different protrusions above the dome as needed
- two spline balls, one with a radius of 37 cm and the other with a radius of 9 cm
- a single wire ~3 mm in diameter
- a wire such as the single one but formed into a "V" shape with the tips approximately 40 cm apart.

In the investigations of the "laboratory factor", the Franklin rod and the 350 mm ellipsoid with a 15 cm tip protrusion were used. Each terminal was set at a fixed height of 1 m and the air gap was varied from 1 m to 5 m in steps of 1 m.

In the comparative assessment of corona emission characteristics, all of the above air terminals except for the ellipsoidal family were used, i.e., all of the "passive" devices. Each terminal was set at a height of 1 m above the ground and corona measurements were made with two different air gaps, namely 2 and 3 metres.

The three ellipsoidal air terminals were used in the investigations where the intent was to obtain a scaling relationship describing the corona current parameters as a function of height. In these experiments, the air gap was fixed at 2 m and the height of each air terminal above the ground was varied in three steps, namely, 2, 4 and 6 metres (although a limited quantity of data were obtained for heights of 1 and 3 metres). The length of the protruding central rod was also varied in three steps but the amount differed for each ellipsoidal terminal in such a way that the "rod protrusion to dome diameter ratio" was constant across the three terminal sizes. The three ratios used were 0.143, 0.286 and 0.429.

3. Results

The measured values of corona current were plotted against the calibrated electric field for each of the cases described above.

Figures 2 and 3 display the results of the investigations into the variation of corona current with the size of the air gap. Although the curves are difficult to see for the larger gaps because of the smaller range of electric fields (and hence currents) that could be generated, there is a clear dependence of the corona current parameters on air gap. This dependence is also evident in the very early results obtained by Kip [6] if the independent axis is converted into a field strength rather than just potential.

Figure 4 displays the corona current curves for the Franklin rod, two spline balls, single wire and V-shaped wire for air gaps of 2 and 3 metres. The data are all plotted on the same graph in order to provide an instant visual assessment of the difference in point discharge characteristics of each air terminal.

In the third set of measurements, in which a large matrix of results were obtained because the size, height and tip length of the ellipsoidal air terminals were varied, there are too many plots to display here. Hence, only a sample set of plots is shown which is typical of the results obtained. These are shown in Figure 5, which displays the results for the 350 mm air ellipsoidal air terminal.

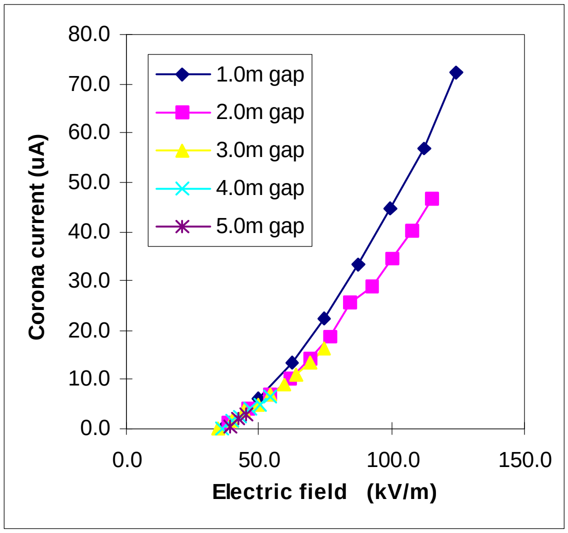

Figure 2: Corona currents for the 350 mm ellipsoidal air terminal with a 15 cm tip protrusion as a function of the air gap.

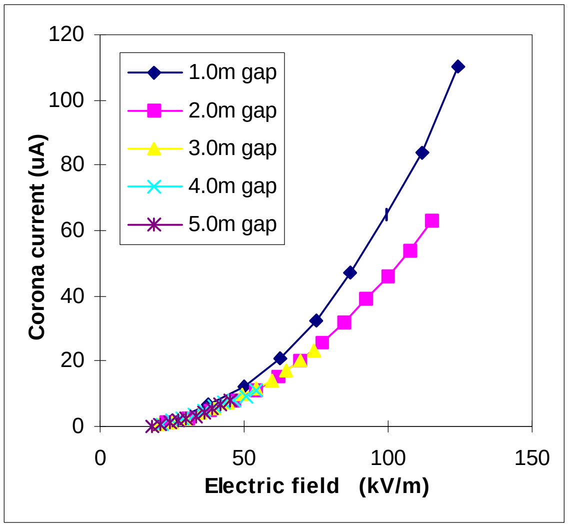

Figure 3: Corona currents for the Franklin rod as a function of the air gap.

4. Analyses and Discussion

The data curves shown above were modelled with a standard point discharge equation in terms of the ambient field (e.g., see [5], [7], [8]):

$$I_c = AE(E - E_c) \qquad (1)$$

This enabled the “corona inception electric field”, E_c (in units of kV/m), which we define as the ambient field needed to initiate corona emission at the terminal tip, and the “corona current amplitude coefficients”, A (in units of μA/(kV/m)^2), to be extracted. Some of these parameters were then used for further analyses as described in the following sections.

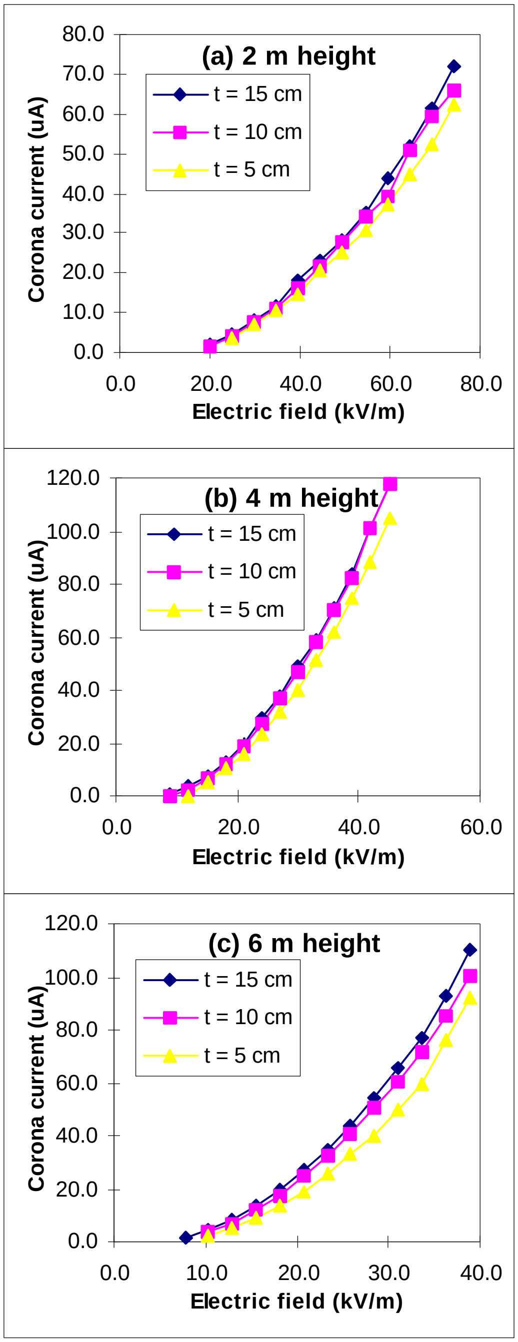

Figure 5: Multi-parameter corona current plots for the 350 mm ellipsoidal air terminal. The variable t is the distance the central rod protruded above the dome of the air terminal.

4.1 Investigation of the "laboratory factor"

The parameters A and E_c obtained from the curves shown in Figures 2 and 3 (350 mm ellipsoid and Franklin rod) were plotted against the air gap. These plots are shown in Figure 6.

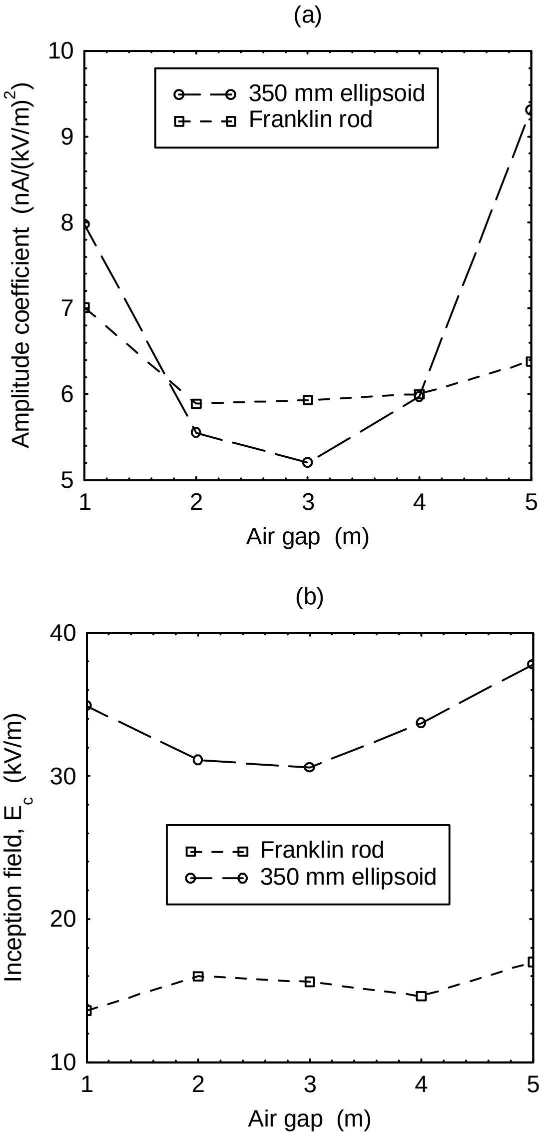

Figure 6: Variation in corona amplitude coefficient and inception field with changing air gap for the 350 mm ellipsoidal air terminal and Franklin rod. Both terminals were placed at a height of 1 metre.

The main characteristic in Figure 6(a) is the flat region corresponding to intermediate gaps. This region extends from 2 to 4 m, a range which is evident in the data from both laboratories. A number of theories can be put forward for the significant variation in amplitude with the size of the air gap. For example, for gaps smaller than the lower limit of 2 m, "near field" effects take over. In these small gaps, the nature of the electric field around the tip of the air terminal may be completely different because of the much closer proximity of the overhead screen. The field lines will be highly divergent all the way to the screen, causing the ions to be swept out much more swiftly. This in turn produces a higher corona current and, hence, amplitude coefficient. Detailed analyses of these results are presently being conducted and will be reported elsewhere.

On the other hand, and not unexpectedly, the corona inception field values shown in Figure 6(b) are relatively insensitive to the air gap used in the experiments.

These results have led us to postulate that, in laboratory work, air gaps of 2 – 4 metres may provide corona current data that are relatively independent of the air gap and comparable to what would be measured under natural conditions. The only data we presently have available for direct comparison comprises a sequence of measurements from a sharp corona point mast exposed to storms on South Baldy Peak near Langmuir Laboratory, New Mexico. Prior tests conducted at TRL, with the overhead screen 1 metre above the sharp point resulted in corona currents that were 20–30% higher than in the field (after corrections were applied to the field data to allow for the lower air density and humidity). Comparison of the amplitude coefficients for 1 and 2 metres in Figure 7(a) shows agreement with this observation.

4.2 Comparative assessment of corona current characteristics

The curves shown in Figure 4 provide an interesting comparison of the magnitude of corona emission from the various passive air terminals. It can be seen that neither spline ball produces more corona than the Franklin rod or single wire. Furthermore, the V-shaped wire produces significantly more corona than the other.

The implication of these results for spline balls and their use in lightning protection is quite clear – these so-called dissipation or discharge devices are clearly ineffective. Ignoring the fact that much debate exists regarding the ability of any device to hinder or inhibit a lightning strike, our laboratory tests have shown that these devices do not produce the high levels of corona required and, in fact, are outperformed by what is essentially a metallic coathanger cut in the middle and shaped in the form of a "V" !

In addition, Chinese research groups have been conducting investigations into lightning elimination with multipoint conductors in recent times and they have arrived at similar conclusions (e.g., see [9]).

4.3 Characteristics of the ellipsoidal air terminals

The curves shown in Figure 5 and those for the other two ellipsoidal terminals were also modelled with the general point discharge current equation (1), yielding a matrix of 27 estimates each for A and E_c, i.e., three air terminals at three heights with three tip lengths. A table of all the individual results cannot be included here due to space restrictions but the results can be summarised as follows:

- The parameters A and E_c are strong functions of the air terminal height and tip curvature; physically, this is the "field intensification factor" of the air terminal
- The parameters A and E_c are only weak functions (10-20% variations) of the: (i) tip length (for the range of tip lengths used in this study), and (ii) the size of the air terminal dome

In other words, the tip length and dome size are only second order effects which can be utilised when fine tuning a system installation.

Figure 7 displays the mean values of A and E_c for five different heights, using data obtained from the TRL and MSU laboratories. The uncertainties are 1σ errors on the mean values.

The larger scatter at lower heights in Figure 7(b) is due to a stronger dependence of the inception field on tip length at those heights. This dependence can be understood by realising that, at greater heights, the dominant geometry is that of the air terminal on a mast penetrating the ambient field, whilst at lower heights the tip will be the dominant geometry relative to the dome of the air terminal (which is effectively at ground potential under static conditions).

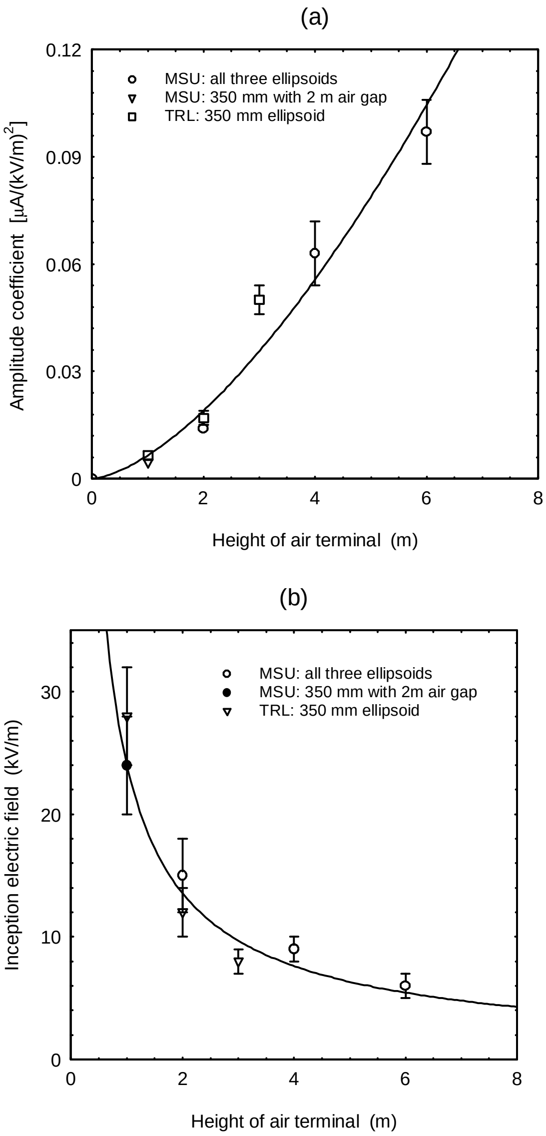

Figure 7: Mean amplitude coefficients and inception fields for the ellipsoidal air terminals, derived from TRL and MSU laboratory data.

Next, the A and E_c data in Figures 7(a) & (b) were fitted to a range of mathematical functions. Standard polynomial and exponential functions did not provide a good fit. The best results were achieved with an inverse power law function for both the A and E_c data and these curves are shown in Figure 7. Mathematically, these curves are described by:

$$A = 6.5 \text{ x } 10^{-3}\, h^{1.55} \tag{2}$$

$$E_c = 28.5\, h^{-0.85} \tag{3}$$

and so

$$I_c = 6.5 \text{ x } 10^{-3}\, h^{1.55}\; E\,(E - 28.5\, h^{-0.85}) \tag{4}$$

This result has been confirmed recently by another series of laboratory experiments in France and a theoretical analysis [10] of the empirical function obtained for E_c.

One important result from this analysis is that the inception field ranges from 14 to 6 kV/m for heights from 2 to 6 metres. Hence, these curves provide a guide to the corona current inception vs height relationship for the ellipsoidal air terminals, regardless of size, placed a certain height above the ground. A natural extension of this work is to consider how we might read values off these curves when an air terminal is placed on top of a building of given height and width. Because there is no way of doing this in the laboratory, such an exercise requires the use of electric field modelling software. This line of research is presently being pursued.

5. Conclusions

A number of key results were obtained from the research described above. These can be summarised as follows:

- A framework for future laboratory experiments involving corona current investigations has been developed in which air gaps in the range 2 to 4 metres should be used as these appear to give the best scaling to natural conditions
- Corona emissions from a range of passive air terminals have been measured and compared with the result that the two spline balls, which are supposed to produce high levels of corona, were *comparable* to those from the Franklin rod and single wire, and *lower* than the discharge from a simple “V-shaped” wire
- Empirical equations for the corona current amplitude coefficient, A, and the corona inception field, E_c, of the ellipsoidal CRT air terminals as a function of the height above the ground have been derived; these equations are useful for optimising their installation on buildings for direct strike protection

During the course of this work, a number of other issues and topics arose which now constitute a set of further investigations that are presently in progress. These can be summarised as follows:

- The equation for E_c is based on a theoretical “zero current” definition for the inception. In practice, this strict definition may be relaxed, resulting in larger values for the inception field, e.g., for a 10 μA current, the inception field is approximately doubled. But such flexibility raises the question: “How much corona is too much ?” which relates to the next point.
- There is an urgent need for detailed theoretical modelling which can quantify the space charge effects around air terminals, particularly in relation to upleader development.
- A scientific study which computes field intensification factors for air terminals and structures because only then can an efficient and reliable protection system be designed.

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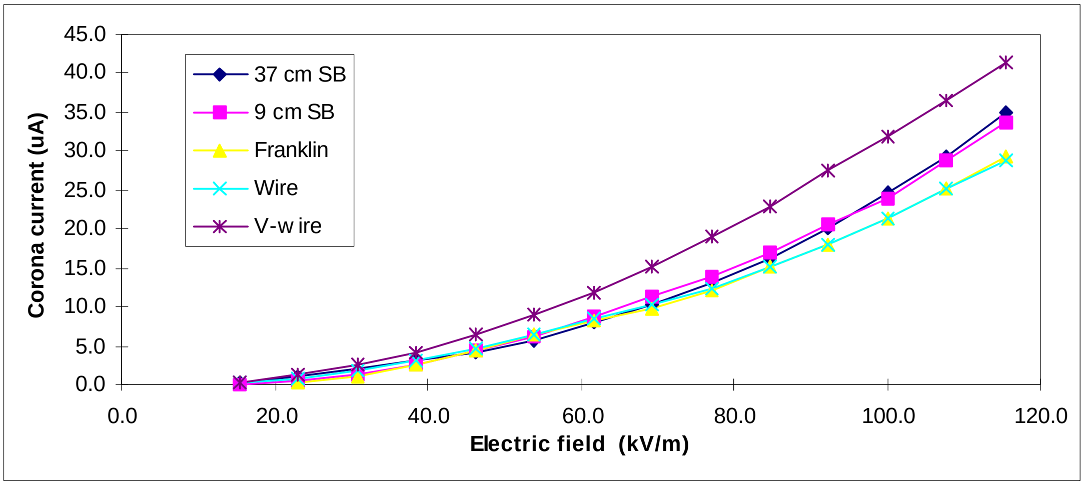
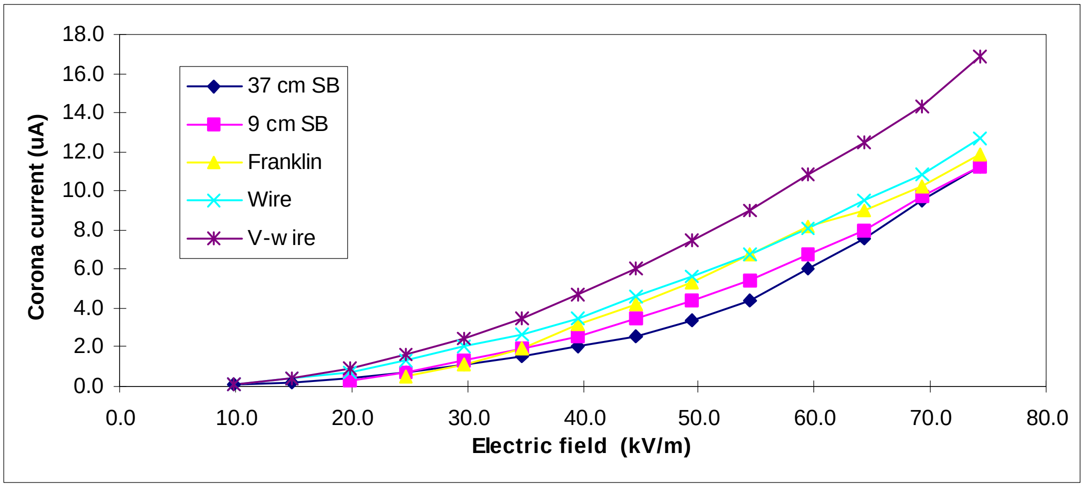


(a) 2 metre air gap



(b) 3 metre air gap

Figure 4: Comparison of corona current emission from a selection of air terminals standing 1 m high for two different air gaps.