CORONA DISCHARGES
ON THE SURFACES OF
HIGH VOLTAGE COMPOSITE INSULATORS

A thesis submitted for the degree of

Doctor of Philosophy

by

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2009
ABSTRACT

The degradation of high voltage electrical insulation is a prime factor that can significantly influence the reliability performance and the costs of maintaining high voltage electricity networks. Little information is known about the system of localized degradation from corona discharges on the relatively new silicone rubber sheathed composite insulators that are now being widely used in high voltage applications.

This current work focuses on the fundamental principles of electrical corona discharge phenomena to provide further insights to where damaging surface discharges may localize and examines how these discharges may degrade the silicone rubber material. Although water drop corona has been identified by many authors as a major cause of deterioration of silicone rubber high voltage insulation until now no thorough studies have been made of this phenomenon.

Results from systematic measurements taken using modern digital instrumentation to simultaneously record the discharge current pulses and visible images associated with corona discharges from between metal electrodes, metal electrodes and water drops, and between waters drops on the surface of silicone rubber insulation, using a range of 50 Hz voltages are inter compared. Visual images of wet electrodes show how water drops can play a part in encouraging flashover, and the first reproducible visual images of water drop corona at the triple junction of water air and silicone rubber insulation are presented.

A study of the atomic emission spectra of the corona produced by the discharge from its onset up to and including spark-over, using a high resolution digital spectrometer with a fiber optic probe, provides further understanding of the roles of the active species of atoms and molecules produced by the discharge that may be responsible for not only for chemical changes of insulator surfaces, but may also contribute to the degradation of the metal fittings that support the high voltage insulators.

Examples of real insulators and further work specific to the electrical power industry are discussed. A new design concept to prevent/reduce the damaging effects of water drop corona is also presented.

Keywords: Corona discharges, discharge current, onset voltage, point-plane, repetition rate, Trichel pulse, emission spectra, silicone rubber, water drop corona, high voltage insulators.
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Declaration of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this, or any other higher education institution. To the best of my knowledge and belief, this thesis contains no material previously published or written by another person except where due reference is made.

Signature ......................................................

Date .......................................................
Acknowledgements

I sincerely thank my principal supervisor, Adjunct Professor David Birtwhistle for his encouragement and guidance, and associate supervisors; Emeritus Professor Graeme George and Dr. Gregory Cash for interesting and informative discussions.

I also thank Dr. Peter Bruggermann (Belgium) and Dr. Manolis Panousis (Paris) for their interpretations of atomic emission spectral data and advice with SPECAIR®.

This research was funded by the Australian Research Council and TransGrid.
Chapter One

HIGH VOLTAGE SILICONE RUBBER COMPOSITE INSULATORS

1.1 Introduction

Australian electricity utilities have a significant population of new polymeric type insulators which are key components in their high voltage transmission and distribution networks. The latest material to be used for indoor and outdoor insulators is now silicone rubber (SiR). Working voltages for these new components generally range from 3.3 kV for use in small pumping stations up to 500 kV for high voltage transmission line insulators. Power plant and substation components such as surge diverters, instrument transformers, bushings, and cable terminations are now made of SiR insulating components. Recently a new 330 kV Queensland – New South Wales interconnector was constructed using insulators of this new type of material. In the future it is likely that a considerable portion of Australian high voltage power systems will have components that rely on silicone rubber insulation.

At this time there is very limited knowledge of factors determining the end of life of silicone rubber insulation in high voltage applications where the material is exposed to UV radiation from the sun and from surface discharges on wet and polluted insulator surfaces or from the effects from nearby bushfires. A complete understanding of how discharges that involve water drops is confused by movement of drops and discharges under combined influences of moisture deposition, electrical stress, and changing surface condition.

The focus of this research is on the fundamentals of the high voltage phenomena by which electrical surface discharges cause ageing of composite insulators in both wet and dry conditions and aims to explore fundamental factors that contribute to the understanding of why and how corona discharges localize and degrade composite insulator materials.
1.2 Composite high voltage insulators

In 1963 polymeric insulators were first developed [1] and have been widely used by electrical utilities since the mid 1980’s. Composite insulators have many advantages over ceramic and glass insulators such as good performance in a contaminated environment, light weight, easy handling, low maintenance, and low cost. Because of these properties this type of insulator is gaining popularity worldwide and replacing the conventional ceramic and glass insulators.

Figure 1.1 A typical 132 kV twin circuit high voltage transmission line tower fitted with composite insulators. The arrow shows an insulator that has failed to hold the line up.

Composite transmission and distribution line suspension insulators originally were made with a fibreglass structural core rod covered by protective weather sheds or skirts of a moulded polymer material (Figure 1.1). The latest designs also use a fibre glass core rod but they are made with a one piece moulded SiR protective sheath which excludes the need for individually glued weather sheds.
Figure 1.2 presents a collection of some currently available SiR sheathed insulators and includes a cross section of a typical insulator showing the SiR weather sheds, core to housing and housing to fitting interfaces, and metal end fittings which are crimped to the fibre glass core rod. These are called ‘composite’ insulators because they are made with at least two insulating parts; a fibre glass structural core and a weather resistant SiR moulded sheath or housing.

The weather sheds provide the added surface creepage distance (kV/mm) necessary for the insulator to operate in wet conditions and in polluted environments. In highly polluted locations, such as near large industrial areas where natural washing of pollution from the insulator surface by rain is inadequate for the insulator to maintain its insulating properties, it is often necessary to regularly wash the insulators and in extreme cases apply remedial coatings to damaged surfaces [2].
1.3 Failure modes of composite insulators

Failures of composite insulators can be placed into the following two categories:

1) Electrical failure where the insulator cannot sustain working voltage due to deterioration of the silicone rubber polymer housing, and;

2) Brittle fracture where the core rod fails to support the load. The failure of the core rod usually occurs very suddenly and for various reasons this type of failure is termed a ‘brittle fracture’ failure. This type of failure can have serious safety implications especially if for example, a high voltage line falls onto a public roadway as a result.

Section 1.3.1 reviews selected literature on the subject of brittle failures and shows that damage to the silicone rubber sheath by water drop corona discharges can lead to moisture ingress into the fibre glass core rod to initiate stress corrosion fatigue cracking which is believed to be one of the primary causes of brittle fracture failure of composite insulators. Section 1.4 reviews the silicone rubber sheath material.

1.3.1 Brittle fracture failure of composite insulators

Figure 1.3 from [3] shows an example of a brittle fracture failure of a SiR composite insulator. The silicone rubber sheath has been removed.

Figure 1.3 A 500 kV field-failed composite insulator; brittle fracture above the hardware.
The structural core rod consists of many glass fibres enveloped in resin. These fibres are known to break by stress corrosion cracking \[3\] \[4\] and in the presence of acids \[5\]. As the fibres break the ultimate load carrying capacity of the insulator reduces until eventually there are not enough fibres to support the load and the insulator breaks apart dropping the conductor that it was supporting.

Montesinos et al \[4\] have studied the possibility of microscopic flaws in glass reinforced core rods causing brittle fracture failure of composite insulators. They conclude that internal deterioration from electrical discharges inside tiny voids trapped during manufacture would be unlikely as the applied voltage would have to be higher than the highest system voltage currently being used. Montesinos et al explains how acid generation from discharges within the rod is therefore not possible and proposed that the acid to cause brittle fracture must be transported from the environment via defects in the sheath or the sheath seal at the metal fittings.

Montesinos et al also showed that the conductivity of water increased when the water was exposed to discharges. Three different samples each using 8 ml of de-ionized water, tap water, and salty water, were subject to electrical discharges from a Tesla coil. The pH for all three types of water dropped from approximately 7.5 - 8 to 2 within 30 minutes and decreased only slightly below 2 during the next two and a half hours which was the remainder of the experiment. The conductivity also increased from below 2000 µS/cm to over 9500 µS/cm for all three water types.

Suginuma et al \[6\] have also shown this same characteristic reduction in pH of water due to electrical discharges creating weak nitric acid. The exact mechanism by which this occurs is not fully known although Montesinos et al suggest that the hydrogen ion H⁺ may be produced by corona discharges at the metal fittings.

Montesinos et al \[4\] described results of an investigation of brittle fracture with new commercial grade core rods, and rods from insulators that had been in service. The core rods were exposed to ultra pure water, sulphuric acid, oxalic acid, and nitric acid of 2 pH strength while being subjected to mechanical stress. The results found regardless of the type of acid used multiple transverse fractures developed within 24 to 48 hours. In addition, they found that the mechanism of brittle fracture was not confined to small rods from suspension type insulators, but also occurred in rods from
cantilever-type insulators which were up to 60 mm in diameter. The brittle fracture mechanism was found to propagate quicker with ultra pure water than with acids and brittle failure occurred with cyclic stresses of only 10% of the insulator stress rating.

Kumosa [7] commenced studies on brittle fracture from failed in-service insulators during the mid 1990’s. Figure 1.4 from [7] shows the resistance to stress corrosion cracking for recently-available glass-fibre-core rod materials (E-glass) with three different types of adhesive polymers. Glass fibre breakages within the core rod were detected by acoustic emission (AE) and monitoring techniques while the glass core rod was under mechanical stress. From Figure 1.4 it can be seen that the E-glass with vinyl ester out-performs both modified polyester and epoxy resins by having the lowest number of breakages (averaged acoustic emission events) in 24 hours.

![Figure 1.4](image)

*Figure 1.4* Resistance to stress corrosion cracking for core rods in nitric acid composed of E-glass with polyester, epoxy, or vinyl ester resins.

On the conclusion of their research Kumosa [7] presented Figure 1.5 which shows the stages of the brittle fracture phenomena near the metal end fitting. This picture shows that either the integrity of the sheath, or sheath to metal fitting seal, must be breached to start the degradation process of the highly-stressed glass fibres. This process continues until the tensile strength of the remaining core rod fibres equals the tensile load. Once past this event, the remaining fibres break and the insulator rod severs.
Kumosa acknowledges work by others [4] that suggested brittle fracture may also be caused by water ingress alone for some types of core materials without the need for nitric acid, or electric stress, and reinforced the need for sheath integrity and adequate sealing at the metal fittings to prohibit the ingress of moisture into the surface of the structural core rod.
1.4 Polydimethylsiloxane (PDMS) - Silicone Rubber (SiR)

As the name suggests, the SiR polymer consists of two methyl groups bonded to a backbone of silicone and oxygen atoms. Two methyl groups bond to the backbone at each silicone atom. A typical process for producing SiR consists of a primary crosslinking reaction between a vinyl functional silicone polymer and a silicone-hydride crosslinker in the presence of a heavy metal catalyst, such as Platinum (Pt) or Rhodium (Rh), which is followed by post cure reactions at elevated temperatures (~170°C). Figure 1.6 from [8] summarises these reactions.

![Chemical diagram of reaction processes](image)

**Figure 1.6** Primary and post cure reactions during the process of manufacturing polydimethylsiloxane (silicone rubber).

In Figure 1.6 the first post cure reaction (2) is the catalysed hydrolysis of the SiH groups to form silanol. The newly formed silanol group (SiOH) then catalytically reacts with any remaining SiH groups via the ~Si-O-Si~ bonds producing hydrogen as a byproduct (3), and finally, a thermal cure condensation reaction of two silanol groups to form a ~Si-O-Si~ linkage with water as a byproduct (4).
Organic peroxide may also be used as a free radical curing system. Although it is cheaper than the platinum (Pt) addition method shown in Figure 1.6 it has a disadvantage in that it produces acetic acids that remains as a by-product of the cross-linking process [9]. These volatile organic acids can be removed by exposing the cured product to elevated temperatures for an extended period during a post cure process [10]. The chemical notation for PDMS [11] is shown in Figure 1.7. The repeat unit is shown in square brackets and the chain is terminated at each end by a CH₃ methyl group. The viscosity increases as n increases.

\[
\begin{align*}
\text{CH}_3 - & \text{Si} - \text{O} & & \text{Si} - \text{O} & & \text{Si} - \text{CH}_3 \\
\text{CH}_3 & & \text{CH}_3 & & \text{CH}_3 & & \text{CH}_3 \\
\end{align*}
\]

**Figure 1.7** Chemical structure of the Polydimethylsiloxane (PDMS/SiR).

The structure of the final product consists of the cross linked base material and low molecular weight (LMW) silicone fluid in equilibrium. The LMW fluid consists of short cyclic and linear chains which have between 4 and 20 silicone units [12]. Figure 1.8 from [13] shows a stick and ball model of PDMS/SiR. Note that the hydrogen atoms belonging to the methyl CH₃ groups are at the surface. This configuration gives the PDMS/SiR a surface that has low residual energy and this makes the surface hydrophobic [13] [14].

**Figure 1.8** Stick and ball model of Polydimethylsiloxane (PDMS/SiR).

The natural color of PDMS/SiR is opaque; the final gray color product utilized in high voltage insulators is due to pigments and fillers such as Alumina trihydrate (ATH) which are mixed with the base material prior to the vulcanization process.
1.5 Surface properties of silicone rubber

Some physical properties of the material used for high voltage applications published by the manufacturer [15] are presented below in Table 1.1. Lee et al [14] worked on solvent compatibility with PDMS/SiR and found solvents that swelled PDMS/SiR the most were diisopropylamine, triethylamine, pentane, and xylenes which are organic solvents.

Table 1.1 Typical properties for PDMS/SiR used in high voltage power systems.

<table>
<thead>
<tr>
<th>Test Method</th>
<th>Property</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colour</td>
<td></td>
<td></td>
<td>Gray</td>
</tr>
<tr>
<td>D792</td>
<td>Specific gravity</td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>D2204</td>
<td>Hardness</td>
<td>Shore A</td>
<td>65</td>
</tr>
<tr>
<td>D412</td>
<td>Tensile strength</td>
<td>MPa (psi)</td>
<td>4.2 (610)</td>
</tr>
<tr>
<td>D412</td>
<td>Elongation at break</td>
<td>%</td>
<td>280</td>
</tr>
<tr>
<td>D624B</td>
<td>Tear strength</td>
<td>kN/m</td>
<td>13</td>
</tr>
<tr>
<td>IEC 60093</td>
<td>Volume resistivity</td>
<td>Ohm.cm</td>
<td>2x10^24</td>
</tr>
<tr>
<td>IEC 60250</td>
<td>Dielectric constant at 100 Hz</td>
<td></td>
<td>3.67</td>
</tr>
<tr>
<td>IEC 60250</td>
<td>Dissipation factor</td>
<td></td>
<td>0.017</td>
</tr>
<tr>
<td>IEC 60587</td>
<td>Tracking resistance</td>
<td></td>
<td>1A45</td>
</tr>
<tr>
<td>ASTM</td>
<td>Tracking resistance</td>
<td>kV</td>
<td>6.0</td>
</tr>
<tr>
<td>IEC 60243</td>
<td>Dielectric strength</td>
<td>kV/mm</td>
<td>17.3</td>
</tr>
</tbody>
</table>

Properties obtained on test slabs: Press cured 10 minutes at 171 °C (340 °F).

Polysiloxanes differ from other polymers in that their backbones consist of Si-O-Si units unlike many other polymers that contain carbon backbones such as polyethylene and ethylene propylene rubber (EPR).

Polysiloxane is very flexible due to large bond angles and bond lengths when compared to basic polymers such as polyethylene. For example, the siloxane backbone unit Si-O has a bond length of 1.63 Å and a bond angle of 130° where as a C-C backbone unit has a bond length of 1.54 Å and a bond angle of 112° [11].

An interesting characteristic of PDMS/SiR is that it is viscoelastic, meaning that at long flow times (or high temperatures), it acts like a viscous liquid. However, at short flow times (or low temperatures) it acts like an elastic solid. Another interesting property of PDMS/SiR is that it has an extremely low glass transition temperature $T_g$, about 148 Kelvin (-127 °C) [11] making it suitable for very low temperatures. The manufacturer in [15] recommends a working temperature range for PDMS/SiR
between 55˚ C and 180˚ C where in comparison EPDM materials have a lower service operating temperature range of between -40˚C and 120˚C [16].

Solid PDMS samples, whether the surface is oxidized or not, will not allow aqueous solvents to infiltrate and swell the material. Thus, PDMS structures can be used in combination with water and alcohol solvents without material deformation. However most organic solvents will diffuse into the material and cause it to swell, making them incompatible with PDMS [14].

In a series of very recent (2008) experiments Ali and Hackman [17] studied weight gained or lost by SiR/PDMS specimens immersed into saline water at various concentrations for 3000 hours. Table 1.2 from [17] shows the weight gain by submersion of SiR/PDMS in a various concentrations of saline solution. It is interesting that the SiR absorbs the saline solution below 50 ºC making it heavier, in contrast to losing weight if the material was submersed in the saline solution at temperatures above 50 ºC.

Table 1.2  Percentage of weight gain of SiR/PDMS specimens after immersion in saline solutions at 0 ºC to 98 ºC for 3000 hours.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>In Air (%)</th>
<th>In Saline water (mS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In Air (%)</td>
<td>0.005</td>
</tr>
<tr>
<td>0</td>
<td>0.09</td>
<td>0.70</td>
</tr>
<tr>
<td>22</td>
<td>0</td>
<td>1.41</td>
</tr>
<tr>
<td>50</td>
<td>-0.14</td>
<td>1.08</td>
</tr>
<tr>
<td>75</td>
<td>-0.28</td>
<td>-0.11</td>
</tr>
<tr>
<td>98</td>
<td>-0.97</td>
<td>-10.8</td>
</tr>
</tbody>
</table>

The weight gain was explained by the saline solution being absorbed into the surface of the SiR/PDMS and the weight loss was explained by the loss of silicone fluid from the surface into the saline solution. The weight loss in air at 98 ºC was initially rapid for the first 50 hours to -0.4 %, then weight loss continued linearly throughout the 3000 hour experiment to -0.97 %, whereas the weight loss for all other temperatures shown ceased to change after approximately 50 hours into the experiment.
1.5.1 Surface energy and water drop contact angle

Low surface energy, or surface tension, is another key feature of polysiloxanes. After polymerization and cross-linking, solid PDMS/SiR samples will have an external hydrophobic surface that makes it difficult for polar solvents such as water to wet the PDMS/SiR surface (Section 1.3). An indication of the surface free energy can be obtained by measuring the contact angle of a drop of liquid on the surface of a solid material as shown in Figure 1.9 from [18].

![Contact Angle Diagram](image.png)

Where $\gamma^w$ has a polar (h) and a dispersive (d) component such that $\gamma^w = \gamma^d + \gamma^h$.

**Figure 1.9** Contact angle of a liquid on a solid surface.

The contact angle can be measured in two ways:

(i) Advancing contact angle is measured as water is added to the drop, and;

(ii) Receding contact angle when water is removed from the drop or it is evaporating.

Today, with the use of digital CCD cameras and advanced computer software, the measurement of the contact angle of a water drop to any solid surface has been automated and laboratory equipment is now commercially available [18].

In 1990 Gubanski and Vlastos [19] studied contact angle measurements of water drops on surfaces of a range of naturally aged EPDM and SiR insulators that had been in service from 5 to 9 years. It was suggested that tiny surface cracks in the insulator surfaces can act as capillaries that appear to assist a water drop to spread over a large area.

Exposure of samples cut from insulators to multipoint corona discharges was also investigated. It was found that EPDM surfaces sustain permanent loss of
hydrophobicity whereas the contact angle of water drops on SiR insulator surfaces recovers after 10’s to 100’s of hours after exposure to corona discharges.

Contact angle measurements of water on silicone rubber samples taken from the surfaces and from the bulk of new insulators showed no significant differences. However, on aged insulators a significant difference between contact angles from the bulk and from the surface material was observed indicating there may be little or no change to the bulk material during the years that the insulator was in service. For the EPDM type insulators the surface can become completely hydrophilic.

Measured contact angles for new PDMS/SiR insulator surfaces by previous researchers were collected by Ali and Hackman [17] (2008). Typical water drop to surface contact angles were found to be in the range 95º to 105º for new PDMS/SiR materials. Ali and Hackman [17] also studied the effects of saline solution and temperature on the surfaces of silicone rubber insulator materials by submersion and subsequent weight measurements which were followed by two contact angle measurements; one with distilled water and another measurement with a drop of methylene iodide, to resolve the polar and dispersive components of the surface energy.

<table>
<thead>
<tr>
<th>Table 1.3</th>
<th>Effects of temperature on the surface energy of virgin HTV SiR specimens after immersion in saline solution of 1mS/cm for 3000 hours. The virgin sample was also measured at 22 ºC and was not immersed in saline solution.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (ºC)</td>
<td>$\gamma^{\text{vd}}$ (mJ/m$^2$)</td>
</tr>
<tr>
<td>Virgin (θ=100º)</td>
<td>28.4</td>
</tr>
<tr>
<td>0</td>
<td>29.8</td>
</tr>
<tr>
<td>22</td>
<td>29.9</td>
</tr>
<tr>
<td>50</td>
<td>30.4</td>
</tr>
<tr>
<td>75</td>
<td>30.2</td>
</tr>
<tr>
<td>98 (θ=25º)</td>
<td>43.3</td>
</tr>
</tbody>
</table>

The results from [17] for saline solution of conductivity 1 mS/cm are reproduced as Table 1.3 which shows that the surface free energy of virgin SiR/PDMS was 30.8 mJ/m$^2$ at 22 ºC. The effect of increased temperature of the saline solution corresponds to an increase in surface energy with the most significant change being in the polar component $\gamma^{\text{sh}}$, which was referred to as changes in hydrogen bonding. It was found
that the hydrophobicity of the PDMS/SiR decreased rapidly when it was immersed in the saline solution at 0 ºC to 98 ºC regardless of the level of conductivity.

Figure 1.10 from [17] shows the measured contact angles increasing in time for SiR specimens aged in air at 50 ºC, 75 ºC, and 98 ºC. This increase with temperature was reported to be associated with higher diffusion of LMW silicone fluid from the bulk to the surface.

![Figure 1.10](image)

**Figure 1.10** Changes in contact angles for SiR specimens aged in air for temperatures 0 ºC, 22 ºC, 50 ºC, 75 ºC, and 98 ºC for 3000 hours.

A hydrophobic surface is important for high voltage insulators. The air spaces between the water drops provide the electrical insulation during wet conditions. Figure 1.11 from [20] shows a hydrophobic surface of a new SiR composite insulator.

![Figure 1.11](image)

**Figure 1.11** Hydrophobic surface of a new silicon rubber sheathed composite insulator showing that water does not continuously wet the surface.
1.6  **Environmental stress factors**

SiR composite insulators are widely used in high voltage electricity networks where they are exposed to environmental, mechanical, and electrical stresses which the SiR housing must endure [4]. Some typically well known environmental factors are:

1. Heat from solar radiation, supported conductor operating temperatures, and elevated air temperatures from nearby bushfires as well as thermal radiation from nearby high temperature industrial processes such as those used in foundries and thermal power stations.

2. Pollution includes atmospheric dust such as dirt, fertilizers, pollen, smoke from fires, salt deposits from sea spray, and manmade pollution including smog from carbon based fuels and airborne chemicals from industrial processes.

3. Abrasion from dust, dirt, and sand, during windy weather.

4. Impact from handling prior to commissioning and from flying debris and hail during storms.

5. Mechanical stress from gravitational forces due to the weight of the line, and from steady and dynamic wind loads from gusts and line vibration. Mechanical damage can also occur from poor handling practices and extraordinary circumstances such as natural disasters and vehicle accidents [4].

6. Corona discharge from areas of high electric stress during dry weather.

7. Corona discharges from between water drops during times of dew, fog, and rain.

Any combination of the above is also possible. For example; pollution, dirt, and dew would be expected to be found on the surfaces of insulators in rural regions, and smog and salt sea spray over insulators in coastal cities.

To learn more about the significance of these stresses and how they may lead to surface changes that encourage insulation failures it is required to review the effects these factors have on the performance of SiR composite insulators.
1.6.1 Thermal decomposition of PDMS/SiR

At elevated temperature Polydimethylsiloxane degrades thermally into basic components. Kumagai et al [21] slowly heated a 7 mg sample of silicone rubber at a rate of 10 °C/min up to 600 °C in argon gas with a flow of 200 ml/min and analyzed the gaseous by-products using pyrolysis mass spectroscopy. The results of these tests are shown in Figure 1.12.

Figure 1.12 (a) shows hydrogen is released from the material from 100 °C and above with a peak at approximately 250 °C. There is a minimum at approximately 400 °C after which the rate of hydrogen release continues to increase with applied heat through to 600 °C. Hydrogen is also released as part of the post cure process which is fixed at approximately ~ 170 °C as seen in Figure 1.6.

![Figure 1.12 Results of heating a sample of silicon rubber in argon gas at a rate of 10 °C/min up to 600 °C. M = Atomic Mass. (a) For H⁺, CH₄, and H₂O. (b) For CO₂, and C₂H₆.](image)
At 250 °C the commencement of carbon dioxide (CO$_2$) is clearly seen in Figure 1.12 (b) and it is produced up to approximately 475 °C. The sample liberates ethylene (C$_2$H$_2$) and the compound SiOCH$_3$CH$_2$ shown with an asterisk in Figure 1.12 (b) from about 450°C to 550°C.

The SiR material undergoes certain stages of disintegration as the temperature is increased. Firstly, hydrogen is produced. This may be from further crosslinking at temperatures higher than the post cure temperature (170 °C) and from dissociation of the methyl groups –CH$_3$ and the ATH Al$_2$(OH)$_3$ filler to produce CO$_2$ and water vapour H$_2$O from 250 °C. At 370 °C the process is producing the maximum rate of water vapour H$_2$O and methane CH$_4$.

It appears that the system runs out of freely available oxygen at about 475 °C and in the absence of this free oxygen the system produces ethylene C$_2$H$_2$, hydrogen, and fragments of the SiR backbone, up to 550 °C. There was also a small amount of moisture detected up to 100 °C which may be due to some surface moisture in the apparatus.

Results of thermal degradation studies by Lui et al [22] are in general agreement with those referenced in [21] except the measured peak temperatures are slightly less. For example: Lui et al [22] observed H$_2$O peak at 310 °C compared with 370 °C measured by Kumagai et al [21], and 450 °C to 475 °C for fragmented silicone structures. This discrepancy may be due to different amounts of filler material in the samples used or may be due to different measurement techniques that were used to determine the temperature of the sample surface.

Kumagai et al [21] also placed several pieces of SiR in the same pyrolysis chamber and heated the samples in dry nitrogen gas. The nitrogen carried the gaseous by-products from the heated SiR samples into a second chamber with a sphere-plane spark gap that was vented to the atmosphere. The sphere was 20 mm in diameter and 2 mm from a plane electrode. The experiment showed the spark breakdown voltage of the gap was lower with gas by-products than nitrogen alone (38 kV/cm). The lowest breakdown voltage of 34 kV/cm was when the samples were at 600 °C.
The breakdown voltage increased to 38 kV/cm as the temperature further increased to 800 °C. The recovery of breakdown voltage after 600 °C is most likely due to limited amount of readily ionized gases being produced from the samples at these higher temperatures. Table 1.4 from [21] shows the spark onset of various pure gases tested in the spark chamber. These are important in relation to studies of electrical tracking and flash-over breakdown of the insulator.

**Table 1.4** Spark onset electric fields of various gases for a 20 mm diameter sphere to plane electrode test cell.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Electric Field Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>15.5 kV/cm</td>
</tr>
<tr>
<td>CH₄</td>
<td>22.3</td>
</tr>
<tr>
<td>CO₂</td>
<td>26.2</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>26.2</td>
</tr>
<tr>
<td>O₂</td>
<td>29.1</td>
</tr>
<tr>
<td>Air 15%-35% RH</td>
<td>35.5</td>
</tr>
<tr>
<td>N₂</td>
<td>38.0</td>
</tr>
</tbody>
</table>

### 1.6.2 Pollution and surface tracking

It is shown by Kumagai et al [21] that the gas by-products of thermally degrading SiR can further lower the insulation level of the gap which encourages track propagation processes that led to flashover failure. Surface pollution can also enhance the electric field strength at the metal fittings of composite insulators by reducing the clean surface gap between the end fittings, thereby encouraging the onset of discharges which lead to surface tracking [21].

SiR was found to track under applied alternating high voltage of approximately 4.5 kV\textsubscript{rms} during inclined surface tracking experiments on samples of SiR to IEC 60587 and ammonium chloride NH\textsubscript{4}Cl solution as a surface pollutant. In another experiment by Kumagai et al [21] silver paint was used as a conductive medium to initiate electrical tracking on SiR.
Although less than ~1% wt residual carbon was found in the track, Silica SiO$_2$, and Mullite 3Al$_2$O$_3$.2SiO$_2$ were also found. The conductive tracking propagation process was conceptually hypothesised as being caused by gaseous by-products of electrical discharges at the head of the track.

1.6.3 Affects of UV Light and ozone on PDMS/SiR

Kumagai et al [23] measured contact angles for water drops on the surface of silicone rubber samples aged in UV light (Xenon) and aged by corona discharges. They also subjected samples to determine the effects of ozone alone. It was discovered that UV and corona discharges both caused the loss of LMW silicone fluid and hence loss of hydrophobicity from the silicone rubber insulator samples. Recovery of the LMW silicone fluid from the bulk material, following the application of corona, occurred over tens of hours while the application of UV light caused permanently reduced hydrophobicity. Ozone alone had no effect on the silicone rubber surface.

Schnyder et al [24] also studied changes to the surface of PDMS by irradiation with a Xenon excimer lamp that produced radiation with wavelengths of 172 nm. The frequency of irradiation ranged between 225-280 kHz. The samples were irradiated with an intensity of 30 mW/cm$^2$ at a distance of 5 mm from the lamp. X-ray photoelectron spectroscopy (XPS) was used to identify loss of carbon and increased SiO$_2$ on the surfaces of the samples.

In [23], UV was produced by a xenon lamp that produced spectral energy with photon wavelengths from 290 nm to 400 nm. This means no visible or infrared parts. The bonding energy of 338.32 kJ/mol of the C-H bond [25] corresponds to a photon wavelength of approximately 354 nm which is in range of the xenon light which implies that UV photons could possibly cause cleavage of the hydrogen from the methyl groups that are on the surface of PDMS. UV radiation from the xenon lamp was shown to cause permanent loss of hydrophobicity.

Blackmore [26] described how PDMS might absorb a photon which can cleave the methyl group from the bulk material with subsequent cross linking occurring with the production of water vapour. The Si – Si cross linking hardens the material surface as it becomes denser and the shrinkage causes cracks to appear in the surface.
Blackmore suggested an alternative mechanism whereby in the presence of oxygen the silyl radicals may oxidize to produce H$_2$O as a by-product. The process described by Blackmore in [26] is considered to start with the cleaving of two nearby CH$_3$ groups by UV photons to form two silyl radicals Si-OH which then react together to form a cross link. This is similar to the cross linking phase in Figure 1.6.

The photon energy for the methyl group cleavage using bond energy of 451.5 kJ/mole [25] corresponds to an electromagnetic wavelength of approximately 265 nm for a single photon. In-service, this UV radiation does not come via the stratosphere but might come from the radiation produced by corona discharges. Nevertheless, from [23] UV light in the range 290-400 nm is sufficient to cause permanent damage to the surface of PDMS.

Interestingly, 355 nm lasers were used to etch SiO$_2$ in the semiconductor industry by exciting the Si-O bonds [27]. When Holgerson et al [28] tried 355 nm laser pulses on SIR/PDMS, they found that the SIR/PDMS easily melted and ablated without SiO$_2$ forming. This is considered very important for laser surface patterning where chemical changes to the SIR/PDMS material are considered undesirable. The modified surface, without the SiO$_2$, was also found to cause a permanent loss of hydrophobicity of about 10-15 degrees.

**1.6.4 High voltage humidity tests**

High voltage humidity tests on EPDM, SiR, and a blend of EPDM and SiR by Moreno et al [29] showed cracks and splits up to 3 mm deep in the surface of SiR samples that were subjected to 500 hours of corona discharges in 35 to 40 % RH. Corona was produced by a point-plane discharge by applying 60 Hz alternating voltage of 7.2 kV$_{rms}$. Table 1.5 from [29] shows the summary of results for these tests.

The humidity played an important role in the amount of degradation observed. When mechanical stress was also applied to the samples the cracks and splits were much more obvious.
Table 1.5  Results of humidity tests on insulators of various materials.

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Material</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>High relative humidity (95-100%), mechanical stress</td>
<td>SiR</td>
<td>Deep cracking (~3 mm in depth), surface whitening.</td>
</tr>
<tr>
<td></td>
<td>EPDM</td>
<td>Surface darkening, shallow cracking.</td>
</tr>
<tr>
<td></td>
<td>Blend</td>
<td>Deep cracking (~1.5 mm in depth), surface whitening.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High relative humidity (95-100%), No mechanical stress</td>
<td>SiR</td>
<td>Deep cracking (~2 mm in depth), surface whitening.</td>
</tr>
<tr>
<td></td>
<td>EPDM</td>
<td>Surface darkening, slight roughening</td>
</tr>
<tr>
<td></td>
<td>Blend</td>
<td>Shallow cracking (~0.5 mm in depth), surface whitening.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low relative humidity (35-40%), No mechanical stress</td>
<td>SiR</td>
<td>Deep cracking (~2.5 mm in depth), surface whitening.</td>
</tr>
<tr>
<td></td>
<td>EPDM</td>
<td>Surface darkening, slight roughening</td>
</tr>
<tr>
<td></td>
<td>Blend</td>
<td>Shallow cracking (~0.5 mm in depth), surface whitening.</td>
</tr>
</tbody>
</table>

1.6.5 Rain tests on SiR insulators

Rain tests conducted by Shaowu et al [30] on representative sections of real insulators comprising several weathersheds it was revealed that the surface discharges always originated where the hydrophobicity is inferior, and that the critical flashover channel always consists of a water film, water strips, or water threads dropping off the rim of the weathersheds. Figure 1.13 is from [30].

![Figure 1.13](image_url)  
**Figure 1.13** Drawing showing location of arcing during rain water experiments on a section of a SiR composite insulator.
The section of the insulator had a creepage length of 320 mm and an arcing length of 180 mm. Water with conductivities in the range 100 µS/cm to 100,000 µS/cm was sprayed both horizontally and vertically over the section of insulator through separate control valves. It was observed that the water drops that formed on the surface were all of similar size irrespective of water drop conductivity.

The effect of losing hydrophobicity significantly reduces the power frequency withstand voltage properties of the insulator. In Figure 1.14 from [30] it can be seen that the flashover voltage gradient, which was calculated by dividing the applied voltage by the arcing length, of a wet hydrophobic insulator declined to approximately 32 kV/cm, compared to a decline to 13 kV/cm for a clean wet hydrophilic insulator surface, with water conductivity of 4000 uS/cm, for example.

![Figure 1.14](image.png)

**Figure 1.14** Relationship between conductivity and flashover gradient for hydrophobic and hydrophilic polymer surfaces.

It was also shown that after a number of flashovers the withstand voltage of the insulation is reduced after repetitive flashovers as shown in Figure 1.15 from [30]. For each flashover, loss of hydrophobicity to the surface was observed to be localized. Current measurements showed only a capacitive component for new hydrophobic surfaces. For hydrophilic surfaces an additional resistive component of current was detected. Figure 1.15 shows that significant (approximately 25%) reduction in
insulating properties appears to have occurred to the insulator as a result of the first few flashovers. The time between flashovers was not stated in [30].

**Figure 1.15** Flashover voltages as a function of number of flashovers for water spray conductivity of 630 µS/cm.

### 1.7 Loss of hydrophobicity by water drop discharges

Studies by Zhu et al [31], and by other researchers [19] [26] [32] [33] [34], show loss of hydrophobic surface properties (increased surface energy) after the application of corona discharges to the surface of SiR.

Figure 1.16 shows a water drop on the surface of a sample of SiR from [31] before corona and after the application of multi point corona discharges to the surface of a sample of SiR and shows the contact angle \( \theta \) which has been overlaid onto these images. The time to lose hydrophobicity is about 100 seconds after the application of corona discharges.

**Figure 1.16** A water drop on a SiR surface (a) contact angle slightly greater than 90 ° and (b) contact angle has reduced to approximately 60 ° after application of corona discharges.
Drops of various volumes were also presented by Guan et al. [34] with respective measured contact angles and the electric field enhancement deduced. In their experiments corona between water drops was observed by using ultra violet light sensitive photo-multiplier. A video camera was connected to the output of the photo-multiplier. Initially at working voltage of 40 kV no corona was observed on a dry sample of silicone rubber placed between two electrodes. Guan et al. [34] showed that the electric field strength on the insulator surface with no drops could be enhanced by about three times for drops with contact angles of 90 degrees and up to four times for drops with contact angles of 20 degrees.

### 1.8 Water drops on insulator surfaces

If the surface becomes hydrophilic then the surface can continuously wet and cause high values (milliamperes) of leakage current to flow over the surface of the insulator [35]. This leakage current heats the thin water film, and as this film thins by evaporation, the local voltage gradient increases [26]. Eventually the thin film breaks and the surface leakage currents arc across the dry band. This is known as dry-band arcing. Surface damage from dry-band arcing is a serious problem for SiR insulation [36] [37].

Kim et al. [38] showed chemical changes to SiR during dry band arcing and proposed that high energy ultra violet photons assist the degradation process by providing quantum energy capable of cleaving the hydrogen atoms from the carbon atom of the methyl groups, then subsequent photons can remove the carbon from the silicon, or oxygen products react and build onto the carbon making the surface hydrophilic.

Blackmore [26] showed fog coalescing into droplets on an EPDM insulator surface between two energized carbon electrodes with 50 Hz applied voltage between the electrodes. Fine mist condensed on the insulator surface and coalesced into drops which increased in size. Dry band discharges commenced between the water drops near the grounded electrode. Increasing the voltage caused the dry band discharges to move away from the electrode. The area behind the dry band became hydrophilic.
Figure 1.17 from [26] shows a dry band increasing from the grounded electrode on the surface of a piece of EPDM insulator during one of Blackmore’s experiments. This effect was different to the behavior Blackmore [26] observed when discharges were produced on the surface of SiR. In this case, discharges occurred in series between drops and dispersed away from the high voltage electrode. The 50 Hz current waveform shown with SiR was non symmetrical, larger (15 mA peak) and smaller (4 mA peak) on the positive half cycle when compared to the 50 Hz current waveform for the EPDM surface which was symmetrical, smooth and continuously rose to a peak level of approximately 6 mA and 4 milliseconds in width for both positive and negative half cycles.

The difference between the current waveforms was attributed as being due to the different type of discharge processes that were observed to occur on the surface of the different materials. Blackmore’s explanation of the process for the dry band discharges on the EPDM was that current was flowing across the dry band from the electrode which charged the droplets changing the local potential.

Blackmore [26] also showed that the water drop contact angle reduced to less than 30º as a result of dry-band arcing on SiR during salt fog tests and proposed scission of the entire methyl group from the silicon atom was also feasible.
1.9 Insulators aged in wet and fog conditions

It is apparent that water drops lessen the effective creepage length across the insulator surface thereby increasing the electric field strength in the gaps between the water drops. During rain and foggy conditions, water drop discharges from transmission lines and insulators have been found to occur at normal operating voltages [32]. A combination of pollution and fog can lower the discharge onset threshold voltage further which increases electrical surface discharge intensity between water drops and raises the risk of flashover due to generation of ionized charged particles from the discharging sites [21] [29].

Philips et al [39] performed accelerated ageing tests in a salt fog chamber on twenty complete 500 kV SiR composite insulators. Sunlight was replicated by 896 fluorescent lamps providing UV light equal to noon sunlight. Ageing cycles were set to include rain, fog, and salt mist. Insulators were aligned as they would be in-service. ie horizontal dead ends, Vee and in vertical formations. They were energized at 288 kV to ground (500 kV line to line).

They conclude that water drop corona can be seen visually and that permanent damage to non ceramic insulators can occur at the high voltage end of the insulators, particularly at the location where the thin SiR sheath protects the fibre glass core rod, and the sheath to underside of the first and second weathershed interface. It was shown that continued operation resulted in cracking and splitting of the sheath at these locations leading to exposure of the fibre glass core rod. Once hydrophobicity was lost, hydrophilic wetting was observed to move further along the insulator.

Ramirez-Vazquez et al [40] studied electric field measurements of several different designs of composite insulators from 115 kV, 230 kV, and 400 kV transmission lines to compare with aged insulators in a salt fog chamber to determine relationships between leakage current measurements and defects. Discrete electric field measurements taken using an electric field sensor between weather sheds from fifteen insulators were compared before and after ageing in the salt fog chamber and to those removed from service. Insulators were artificially polluted with kaolin, and a fertilizer.
When an insulator flashed-over it was removed from the chamber for inspection and electric field pattern measured.

At rated voltage the insulator polluted with kaolin lasted only 1430 hours in the salt fog chamber until flashover occurred. The insulator polluted with fertilizer lasted 1590 hours and a clean insulator lasted 2464 hours. The results showed that the structure of the insulator influenced the electric field pattern and that the main defects detected were due to tracking and cracks in the mould line. Ramirez-Vazquez et al [40] also report ‘too many hidden degradations’ between the sheath and the rod.

The results of Ramirez-Vazquez et al [40] displayed an unusual trend in the electric field distribution. The field is a minimum at the ground end which increases to approximately 10% at half way along the length of the insulator then increases to a maximum at the high voltage insulator fitting. This field distribution implies that the insulators were not connected between two symmetrical electrodes in the salt fog chamber and possibly all the insulators were connected to a ground plane (possibly the wet floor of the chamber). This shows one significant difficulty of simulating in-service conditions in the laboratory of a suspension insulator, which normally ages in service between a power line and transmission tower.

Lopes et al [36] also have experimented with water drop arcing on SiR and used modern commercially-available partial discharge measuring equipment to continuously monitor partial discharges (PD) from a silicone rubber insulators wetted with salt water. Visual observations were made to verify the onset of dry band arcing. The experiments were performed on dead-end type silicone rubber composite insulators with creepage distance of 305 mm, with salt water conductivity of 1800 µS/cm and 2300 µS/cm, and with voltage gradients of 26 V/mm (7.9 kV$_{\text{rms}}$) and 33 V/mm (10 kV$_{\text{rms}}$) using 60 Hz applied alternating voltage. Leakage current was monitored with a 100 Ohm series resistor.

With an electric surface gradient of 33 V/mm the leakage current increased to critical levels of about 1 mA at which dry band arcing was visually observed, after 20 minutes with salt water conductivity of 2400 µS/cm, and after 25 minutes with conductivity of 1800 uS/cm. With an electric surface gradient of 26 V/mm the leakage
current increased to critical levels of about 1 mA at which dry band arcing was visually observed after 60 minutes with salt water conductivity of 1800 µS/cm.

Results of partial discharge testing from [36] showed the mean charge (pC) plotted against maximum charge (pC) showed two clear and distinct clusters of data. The first cluster corresponded to PD from water drops (< 1mA) and the second cluster corresponds to PD from dry band arcing (> 1 mA) superimposed on water drop corona.

During dry-band arcing the 60 Hz current led the voltage waveform with some distortion coinciding with the peak of the applied voltage depicting a resistive or work done conduction component. It was found that the partial discharge equipment was much more sensitive to the onset of dry band arcing than the leakage current monitoring equipment. In addition, the dynamic behaviour of the water drop discharges made some difficulties in measurement repeatability as the discharges were not always in the same location but danced about.

Studies were also undertaken into the loss of hydrophobicity on a population of SiR service-aged insulators from China [41]. The profile of the wetability of the weather sheds for each entire insulator shows the highest wetability was at the high voltage end of the insulator, and another high wetability region at the ground end of the insulator. It was stated that the bottom shed and shank towards the metal fittings are worst affected. The rims of the sheds were also deteriorated.

1.9.1 Observed locations of corona on SiR composite insulators

The observed locations of corona discharges reported in the research papers discussed above are always at the high voltage end of the insulator. In contrast to the surface of the weather sheds, the thin SiR sheath covering the structural core rod near the high voltage fitting seems to be the most critical location, as splitting of the SiR sheath can expose the core rod to moisture and pollution from the atmosphere initiating tracking under the sheath against the surface of the structural core rod. In addition to initiating tracking, moisture ingress and discharges on the exposed core rod can lead to brittle fracture failure of the insulator. Table 1.6 shows a summary of the locations of discharges observed by other researchers on the surfaces of SiR composite insulators.
Table 1.6  *Observed locations of water drop corona discharges on suspension type SiR composite insulators.*

<table>
<thead>
<tr>
<th>Discharge Location</th>
<th>Method and Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shank and Shed nearest the fittings</td>
<td>AC and DC [29], Confirmed by measured loss of hydrophobicity [34] [41], Observed in salt fog chamber [39] [40] [42] [43]</td>
</tr>
<tr>
<td>Rim of sheds</td>
<td>Observed in HV experiments [42]</td>
</tr>
<tr>
<td>Shank-Shed interface</td>
<td>Observed in HV experiments [39] [44] [34]</td>
</tr>
<tr>
<td>Mold line</td>
<td>Observed in salt fog chamber [40]</td>
</tr>
<tr>
<td>Metal Fittings</td>
<td>Observed in salt fog chamber [42] [43], At the triple junction of the SiR-metal-air interfaces [29].</td>
</tr>
</tbody>
</table>
1.10 Examples of surface damage by corona discharges

Figure 1.18 (a) from Pinnangudi et al [42] shows what is normally termed as ‘corona cutting’ in a radial direction on the underside of a moulded weathershed from a 230 kV power system SiR composite insulator aged in a salt fog chamber. Darkening of the surface is visible on the cylindrical sheath immediately below the bottom of the damaged shed. Erosion of the SiR material where the underside of the weathershed meets the cylindrical sheath can also be seen. Corona under dry or wetted conditions has been shown to result in damage at this location.

![Figure 1.18](image)

**Figure 1.18** (a) Corona cutting on the underside of the first weathershed of a SiR composite insulator. (b) Water drop corona on the sheath under the first weathershed.

![Figure 1.19](image)

**Figure 1.19** A severely degraded SiR composite insulator from [22] that was found in service in a very high humidity location. Samples have been cut from the weathershed for chemical analysis.
Figure 1.20  Corona damage and evidence of tracking from the sharp edge of the metal end cap of a 36 kV SiR composite lightning arrester from rural Queensland [45].

Figure 1.21  An example of corona from a wet insulator interacting with underside of the first weather shed on an energized insulator and corona from water drops on the rims of several weathersheds [46].

Figure 1.22  Surface of a sample of SiR from [29] showing splits and surface damage by 145 hours of corona discharge testing in high humidity conditions (95 % RH to 100 % RH).

Additional examples of damage to surfaces of SiR by corona discharges can be seen in works by Phillips et at [39], and by Vosloo and Holtzhausen [47].
1.11 Electric field gradients

The electric field gradients provide information about where discharges are likely to occur. The presence of the water drops and surface pollution has been shown to change the electric field gradients over the surface of the insulator [30] [47]. The presence of the supporting structures, for example a steel tower; conductor bundling and proximity of insulators to grounded structures can also alter the electric field gradients about an insulator [46].

1.11.1 Electric fields about metal end fittings

Que and Sebo [48] developed a computer model of the electric field about the end fitting of a typical polymer insulator using COULOMB software. Their model produces equipotent contours and shows comparative electric field distributions over one end of a normally orientated insulator surface for ‘dry and clean’, ‘rain’, and ‘fog’ models (Figure 1.23). The difference between the rain and fog models is the assumption that the underside of the shed is wet during fog.

![Figure 1.23](attachment:image.png)

Figure 1.23 Equipotential contours about an end fitting of a typical SiR composite insulator. (a) dry and clean (b) rain model (c) fog model. Contours are presented as percent of the applied voltage.
The degree of electric field enhancement determined by Que and Sebo is between 2.9 to 3.5 at the interface of the water drop-air-insulation of the sheath region, and between 2.76 to 3.5 for the shed region of the insulator. In wet conditions, the electric field strength increases to about 3 times that of dry insulation in this region.

Que and Sebo [48] conclude that the presence of water drops over the hydrophobic surface of the weathersheds tends to make the electric field more uniform across this surface and that most of the voltage will be distributed between the drops along the sheath of the insulator. In a normally orientated insulator this surface is a vertical cylinder of SiR. The voltage gradient is highest across the first vertical cylindrical section of the sheath adjacent to the surface of the metal end fitting to the underside of the first weather shed. In fog conditions the cylindrical region between the first and second weather sheds also appears to have an increased voltage gradient.

### 1.11.2 Electric field gradient with a corona ring fitted

One technique most commonly used to shield the small metal fitting from developing field gradients higher than corona inception voltage is the fitting of a corona ring. The corona ring provides a smooth and much larger surface area than the end fitting and is designed to reduce the concentration of surface charge to values lower than the corona inception voltage. Figure 1.24 shows an electric field plot near the end fitting of an insulator with a corona ring fitted by Lopes et al [36]. When compared to Figure 1.23 it can be seen that the electric field gradient, from the presence of the corona ring, has been reduced at the metal fitting and the voltage gradient is smoothed over a distance of several weather sheds.

![Electric field plot near the HV End of Insulator with a fitted corona ring.](image)
1.11.3 Electric fields about the insulator

Results from electric field modelling by Moreno and Gorur [29] for a 345 kV composite insulator fitted with corona rings is presented in Figure 1.25. This figure shows water drop corona inception threshold is exceeded on the insulators up to and including the second weather shed. On 500 kV insulators it is shown that water drop corona is to be expected up to and including the fourth weather shed from the high voltage end of the insulator. The electric field gradient required for the onset of corona discharges from water droplets is 5 kV/cm to 7 kV/cm on the surfaces of insulators.

![Figure 1.25](image)

**Figure 1.25** Electric field voltage gradient across the length of a 345 kV SiR composite insulator with 28 weather sheds showing the inception voltage of water drop corona discharges.

The water drop corona threshold voltage gradient profile presented in Figure 1.25 by Moreno and Gorur [29] was derived from Phillips et al [43] where it was shown for drops in the range 10 µl to 100 µl that the water drop corona discharge onset threshold voltage gradient lies between 0.44 kV/mm and 0.72 kV/mm for water drops with contact angles of 88° and 115° respectively. Phillips et al [39] also showed that corona onset threshold voltage gradient for water drops 50µl to 125 µl on the surface of new SiR with contact angles of 115° were 0.86 kV/mm and 0.96 kV/mm showing that the onset threshold voltage gradient for water drop corona reduces with surface reduced hydrophobicity.
Shaowu et al [41] also studied the hydrophobic degradation of SiR insulators and derived that for long term performance of SiR insulators the electric field voltage gradients should be lower than 7 kV/mm.

The electric potential gradient distribution in Figure 1.25 shows the electric field gradient highest at the high voltage end. If the insulator was symmetrical the voltage gradients would be the same at each end. The lower voltage gradient at the grounded end is due to the proximity of the structure suspending the insulator which usually is a conductive metal or concrete tower.

For comparison purposes Figure 1.26 was produced from Table 12.4 of [49] and shows the electric field gradient over ceramic insulators on a simulated structure for various numbers of 254 mm diameter disc insulators. The individual disc voltages were measured by raising the voltage until a small spark gap fitted across the disc broke down. The portion of the applied voltage for that disc was then known. The test was repeated for each measurement.

![Figure 1.26](image)

**Figure 1.26** Electric field potential gradients across several ceramic insulator strings comprising 254 mm diameter discs.

The profile of the electric field gradient across the strings of ceramic discs are similar to that of Figure 1.25 for SiR insulators in that the highest electric potential field gradient is at the high voltage end of the insulator.
1.12 Chemical analyses of polymer insulator surfaces

In recent years QUT researchers have worked towards furthering the understanding of high voltage polymeric insulator deterioration and have developed surface sampling and analysis techniques, and condition monitoring indicators [26] that provide consistent results of the condition of both laboratory and service aged polymeric insulation. The sampling technique has been further developed [50] to take surface samples from in-service insulators energized at high voltage.

In essence this technique involves taking very small samples of surface material by swabbing with solvent, taking small slices, or by abrading the surface of insulators. Samples are subsequently subjected to physical and chemical analysis. Details of these chemical analysis techniques can be found in the work by Blackmore in [26] and [51].

Initial research work by the QUT group concentrated on older style EDPM insulators for which a number of numerical indicators of surface condition were produced from analysis of samples. One indicator that showed promise was the Oxidation Index OI which is the ratio of spectral peak heights associated with carbonyl C=O at 1735 cm\(^{-1}\) to 1745 cm\(^{-1}\), to the hydrocarbon C-H peak at 1460 cm\(^{-1}\).

Condition assessment of in-service insulators [50] show that for EDPM insulators Ester/Ketone ratios also have significance in identifying UV aged insulation in the absence of fog or sea spray such as dry inland areas compared to insulators in areas of salt sea spray and areas of frequent fog which have surfaces diagnosed with higher oxidation index. The findings for EDPM that surface oxidation is dominant in wet areas agrees with laboratory ageing experiments [26] where dry band discharges on the surface of insulators in wet and contaminated environments cause surface oxidation.
Figure 1.27 from [51] shows the profile of the surface oxidation index from results of surface analysis of a service aged EPDM composite insulators for both energized and non-energized service-aged insulators.

![Figure 1.27](image)

**Figure 1.27** Oxidation index as a function of normalized distance from the line end energized and non energized for a 275 kV EPDM composite insulators.

The profiles of the electric field gradients in Figure 1.25 and in Figure 1.26 both show a distinct resemblance to the oxidation index profile in Figure 1.27 presented by Blackmore et al [51]. These degradation profiles are also similar to the loss of hydrophobicity profile presented by [41] in a separate study of service aged SiR insulators. The locations of observed corona summarized in Table 1.2 are the same as the surface degradation in [51] which again is similar to the profile of the electric field gradient across the insulator confirming that the electric field strength causes the corona that accelerates degradation of the SiR surface nearest the high voltage end of the insulator.

### 1.12.1 Silica levels on SiR weather sheds

Silicone rubber insulators with a highly-oxidized surface have been shown to have significantly reduced LMW surface silicone fluid, and increased surface Silica SiO₂ [22] [31]. Experiments on SiR samples by Kim et al [38] also show increased surface silica. Both Zhu et al [31] and Liu [22] used X-ray photoelectron spectroscopy (XPS) to determine the presence of Silica from the surface of weather sheds of SiR insulators. Liu et al found up to 32 % Silica on a surface sample from a severely degraded SiR insulator and that the carbon to silicone ratio C/Si decreased from 2 to
1.71, and the ratio of O/Si increased from 1 to 3.5. The surface samples were between 50 and 100 molecules thick.

The missing carbon C is consistent with losing methyl CH\textsubscript{3} groups from the backbone Si-O structure. The increase in oxygen to silicon O/Si ratio can occur in two fundamental ways; by losing silicon Si atoms, and by the gaining of oxygen O atoms. If the oxygen O does not come from the destruction of the Si-O polymer backbone extra oxygen O can only come from external to the material, such as from dissociated O\textsubscript{2} from nearby electrical discharge activity [31].

Using XPS Zhu et al showed the ratio of Si-CH\textsubscript{3} increases linearly with time after the application of corona discharges and that hydrophilic OH are a product of aging that can be formed instead of the CH\textsubscript{3} groups.

A part of the ARC Transgrid Project was to obtain surface samples from TransGrid 500 kV network. Table 1.7 shows results from XPS analysis on slivers of surface samples received from the TransGrid network. The insulators had been in service 12 to 13 years [52]. Results from insulators numbered 9, 10, 14, 17, and 18 were selected for the study. The chemical analysis was performed by Dr G. Cash.

**Table 1.7** XPS results (in percent atomic concentration) and calculation of surface silica levels of aged HV silicone rubber insulators. (Shed 1 refers to the HV end of the insulator)

<table>
<thead>
<tr>
<th>No</th>
<th>QUT#</th>
<th>Shed</th>
<th>C</th>
<th>O</th>
<th>Si</th>
<th>Al</th>
<th>% SiO\textsubscript{2}</th>
<th>% Al\textsubscript{2}O\textsubscript{3}</th>
<th>Details</th>
<th>Age</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>601</td>
<td>56T</td>
<td>45.2</td>
<td>32.0</td>
<td>19.9</td>
<td>2.9</td>
<td>7.6</td>
<td>4.4</td>
<td>Hoechst</td>
<td>12</td>
<td>Kemps Ck Earing</td>
</tr>
<tr>
<td>9</td>
<td>602</td>
<td>32T</td>
<td>48.0</td>
<td>29.4</td>
<td>20.1</td>
<td>2.5</td>
<td>5.7</td>
<td>3.75</td>
<td>Ceramtec</td>
<td>500kV</td>
<td>Kemps Ck Earing</td>
</tr>
<tr>
<td>9</td>
<td>603</td>
<td>1T</td>
<td>47.1</td>
<td>31.0</td>
<td>20.0</td>
<td>1.9</td>
<td>9.4</td>
<td>2.9</td>
<td>Ceramtec</td>
<td>500kV</td>
<td>Kemps Ck Earing</td>
</tr>
<tr>
<td>10</td>
<td>604</td>
<td>56B</td>
<td>48.3</td>
<td>28.9</td>
<td>20.5</td>
<td>2.3</td>
<td>5.6</td>
<td>3.45</td>
<td>Hoechst</td>
<td>12</td>
<td>Kemps Ck Earing</td>
</tr>
<tr>
<td>10</td>
<td>605</td>
<td>32B</td>
<td>49.5</td>
<td>27.8</td>
<td>21.3</td>
<td>1.4</td>
<td>4.1</td>
<td>2.1</td>
<td>Ceramtec</td>
<td>500kV</td>
<td>Kemps Ck Earing</td>
</tr>
<tr>
<td>10</td>
<td>606</td>
<td>1BS</td>
<td>37.0</td>
<td>39.0</td>
<td>23.2</td>
<td>0.8</td>
<td>26.0</td>
<td>1.2</td>
<td>Ceramtec</td>
<td>500kV</td>
<td>Kemps Ck Earing</td>
</tr>
<tr>
<td>11</td>
<td>611</td>
<td>56T</td>
<td>47.6</td>
<td>32.1</td>
<td>20.3</td>
<td></td>
<td>9.1</td>
<td>3.0</td>
<td>Hoechst</td>
<td>13</td>
<td>Kemps Ck Earing</td>
</tr>
<tr>
<td>11</td>
<td>612</td>
<td>56B</td>
<td>49.7</td>
<td>29.6</td>
<td>18.7</td>
<td>2.0</td>
<td>4.0</td>
<td>4.9</td>
<td>Ceramtec</td>
<td>500kV</td>
<td>Kemps Ck Earing</td>
</tr>
<tr>
<td>11</td>
<td>613</td>
<td>1T</td>
<td>48.7</td>
<td>31.4</td>
<td>20.0</td>
<td></td>
<td>4.9</td>
<td>20.4</td>
<td>Ceramtec</td>
<td>500kV</td>
<td>Kemps Ck Earing</td>
</tr>
<tr>
<td>11</td>
<td>614</td>
<td>1B</td>
<td>37.0</td>
<td>41.1</td>
<td>21.8</td>
<td></td>
<td></td>
<td></td>
<td>Ceramtec</td>
<td>500kV</td>
<td>Kemps Ck Earing</td>
</tr>
<tr>
<td>12</td>
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<td>56T</td>
<td>48.9</td>
<td>29.1</td>
<td>20.1</td>
<td>1.9</td>
<td>3.7</td>
<td>2.9</td>
<td>Hoechst</td>
<td>13</td>
<td>Kemps Ck Earing</td>
</tr>
<tr>
<td>12</td>
<td>616</td>
<td>56B</td>
<td>51.2</td>
<td>28.0</td>
<td>19.9</td>
<td>1.0</td>
<td>2.6</td>
<td>1.5</td>
<td>Ceramtec</td>
<td>500kV</td>
<td>Kemps Ck Earing</td>
</tr>
<tr>
<td>12</td>
<td>617</td>
<td>1T</td>
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<td>32.5</td>
<td>20.3</td>
<td></td>
<td>7.2</td>
<td></td>
<td>500kV</td>
<td></td>
<td>Kemps Ck Earing</td>
</tr>
<tr>
<td>12</td>
<td>618</td>
<td>1B</td>
<td>38.1</td>
<td>38.4</td>
<td>22.7</td>
<td>0.9</td>
<td>18.2</td>
<td>1.4</td>
<td>Ceramtec</td>
<td>500kV</td>
<td>Kemps Ck Earing</td>
</tr>
<tr>
<td>13</td>
<td>619</td>
<td>20T</td>
<td>42.1</td>
<td>39.3</td>
<td>17.5</td>
<td>1.0</td>
<td>17.4</td>
<td>1.5</td>
<td>Rosenthal</td>
<td>25</td>
<td>Feeder 968 (T55)</td>
</tr>
<tr>
<td>13</td>
<td>620</td>
<td>20B</td>
<td>36.5</td>
<td>42.6</td>
<td>18.8</td>
<td>0.4</td>
<td>13.6</td>
<td>0.6</td>
<td>132kV</td>
<td></td>
<td>Tamworth-Narrabri</td>
</tr>
<tr>
<td>14</td>
<td>606</td>
<td>1T</td>
<td>37.8</td>
<td>41.3</td>
<td>19.7</td>
<td>1.2</td>
<td>21.5</td>
<td>1.8</td>
<td>132kV</td>
<td></td>
<td>Tamworth-Narrabri</td>
</tr>
<tr>
<td>14</td>
<td>607</td>
<td>1B</td>
<td>46.5</td>
<td>36.3</td>
<td>17.3</td>
<td>0.0</td>
<td>34.8</td>
<td></td>
<td>132kV</td>
<td></td>
<td>Tamworth-Narrabri</td>
</tr>
</tbody>
</table>
SiR Insulator 14 had been in service for 25 years energized at 132 kV without corona rings fitted. Higher concentrations of silica (34.8%) were found on the surface of this insulator when compared to the younger insulators 10 (12yrs) and 18 (13yrs), which were found to have 26% and 18% surface silica respectively.

The XPS method is unable to distinguish between silicon as silica and silicon as silicate in dust and dirt. Dust and dirt are likely to be the source of the silica seen of the two virgin insulators at the top of Table 1.7 [52].

Table 1.8 contains results from a 110 kV post insulator which was recovered from a location adjacent to a marine environment at Moreton Bay east of Brisbane after 14 years in-service. The insulator had been in an exposed area and subjected to wind off the sea. The second insulator in Table 1.8 labelled D was a ‘long rod’ suspension type insulator that was inside a substation by the sea in New Zealand. Several sheds had degraded and fallen apart by the time it was removed for analysis by Liu et al [22]. The significant feature of both these insulators was not the high level of silica but high levels of alumina on the surface.

Table 1.8 XPS and calculation of surface silica levels of two degraded HV silicone rubber insulators.

<table>
<thead>
<tr>
<th>Shed</th>
<th>C</th>
<th>O</th>
<th>Si</th>
<th>Al</th>
<th>% SiO₂</th>
<th>% Si</th>
<th>% Al₂O₃</th>
<th>Details</th>
<th>Age</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1FL</td>
<td>33.3</td>
<td>43.0</td>
<td>15.0</td>
<td>8.8</td>
<td>31.2</td>
<td>14.0</td>
<td>13.2</td>
<td>110kV</td>
<td>14</td>
<td>Moreton</td>
</tr>
<tr>
<td>1FB</td>
<td>31.5</td>
<td>44.8</td>
<td>16.8</td>
<td>6.8</td>
<td>50.1</td>
<td>25.3</td>
<td>10.2</td>
<td>Line Post</td>
<td>12</td>
<td>Bay</td>
</tr>
<tr>
<td>1BT</td>
<td>25.7</td>
<td>51.2</td>
<td>14.3</td>
<td>9.9</td>
<td>58.6</td>
<td>25.1</td>
<td>12.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>core</td>
<td>29.2</td>
<td>48.0</td>
<td>20.7</td>
<td>2.2</td>
<td>69.2</td>
<td>43.0</td>
<td>3.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34FR</td>
<td>28.3</td>
<td>48.7</td>
<td>14.0</td>
<td>9.0</td>
<td>46.4</td>
<td>19.5</td>
<td>13.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34BR</td>
<td>28.3</td>
<td>48.4</td>
<td>14.9</td>
<td>8.4</td>
<td>45.6</td>
<td>20.4</td>
<td>12.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>25.7</td>
<td>49.7</td>
<td>14.1</td>
<td>9.9</td>
<td>32</td>
<td>13.5</td>
<td>14.9</td>
<td>long rod</td>
<td></td>
<td>NZ</td>
</tr>
</tbody>
</table>

By comparison, the TransGrid SiR insulators had very low surface alumina with the highest result of 4.4% compared to 43% alumina from the ‘long rod’ from Moreton Bay. Further work needs to be done to confirm that seaside conditions are conducive to the higher levels of surface aluminium for SiR insulators.

From analysis of what was considered ‘unacceptable for service SiR insulators, QUT in conjunction with the industry partner TransGrid have determined an end of life criteria. The presence of more than 10% atomic concentration for both silica and
alumina indicates end-of-life for these types of insulators. At these levels it was shown from previous work [53] that the rate of migration of LMW silicone to the surface indicated that it was unlikely to recover from a flashover or similar event. Any crack or split in the sheath that could expose the core rod was also deemed to be at an end of life condition.

1.12.2 SEM images of service aged SiR insulators

Figure 1.28 shows SEM images of the top side of the first weather shed from the high voltage end of insulator 18 and shows surface degradation up to 40 µm to 50 µm thick. An uneven inhomogeneous rough surface of degraded SiR can be seen which could assist to hold dirt and pollutants.

Figure 1.28 Surface degradation images of a service-aged SiR insulator (13 years). (a) View of the top side of the weathershed. (b) Higher magnification of (a) showing variation of size and shape of degraded surface material. (c) Cross section view. (d) Higher magnification of (c) showing the interface of the degraded surface to the bulk material.
1.12.3 Surface mapping

Figure 1.29 shows some of the results from the above tables drawn onto a surface map. This map shows one half side of the insulator and is a prototype designed specifically for capturing laboratory data and is used for the first time here. Up to now data has been presented in tabular format that is difficult to visualize common areas on the insulator. In addition, the top and bottom sides of the weather sheds could never be seen simultaneously on any one chart. Locations of where samples were taken can be defined in cylindrical coordinates ($y, r, \theta$) as shown in the insert for further analysis. The end fitting may be changed to reflect different designs.

Results (17) and (18) are from the 500 kV insulators, (14) is from a 132 kV insulator, and (sd) is from the severely degraded 110 kV post insulator.

![Diagram showing results of XPS surface analysis of several service-aged SiR insulators in percent SiO$_2$ concentration.](image)

**Figure 1.29** Diagram showing results of XPS surface analysis of several service-aged SiR insulators in percent SiO$_2$ concentration.
The results clearly show that the sheath and underside of the first weather shed have more surface silica than the top side of the weather shed. These locations are consistent with the higher electric field gradient in this region modelled in Figure 1.23 and Figure 1.25 and measured as in Figure 1.26 and the locations of observed corona discharges in Table 1.2.

1.13 Summary

In this review it has been shown that SiR/PDMS degrades thermally at temperatures above 180 °C. It has also been shown that the silicone rubber housing material is affected by electrical discharges. Both dry and wet discharges result in increased SiO₂ on the surface of the material. It was suggested that discharges ablate the surface removing the CH₃ groups from the energy in the discharge, and that OH hydrophilic groups could also be formed.

The general locality of the damage from discharges seems to be at the high voltage end of the insulator near the metal fitting as this is where corona first becomes visible. The thin sheath and the undersides of the first and second weather sheds seem to be most affected by the discharges. Cracks and splits in the sheath from discharges let moisture into the surface of the vulnerable structural core rod to promote brittle fracture type failure.

Discharges can occur during wet and foggy conditions only, due to the presence of water drops enhancing the electric field gradient. Discharges between water drops damage the surface, and the surface becomes more hydrophilic, and the wetted area increases which causes the discharges to move to the periphery of the wetted area.

It is therefore of interest to further investigate corona discharges for both wet and dry conditions to determine the factors that cause surface degradation to polymer insulator surfaces. In Chapter Two point-plane discharges are revisited and the effects of SiR on these discharges are explored. In Chapter Three water drop discharges between metal electrodes and on the surface of SiR are investigated, and in Chapter Four spectroscopic studies are undertaken to determine active species that can directly interact with the surface of the polymeric material.
Chapter Two

CORONA DISCHARGES FROM METALLIC ELECTRODES

2.1 Introduction

Corona discharges occur when the electric field strength is such that a free electron will cause an ionization avalanche with the surrounding air [54]. Electrical power systems are designed so that corona discharges do not normally occur in service as they represent measurable power and revenue losses [55], produce audible noise to cause public complaints, and cause radio and television interference [56] [57]. If the coronal currents are high enough, the glow from the discharges can be visible to the eye [58].

Most corona observed to this time have originated at the metal conductors at high potential. It is therefore of interest to review previous work on this topic and to explore and possibly expand knowledge in this area before proceeding to the examination of water drop corona.

A literature review of corona discharges from metal electrodes

2.1.1 Critical surface gradient for onset of visible corona

In 1929 Peek [58] presented empirical based formulae for the prediction of the onset of visible corona for thin wires concentrically placed in cylinders with a 60 Hz voltage source. This was done by increasing the applied voltage between the central wire and the surrounding cylinder until the first visible pale blue colour of corona was detected at the surface of the wire electrode. The voltage gradient was calculated and the results provided the numerical constants.

Peek’s empirical equation accurately predicts the onset of corona for wire radii ranging from 0.2 mm to 5 mm, at temperatures from -10 °C to 140 °C, and for pressures ranging from 0.05 bar to 1 bar. Below is Peek’s equation with an inclusion of the factor m which is commonly used in the design of electrical lines.
\[ E_{\text{onset}} = 30m\delta \left(1 + \frac{0.3}{\sqrt{\delta r}}\right) \]

Where:
- \( E_{\text{onset}} \) = Critical gradient for onset of visible corona (kV/cm)
- \( m \) = Surface roughness of wire (0.2 for wet, 0.95 smooth)
- \( \delta \) = Relative air density (eg 0.95)
- \( r \) = Radius of inner conductor (m)

For atmospheric air, the critical voltage gradient at the surface of a wire with 1 cm radius is equal to 30 kV/cm. By comparison, SF\(_6\) gas at atmospheric pressure has a visual corona onset voltage gradient of 90 kV/cm [59].

2.1.2 Negative point corona discharge current pulses (Trichel pulses)

In 1938 Trichel [60] made measurements of current pulses (Trichel pulses) associated with corona discharges for negative point to positive plane corona discharges. Trichel presented oscillograms of negative point corona discharge currents for gaps ranging 0.5 mm to 4.73 mm using copper, platinum, brass, and steel points of various radii using a direct current DC voltage source.

The current waveform, measured in the external electrical circuit, consisted of a continuous stream of pulses each having a very fast rise time to a peak of short duration (less than 0.1 \( \mu \)sec). The pulses then decayed with relatively long duration (10’s to 100’s \( \mu \)sec). Figure 2.1.1 shows an oscillogram of pulses from Trichel’s 1938 paper. Among other factors the duration between pulses was found to be dependent on the applied voltage for fixed gaps and point radii. The duration is described as the time required for negative ions to be swept clear of the gap by the electric field.

![Figure 2.1.1](image)

Figure 2.1.1 Oscillograms of negative point corona for a 0.5 mm diameter point and 3 cm gap. (a) 8000 Hz calibration wave (b) single pulse (c) pulses for 0.7 \( \mu \)A.
Trichel [60] showed a linear relationship between discharge current and pulse repetition rate for the range of point sizes used. It was shown that large point radii produce lower frequencies than points with small radii. Included in his work is a sketch of the visible corona observed via a micro-telescope, reproduced in Figure 2.1.2, which resembles a mushroom cloud slightly off the surface of the tip. It was reported that the bluish light was always slightly detached from the tip and that a small spot on the surface of the tip was observed.

![Figure 2.1.2](image)

**Figure 2.1.2** A sketch of the bluish corona at the tip of a 0.5 mm diameter electrode.

Upon increasing the voltage, for the larger radii points, another spot appeared and the discharge would alternate between the locations of the first and second spots. With higher voltages up to three locations were observed on the surface. Further increasing the voltage caused the disappearance of the regular pulses and caused a noisy irregular corona to be heard.

In 1974 a systematic study of Trichel pulses (TP) for point-plane gaps ranging from 5 mm to 15 mm in atmospheric air was presented by Lama and Galio [61] where it was shown that the charge per pulse $Q$ was independent of the applied voltage. They also deduced that the charge per pulse $Q$ did not change for a given point over the range of gaps.

In 2004 Gurumurthy et al [62] studied corona in atmospheric air between negative point and positive plane electrodes for gaps 20 mm to 40 mm. It was shown that the Trichel pulse repetition frequency increases with decreasing electrode tip radius and that the frequency was different for different electrode materials, suggesting the work function required to remove an electron from the metal tip may play a significant role.
in the rate in which discharges occur. For example; they found that the Trichel pulse frequency dropped by a factor of six when the point material was changed from brass or stainless steel to silver for a fixed gap.

In 2004 Repan [63] and [64] studied effects of transverse air flow across gaps at 3.5 m/s, and in 2005 Ichikawa et al [65] studied the effects of air flow at 7 m/s across a point discharge gap of 30 mm with a 0.02 mm point radius and applied continuous wavelet transformation (CWT) methods to characterise measured Trichel pulses.

Both [63] and [65] show the time interval between pulses increased with the flow of air across the electrode tip. Ichikawa et al [65] showed that there was a 20 % to 30 % increase of time between pulses when a 7 m/s air flow is introduced through the gap. Interestingly, the measured pulses appear to have the same shape for airflow as with no flow which indicates it is the tail of the pulse that contributes to the extended time between pulses. The corona discharge onset voltage for with and without air flow was the same.

### 2.1.3 Summary of the characteristics of Trichel pulses

For Trichel pulses (TP) measured on short point-plane air gaps up to 30 mm previous investigators have established:

**Pulse charge (Q)**

- Q is proportional to the point radius(r) [60], and Q/r $\sim 1.9 \times 10^{-9}$ C/mm [61].
- Q increases with a decrease in air pressure [58].
- Q is independent of gap voltage [60].
- Q is independent of gap length [60] [61].
- Q is independent of TP frequency [60] [61].

**Frequency (repetition rate) of Trichel Pulses (TP)**

- TP frequencies increase linearly with increasing applied voltage [60] [61] [64].
- TP frequencies increase with decreasing tip diameter for a fixed gap. [61].
- TP frequency increases with increasing temperature [64].
- TP frequency increases with decrease in pressure
- TP frequency decreases with increasing transverse air flow [63, 65].
- Additional ions introduced into the gap increases TP frequency [64].
- Application of UV light increases TP frequency [64].
Discharge Onset Voltage

- Onset voltage varies with air density in accordance with Peek’s equation [58].
- Onset voltage is independent of point radius [60] [61].
- Additional ions in the gap lowers the onset threshold voltage [64].
- Prior to onset voltage UV light causes a low steady current flow across the gap [64].

2.1.4 Theoretical models of the corona discharge process

In 1985 Morrow [66] presented theoretical predictions of the development of the charge distribution and the electron attachment role of oxygen in the air that contributes to the repetitive nature of Trichel pulses that has found to occur in electronegative gases including air. Morrow suggested that electrons created by the corona discharge attach to oxygen to form negative ions. Due to their relatively large mass and slow mobility these negatively charged ions set up a negative space charge that reduces the high electric field near the point to below ionization levels.

Morrow’s numerical simulation was based on solution of thin discs which were part of a hypothetical cylindrical discharge channel across the gap. Ion density and electric field intensity were computed for each disc. The first current pulse was triggered by the insertion of 400 seed electrons in the high field region near the tip of the pointed electrode, which was set at a potential of -2250 V with respect to the plane electrode to start the simulated avalanche process. This produced a calculated peak current of approximately 13 mA in 11 nanoseconds. Figure 2.1.3 from [66] shows this first simulated corona discharge current pulse.

Figure 2.1.3 Simulated Trichel pulse for a 10 mm diameter negative sphere to plane corona discharge in oxygen. Pressure = 6.65 kPa, Gap = 20 mm.
According to Morrow [66] in Figure 2.1.3, A to B is the ‘current multiplication phase’. This is due to electron avalanches where the electric field accelerates electrons that collide with and ionize air atoms and molecules creating more free electrons. Until B no negative space charge exists in the gap in the simulation.

B to C was termed the ‘field collapse phase’ where the space charge rapidly builds up by the freed electrons attaching to oxygen producing negative oxygen ions. This weakens the electric field at the cathode. Morrow states that B to C is also when photon emission is maximum and more electrons are released by photons falling onto the negatively charged spherical electrode while the number of secondary electrons from ion bombardment is negligible. Morrow also suggests that the photon flux can cause photon detachment of electrons from negative oxygen ions O\(^-\). Morrow in a later paper [67] expands on this theory and predicts a two stage process that produces a stepped leading edge pulse where the first part of the pulse is from photo ionization and the second part is from positive ion bombardment at the surface of the negatively charged point electrode.

C to D is the ‘cathode sheath formation phase’ where it is stated,” a well defined cathode voltage fall region develops and the current decays steadily from its maximum value. The total numbers of positive and negative ions continue to rise until D as well as a well-defined plasma develops in the region between 0.2 mm and 2.0 mm from the cathode surface as the current continues to decay”.

Interestingly, no exact reference is made of where the initial 400 seed electrons come from in a real discharge although mention was made to electrons being detached from air molecules in the electric field to start the avalanche, so it is not unreasonable to pick a figure of 400 for their numerical simulation.

In 2001 Soria, Pontiga, and Castellanos [68] made a numerical simulation of Trichel pulses occurring in low pressure oxygen between a 4 mm diameter sphere to plane apparatus with a 20 mm gap, and as in Morrow [66], the oxygen pressure was 6.65 kPa, the applied voltage was – 2250 Volts, and 400 seed electrons were inserted to start the first avalanche. Their simulated Trichel pulses were approximately one tenth the size of the pulse produced by Morrow’s simulation. Their repetitive current pulses peaked at approximately 1 mA compared to Morrow’s simulation which provided a
peak current of 13 mA for the first single pulse. Secondary electrons were produced by positive ions impacting on the electrode tip, and by photo-ionization from the discharge plasma which were reported as causing the variations in pulse heights.

The repetitive pulses had rise times of about 100 nanoseconds to reach the peak current of 1 mA compared with Morrow’s initial pulse which had a rise time of 11 nanoseconds to reach the peak current of 13 mA. An excellent description is presented of certain stages of the corona discharge current pulse which agrees with both Trichel and Morrow. Figure 2.1.4 shows the resultant current pulses from their simulation.

![Figure 2.1.4](image)

**Figure 2.1.4** (A) Simulated Trichel pulses for a negative sphere to plane gas discharge in low pressure oxygen. (B) Detail of simulated regular Trichel pulses. Ref: [68]

In 2003 Lowke and D’Alessandro [54] published results of detailed numerical calculations for onset corona fields and electrical breakdown criteria for spherical points and cylindrical wires for gaps 0.01 cm to 20 cm. Their paper presents a comprehensive history of previous works in this area and presents numerical solutions for the onset of corona for both wires in cylinders and spherical points.

Q is the general breakdown criteria $e^{\int_{a}^r \alpha' dt} = Q$, where $\alpha'$ is the net ionization coefficient, $r$ is the radius, and $Q$ is a constant. $Q$ is equal to $1/\gamma$ where $\gamma$ is the secondary coefficient for the emission of electrons at the cathode. For streamers $Q$ was defined as, “the number if electrons in the avalanche necessary for particles to produce space charge fields of the order necessary for ionization”. Calculations were made for $Q = 10^3, 10^4, 10^6$ and $10^8$. Lowke and D’Alessandro [54] found that they got good agreement with experimental results if $Q = 10^4$ and surmised that there must be a source of free electrons for $Q = 10^4$ to be effective.
In 2004 Repan [63] produced examples of results from a numerical simulation of Trichel pulses which was based on Morrow’s work and showed the trailing part of the pulse in various gas ratios of oxygen to nitrogen. Results show the less oxygen there was in the gas the longer the tail for normalised 3 mA peak current pulses. For example: for 1 % oxygen the tail current was 1 mA at 3 microseconds, and for 5 % oxygen the tail was 1 mA at 1 microsecond.

The Trichel pulse phenomena was most recently modelled by Akishev et al [69] in 2005. A discharge between a small cylinder of 0.06 mm radius with a hemispherical cap and a plane electrode with a 7 mm gap at 4.2 kV was simulated in a partial 3-dimensional numerical model of Trichel Pulses in air. This model used a variable mesh method to calculate the finer details near the cathode region. Electrons from ion secondary emission were included in the simulation in contrast to the model of Morrow [66] and Soria et al [68], photo-emission was not included. The ion secondary emission coefficient was set to $\gamma = 0.01$. Figure 2.1.5 and Figure 2.1.6 from [69] show the results of their simulation that took 32 hours to calculate.

**Figure 2.1.5** (a) Simulated Trichel pulses for a negative sphere to plane gas discharge in low pressure oxygen. (b) Detail of simulated regular Trichel pulses.

**Figure 2.1.6** Axial electric field distribution for time moments marked in Figure 2.1.5(b).
Figure 2.1.6 shows the electric field distribution for the gap for the instances marked in Figure 2.1.5 (b). An explanation of the numbers in Figure 2.1.5 and Figure 2.1.6 follows: Time instant 1 in both Figure 2.1.5(b) and Figure 2.1.6 corresponds to minimum current with no spatial charge in the gap. Instants 2 and 3 occur at the leading edge of the pulse which creates a thin low field region which moves away from the front of the cathode. In the simulation, the surface current at 4 covers the full area of the tiny negatively charged hemispherical cap. At 5 to 6 the current is monotonically decreasing.

The first pulse was shown to be larger than the repetitive constant height pulses that followed (Figure 2.1.5(a)). The larger initial first pulse agrees with results from Soria et al [68] (Figure 2.1.4). The established pulses are all similar in height which is in contrast to the results of Soria et al [68] where it was suggested that the photon feedback is the reason for the varying pulse heights.

In addition, Akishev et al [69] state that multiple ion clouds are not formed in the gap because the electron attachment length is longer than negative ion transportation length within the gap for the oscillatory period. This is in contrast to Repan [63] who suggested that separate ion clouds from successive discharges may simultaneously exist in the gap, because a negative ion cannot cross the gap in the time between consecutive pulses using ion cross section calculations for air, implying conduction across the gap may be by other means than ion drift velocity alone. For example; conduction across the gap is a combination of free electrons as well as negative ions.

### 2.1.5 Positive point corona discharge current pulses

Positive point corona appears at higher gap voltages than negative point corona as streamers [70] [71] which are visible streams of light that appear to cross the gap: associated current pulses are found to be different to TPs in that they can be up to 3 to 10 times larger, very erratic in both magnitude and time between pulses, and have a lower breakdown voltage than negative point discharges [72]. For negative corona in small gaps (< 30 mm) the sequence as the voltage increases is: (1) Trichel pulses, (2) negative glow corona and (3) negative streamers. For positive corona the sequence as the voltage increases is: (1) onset streamers, (2) positive glow corona, and (3)
breakdown streamers. In high voltage alternating (AC) power systems both positive
and negative point discharges have been observed to occur in alternate half-cycles In
high voltage alternating (ac) power systems both positive and negative point
discharges have been observed to occur over very large gaps (> 2 m) during alternate
half-cycles [57].

Although the magnitude of the breakdown voltage of a positive point gap in air is less
than the breakdown voltage of a negative point gap, the avalanche process of positive
point corona is similar to that of negative point corona except positive ions move into
the gap in a positive point discharge, whereas negative ions and electrons cross the
gap in a negative point discharge [57]. Figure 2.1.7 is reproduced from [57] and
shows the distribution of space charge near the tip of the pointed electrode for
negative point and positive point type discharges.

![Figure 2.1.7 Distribution of space charge near the point electrode for point-plane discharges. (a) For a negative point corona. (b) For a positive point corona.](image)

Typical positive point discharges were 0.25 mA peak from an 8 mm sphere and 3 mA
off a 30° conical point. Rise times were measured at 30 nsec and a half peak decay of
about 100 nsec [57].

In Figure 2.1.7 (a) the negative ions are ‘lost’, and in Figure 2.1.7 (b) shows positive
ions ‘sweep from the gap’. This concept of losing ions from the gap is now contrary
to the continuity equations and the balance of charge used in the modelling of the
corona discharge process. In addition, the region labelled NEGATIVE IONS actually
contains plasma of equal numbers of positive and negative ions.
Naidis [70] made numerical studies to more accurately predict streamer discharges to breakdown conditions. He examined positive point discharges and described the dynamics of streamers and streamer to breakdown criteria and showed the improvement of including radial expansion of the discharge channel in modelling due to heating of the gases.

2.1.6 Summary of the corona discharge process

From the reviewed literature the significant stages of the corona discharge that might be of significance to degradation of polymer insulators are interpreted as follows:

- An electric field is established between metal electrodes at atmospheric pressure that can cause ionization by electron avalanche if a free electron is available [59] [66].

- The first free electron can come from any source [54] [73], but it must be in the high field region to accelerate to attain high enough velocity to cause further ionization by collision with atoms and molecules in the air. The corona we see is electromagnetic radiation from these excited atoms and molecules.

- For negative point corona, electrons may be produced at the point electrode by the photoelectric effect external to the discharge [57] [73], and from the discharge [67] [74] [68]. Electrons may also be produced at the point electrode by the enhanced electric field created by the positive ions that bombard the negative electrode (secondary electron emission process).

- As the free electrons move out of the high field region away from the negative point they slow and attach to electronegative gases such as oxygen. This sets up an increasing negative space charge cloud that reduces the electric field at the pointed electrode to below ionization levels and the avalanching stops.

- The negative ions that make up the space charge slowly (µsec) move across the gap toward the positively charged electrode. The negative space charge reduces as electrons are conducted into the positive metal electrode. The resultant field at the cathode again increases until it is high enough to cause ionization again at the tip of the pointed electrode and the cycle repeats again.
2.1.7 Conclusions from literature

All the work reviewed has been concerned with corona produced in gaps of up to several centimetres between metal electrodes. Theoretical explanations and estimations of the corona discharge process including electric field and ion distributions have been presented by Trichel (1938), Morrow (1985), Boutlendj and Allen (1993), Rapan et al (2002), Lowke (2003), Naidis (2005), Akishev et al (2005), and with the latest electron diffusion correction factors for the avalanche to streamer transitions from Montijn and Ebert (2006).

The models provide little information on the behaviour of corona discharges in air using power system alternating voltages and no recent work is available using modern instrumentation that provides a holistic and detailed picture of discharge currents under AC conditions that can be used to compare air and water drop discharge current pulses which is needed to further the understanding of insulation degradation from discharges during wet and dry conditions.

Whilst considerable progress in the understanding of the fundamental processes have been made in recent years some aspects of the corona discharge phenomena still remain incompletely understood, for example; the role played by insulation in corona discharges and the effect of the by-products of corona on insulation has not been systematically investigated. It is also of interest to know more of how corona and the associated discharge current pulses behave with silicone rubber insulation in the gap with alternating voltages.

Of particular interest for discharges from metal fittings are the characteristic differences between the positive-point and negative-point discharges that can occur in the same cycle on AC power systems. The rate at which each type of discharge occurs will most likely contribute to the rate of degradation of an insulator surface. Additionally, knowledge of the effects of rising smoke about high voltage lines during bush fire activity is of prime importance to the integrity of the insulators and reliability of supply. For these characteristics to be investigated further several small scale experiments that include the application of a range of power system alternating voltages is required.
Experimental Work

2.2 Corona Discharges in a Point-Plane Gap

In order to obtain greater insights into corona phenomena it was decided to repeat some of the basic experiments done by other researchers. In this work corona discharges in air were examined for gaps ranging 1.3 mm to 16 mm.

2.2.1 Experiment aims

The overall aim of this experimental work is to capture current pulses for further analysis particularly to determine characteristics of both positive point and negative point corona discharges from between metal electrodes with power frequency (50 Hz) alternating voltages.

2.2.2 Experimental apparatus

Figure 2.2.1 shows the apparatus used to study corona discharges. An insulated micrometer functions as the high voltage plane electrode and ensures accurate gap measurement within ±0.0254 mm (0.001”). The point electrode was a standard 1 mm diameter chrome plated steel dressmakers pin with a tip radius of approximately 0.05 mm. The tip radius varied slightly from point to point due to the chrome plating.

Figure 2.2.1 Experimental apparatus consisting of an insulated micrometer connected to the high voltage supply and a 1kΩ shunt resistor with probe connected.
Zero gap was determined with the use of a multimeter on the 10 MΩ range by carefully adjusting the micrometer back and forth until the multimeter registered contact. The layout ensured earth leads were short as possible eliminating as much inductance and stray capacitance as possible from the measurement circuitry.

The neon gas tube across the 1 kΩ resistor protects the oscilloscope from being subjected to very fast over voltages during a flashover. The neon gas tube was selected due to its low capacitance (~80pF) compared to currently available solid state transient suppressors (~1100pF). Capacitance in the measurement circuit diminishes the measured magnitude and extends the decay time of the current pulse.

2.2.2.1 Electric circuit

The apparatus is electrically connected as shown in Figure 2.2.2. Simplifying the layout and maintaining earth leads short as possible minimizes circuit inductance and stray capacitance from the measurement circuitry. Unlike many previously used experimental circuits [60, 61, 63], no ballast resistor was used between the high voltage source and the gap.

![Electric circuit diagram](image)

**Figure 2.2.2** Electric circuit showing 230 V variable autotransformer, step-up transformer, high-voltage resistor divider, and 1 kΩ shunt resistor for current measurement. $V_1$ represents the applied voltage and $V_2$ represents the discharge current.
The gap voltage is measured as $V_1$ across the 500 $\Omega$ resistor (2 x 1 k$\Omega$ resistors in parallel) which is in series with a 5 M$\Omega$ high voltage resistor stack. The discharge current is measured as $V_2$ across a $\frac{1}{2}$ W, 1 k$\Omega$ carbon film resistor.

50 Hz high voltage is supplied via a commercially available 1:62.5 neon lighting transformer capable of supplying 10 mA at $15 \text{kV}_{\text{pk-pk}}$ continuously. By design the transformer has very high impedance which limits the short circuit current to 30 mA. A variable transformer (Variac) is installed between the local 230 V supply and the high voltage transformer enabling variable voltage control.

2.2.2.2 Digital storage oscilloscope

Gap voltage ($V_1$) and discharge current ($V_2$) data were acquired with the use of an Agilent 54621A (200 Mega-samples per second) two (2) channel digital oscilloscope with input shunt resistance of 1 M$\Omega$ and input shunt capacitance of 14 pF. The inputs had 12 bit analog to digital converters and the horizontal resolution was 25 psec from the oscilloscope manual. The memory depth was 4 MB per channel.

Both input channels of the digital oscilloscope were connected via 10:1 Probes, each with input resistance of 10 M$\Omega$, shunt capacitance of 13.3 pF, bandwidth of 100 MHz, and DC coupled rise time for each probe 5.8 nsec. With this configuration the time constant for the circuit measuring system was approximately 14 ns. The probes were adjusted by using the auto compensation facility on the oscilloscope to produce a square signal then by trimming the compensation capacitor in the head of each probe to achieve the best possible square wave reproduction.

Channel 1 probe was connected across the 500 $\Omega$ resistor of the voltage divider ($V_1$) which provided an overall scale of 100,000:1. Channel 1 input range was set to 200 mV/div which provides a display of 2 kV/div. Channel 2 was connected via another 10:1 probe across the 1k$\Omega$ resistor and designated $V_2$. Channel 2 input range was set to 100 mV/div which provides a display of 1000 $\mu$A /div ($I_1$).

All measurements were taken by reading the built in cursor function of the oscilloscope. This measurement has an accuracy of 0.2 % full scale (-$\frac{1}{2}$ LSB). To provide easy reading of the AC voltage $V_1$ the oscilloscope was set to average 8 peak
measurements and display the result automatically. For single shot captures of current pulses the oscilloscope averaging function was set to 1.

### 2.2.2.3 Digital camera

To provide deeper insights into the corona produced by discharges a black and white digital camera with slightly extended UV capability was selected for all experiments. Figure 2.2.3 from the manual shows the relative spectral responses of two such commercially available cameras.

![Relative Spectral Response](image)

**Figure 2.2.3** Relative spectral response of Sony XCD-SX910UV and XCD-X710 digital cameras.

As seen in Figure 2.2.3 the response of the two cameras between wavelengths of 365 nm and 420 nm is almost identical. As the spectral radiation from a discharge is mainly in the range 330 nm to 440 nm the lower cost (3:1) XCD-X710 was selected for these studies. The camera has a maximum transfer rate of 30 frames per second in free run mode.

A standard lens (1:1.4/16 mm) that provided ‘full screen’ of a 100 mm square subject at distance of 100 mm was selected. The camera was able to be controlled by *Sony XCD* and by *Windows Movie Maker™* software.
2.2.3 Effect of applied voltage

For a gap of 3.175 mm the applied voltage was raised until corona discharge pulses were first detected. This onset threshold occurred at $3668 \ V_{pk}$. This onset voltage was recorded as the negative point corona discharge onset voltage $V^-$ referred to in these series of experiments. A further slight increase in voltage to $3670 \ V_{pk}$ established well defined pulse trains as shown in Figure 2.2.4 (a). The pulses were in the form of Trichel pulses and occurred when the point electrode was negatively charged with respect to the plane electrode.

*Figure 2.2.4* Typical measured discharge current pulses for a 3.175 mm (1/8") point-plane gap with increasing 50Hz alternating voltage. Voltage scale = 2 kV/div, Current scale = 1000 µA/div, Time scale = 2 msec/div.
Figure 2.2.4 (b) shows that further increasing the applied voltage does not cause the magnitudes of the pulses to change. The corona discharge onset and extinction voltages remain consistent at approximately 3668 V\textsubscript{Pk}. For this gap of 3.175 mm, 4000 V\textsubscript{Pk} is the highest voltage that can be applied prior to the onset of positive point streamer type discharges. This onset voltage was recorded as the positive point onset voltage V\textsuperscript{+} that is also used in these series of experiments.

As the applied voltage was further increased beyond 4000 V\textsubscript{Pk} large irregular positive-point current pulses were detected. Figure 2.2.4 (c) shows well-established, positive-point type discharges as well as negative point discharges occurring during the alternate half cycle. Slightly additional voltage causes the gap to flashover which damages the tip of the point electrode concluding the experiment.

Figure 2.2.5 shows photographic images of corona discharges in a similar experiment with the gap set to 8.255 mm. The images were taken by the digital camera transferring 1 frame per second with wide open aperture in a darkened room. Also shown are the discharge current pulses and the voltage waveform which were recorded simultaneously during the experiment. The inserts showing the shape of the corona in Figures 2.2.5(b) and 2.2.5(c) are generated by saturating the contrast and enlarging the section of the captured image.

Figure 2.2.5(a) shows the point-to-plane gap at 5.30 kV\textsubscript{Pk} with no corona nor discharge current pulses being detected. The applied voltage was raised slightly to 5.31 kV\textsubscript{Pk} (Figure 2.2.5(b)) and the onset of visible corona and discharge current pulses were both being detected. In a further increase in voltage to 6.37 kV\textsubscript{Pk} establishes well defined Trichel pulse trains with an increase in the size of the corona plasma (Figure 2.2.5(c)). The applied voltage is further increased until large irregular positive-point current pulses are detected. Figure 2.2.5(d) shows both well-established positive point corona discharges, and negative point corona discharges at 6.38 kV\textsubscript{Pk}. Slightly additional voltage causes a spark to cross the gap concluding the experiment.
Figure 2.2.5  Photographic images showing the various stages of corona produced by the discharges. (a) No discharges at 5.30 kV$_{pk}$. (b) Onset of Trichel pulses. (c) Trichel pulse intensity prior to onset of positive point discharges. (d) Both positive and negative point discharges. (Gap = 6.35 mm, 23.6 °C, 48 % RH)
2.2.4 Positive-point and negative-point corona discharge onset voltages

Figure 2.2.6 shows both positive and negative point corona onset voltages for the point – plane configuration shown in Figure 2.2.1. The ‘curve fit’ is a power series curve that shows that the positive point onset voltage is proportional to the square root of the gap length. From Figure 3 in [61], Lama and Galio measured the negative point corona onset voltage for a 6 mm gap at approximately $-2.6 \text{kV}_{dc}$. This is shown as the dotted lines in Figure 2.2.6. The peak onset voltage measured in this experiment, interpolated for a gap of 6mm, was $5.3/2 \text{kV}_{pk-pk} = -2.65 \text{kV}_{pk}$ which is close to that measured by Lama and Galio.

![Figure 2.2.6](image)

**Figure 2.2.6** Positive point and negative point corona discharge onset voltages for gaps 1.3 mm to 16 mm.

The negative point onset voltage was found to be the same as the positive point onset voltage at a gap of approximately 1.3 mm. This phenomenon occurs at approximately $\pm 2.35 \text{kV}_{pk}$. For gaps less than 1.3 mm positive point breakdown occurs prior to any negative point Trichel pulses being detected.

For gaps greater than the diameter of the plane electrode (6.3 mm) a constant difference between the magnitude of the positive point and negative point onset voltages exist. Figure 2.2.7 shows that this difference is a linear function of the gap up to 3.15 mm which is coincidently half the diameter of the plane electrode. The difference in voltage magnitudes was constant for gaps 3.15 mm to 16 mm and was approximately 1170 V.
2.2.5 Negative-Point Discharges (Trichel Pulses)

Figure 2.2.8 shows a train of Trichel pulses (TP) for a 3.175 mm gap. It can be seen that the first pulse is larger than the succeeding pulses which appear to fluctuate around 70% to 80% of the height of the first pulse. The time between the first two pulses is shorter than the time between succeeding pulses. A consistent pattern emerges where a larger pulse is found to occur after a long duration and a smaller pulse occurs after a short duration.

**Figure 2.2.8** Negative point corona discharge current pulses (Trichel Pulses) in air. Gap = 3.175 mm, Applied voltage = 3668 Vpk.

**Figure 2.2.7** Differences in magnitude between positive point and negative point corona discharge onset voltages (dV) for gaps 1.3 mm to 16 mm.
Figure 2.2.9 shows the progression of pulse heights with their corresponding duration from the start of the previous pulse for the first 10 pulses shown in Figure 2.2.8. The average pulse height is 631 µA and the average time between pulses is 69 µsec for these Trichel pulses. The height of the first pulse is not included.

![Figure 2.2.9](image)

**Figure 2.2.9** Pulse heights (µA) against the duration from the previous pulse (µsec) for the first 10 Trichel pulses shown in Figure 2.2.8.

The diagram confirms that the corona discharges have a tendency towards producing an average pulse rate and an average current for a given voltage above the onset threshold voltage. The fluctuations in pulse heights are compensated for by a corresponding following change in duration until the next pulse occurs. Table 2.1 shows some basic statistics for the first 18 Trichel pulses shown in Figure 2.2.8. The standard deviation was calculated by method of least squares.

**Table 2.1** Statistics for the first 18 Trichel pulses shown in Figure 2.2.8.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Pulses</td>
<td>18</td>
</tr>
<tr>
<td>Magnitude of 1st pulse</td>
<td>820 µA</td>
</tr>
<tr>
<td>Magnitude of 2nd pulse</td>
<td>660 µA</td>
</tr>
<tr>
<td>Average Magnitude of succeeding</td>
<td>650 µA</td>
</tr>
<tr>
<td>pulses</td>
<td></td>
</tr>
<tr>
<td>Std Deviation excluding first pulse</td>
<td>25 µA</td>
</tr>
<tr>
<td>Ratio of first pulse to second pulse</td>
<td>1.25</td>
</tr>
<tr>
<td>Average rate of conduction</td>
<td>0.68 nC/µsec</td>
</tr>
</tbody>
</table>
2.2.5.1 Trichel Pulse Repetition Rates

To study the repetition rates the applied voltage was raised slowly until the onset of Trichel pulses was observed as shown in Figure 2.2.10 (a) in which two consecutive Trichel pulse trains can be clearly seen.

**Fig. (a)** Two consecutive Trichel pulse trains at the corona onset voltage of approximately 3670 V.

**Fig. (b)** Trichel pulses at 4000 Vpk.

**Fig. (c)** Trichel pulses at 4540 Vpk (just prior to onset of positive point corona).

**Figure 2.2.10** Trichel Pulses during one-half cycle up to the maximum voltage prior to positive-point discharges occurring in the negative half cycle. Gap = 3.175 mm.
Figure 2.2.10(b) shows the time between pulses decreases as the voltage is increased. Indeed the repetition rate appears to be a function of the applied voltage. Figure 2.2.10(c) shows the increased density of Trichel pulses at the peak of the applied voltage just prior to the onset of positive point discharges commencing.

At this point in the experiment the signals were stored and the oscilloscope time base was adjusted to facilitate counting of several pulses over an amount of time to derive the maximum pulse rate at the peak of the applied voltage waveform.

Twenty similar experiments were conducted for gaps adjusted from 1.3 mm to 12.7 mm in 0.635 mm steps to produce Figure 2.2.11 which shows the pulse frequency rapidly increases for gaps lesser than 4 mm and shows that the time between pulses increases for larger gaps. The repetition rate is the reciprocal of the time function.

![Figure 2.2.11](image)

**Figure 2.2.11** Maximum repetition rates at voltages just prior to the onset of positive point corona discharges for discharge gaps up to 16 mm.

![Figure 2.2.12](image)

**Figure 2.2.12** Trichel pulse repetition rate versus applied voltage for a point-plane gap of 3.175mm (1/8").
Figure 2.2.12 shows the pulse repetition rate as a function of the applied voltage for a 3.175 mm discharge gap. After the initial establishment of regular pulses at about 80 kHz pulse rate the function is linear between 3.9 kV_{pk} and 4.5 kV_{pk}.

The pulse repetition rate for this point-gap can be analytically defined as a straight line from established Trichel pulses at 3.9 kV and has a slope of 160 Hz/Volt using averaged values. The following expression can be written for this point and gap:

\[
\text{Frequency } f = 80,000 + 160 (V - 3900) \quad \text{(2.1)}
\]

Where \( V \) is the peak applied voltage.

In steady conditions the average current is exactly proportional to the charge per pulse multiplied by the frequency. For Trichel pulses, pulse per charge \( Q \) may be assumed constant for a particular tip radius, so the average current may be determined by the basic equation:

\[
I = Qf \quad \text{(2.2)}
\]

Where \( f \) is the frequency from equation (2.1).

The equivalent resistance for the discharging gap may be calculated by dividing the current by the rms value of the applied voltage such that:

\[
R_{\text{eq}} = \frac{V_{\text{rms}}}{Qf} \quad \text{(2.3)}
\]

Equations 2.1 and 2.2 use peak voltages and equation 2.3 require the use of the rms value of the voltage.

Using the pulse rate counting technique to Trichel pulses for several gaps, which involved the counting of several pulses over short time intervals, characteristic frequency curves were generated. The characteristic curves are presented as Figure 2.2.13. This chart provides an insight into the way negative point Trichel pulse frequency changes with gap length from their onset up to the voltage where positive point corona discharges commence on the alternate half cycle of the applied voltage. The chart shows the slope of the frequency curves (Hz per volt) decreases for increasing gap lengths.
2.2.5.2 Negative point ‘Trichel Pulse’ waveforms

Figure 2.2.14 shows a typical first current pulse captured at 100 nsec/div at a sampling rate of 200 MHz (5 nsec per sample point). The pulse has a fast (<14 nsec) rise to its rounded peak. As the rise time of the pulse is precisely the estimated response time of the measurement system the actual rise time for the pulse may be considerably less than shown implying a possibly even higher peak.

Figure 2.2.14  A typical first negative point corona discharge current pulse.

The tail of the pulse reduces to less than 5 % in 200 nsec and the small inflexion arrowed is also seen in Figure 1 in [66]. The amount of charge Q associated with each pulse can be calculated by estimating the area of the pulse. The number of elementary charges can then be calculated by multiplying Q by the number of charges per coulomb.
A triangular area approximation was used for the calculation of Q. Area A1 is equivalent to the total charge in a typical large initial pulse of a Trichel pulse train. The triangular approximation is bound by the vertical line through the zero crossing, 180 nano seconds in base width, and the oblique line from the peak to the base as shown in Figure 2.2.15 below:

![Figure 2.2.15](image)

**Figure 2.2.15** Area estimation of a typical large first pulse and a typical smaller successive pulse. Gap = 3.175 mm

Q is the total number of elementary charges (electrons) that leave the surface of the conductor irrespective of the mechanism to get into the gap.

**Estimation of Q and the number of elementary charges**

\[1 \text{ Coulomb} = 6.241509 \times 10^{18} \text{ elementary charges}\]

\[A_1 = \frac{1}{2} \times 860 \mu\text{A} \times 180\text{nsec} = 77\text{pC}\]

\[= 480 \text{ million (elementary charges)} \quad \cdots (i)\]

\[A_n = \frac{1}{2} \times 580 \mu\text{A} \times 140\text{nsec} = 40\text{pC}\]

\[= 250 \text{ million (elementary charges)} \quad \cdots (ii)\]

The first pulse A1 is approximately 1.5 times the height of the smaller second pulse A2. A1 contains approximately twice as many charges of any successive pulses.
Estimation of point radius

According to [61] 50 pC corresponds to a tip radius of approximately 0.028 mm and 60 pC corresponds to a radius of 0.030 mm. These radii correspond to steady state Trichel pulses using DC voltage. By interpolation, the estimated equivalent radius of the tip used in these experiments would be approximately 0.026 mm.

2.2.6 Positive point corona discharges

From the literature [70] [71] the irregular pulses observed with positive applied voltage are sometimes referred to as *streamers* because of the faint visible stream of light that appears to bridge the gap when they occur. Figure 2.2.5(d) shows photographic images of both negative point corona and *streamers* which correspond to the pulses shown in Figure 2.2.16.

![Figure 2.2.16 Positive point corona current pulses. Gap = 6.35 mm, V = 6.38 kV<sub>pk</sub>.]

Positive point current pulses are very much larger (up to 4000 µA) than the negative point Trichel pulses (up to 800 µAmp). They appear as irregular pulses in groups with each consecutive pulse larger than the previous. The largest pulse is last in each group and each group seems to have their own repetition rate. There are usually several groups per half cycle. If the voltage is slightly further increased, the pulse intensity increases rapidly and flashover occurs burning the point from the electrode.
2.2.6.1 **Positive point discharge current waveforms**

Positive onset discharges occur at a consistently higher voltage except when the gap is small. For small gaps less than 1.3 mm a positive-point discharge always occurred first. Refer Figure 2.2.6. This first discharge always caused flash over before any negative-point Trichel pulses were observed.

Figure 2.2.17 (a) shows a typical current waveform for a positive point discharge. Figure 2.2.17 (b) shows current waveforms for several positive point discharges overlapped to see the differences between the large and small pulses. The pulses are aligned so they have the same starting points. Note that some pulses appear as only one pulse and some appear as double-peaked pulses; the second peak can reach over 3000 µA. If there are two (2) pulses, the second pulse peak is always larger than the first peak. Only single peak pulses exist for discharge currents below approximately 900 µA.

**Figure 2.2.17** Positive point discharge current pulses. (a) A typical double pulse, time scale 500 nsec/div. (b) Several pulses overlapped with common starting points on a time scale of 100 nsec/div. Gap = 6.35 mm (1/4”).

Assuming the rise times of both pulses are similar, the second pulse starts approximately 150 nsec after the start of the first pulse. The larger the second pulse, the shorter the time until the next pulse. Note that the tails of the second pulses in Figure 2.2.17(b) are all very similar making the total duration of the two peaked pulses constant at approximately 540 nsec.
A triangular area approximation was also used for the calculation of $Q$ for the double peaked pulses. Figure 2.2.18 shows the construction lines used for this approximation.

**Figure 2.2.18** Total area estimation for a typical double peaked positive point corona discharge current pulse.

**Calculation of $Q$ and number of elementary charges for a typical 1200 $\mu$A positive point discharge**

$1$ Coulomb $= 6.241509 \times 10^{18}$ elementary charges

Area $A_1 = \frac{1}{2} \times 900 \mu$A $\times$ 250 nsec $= 112$ pC

$\sim 700$ million (elementary charges) …(v)

Area $A_2 = \frac{1}{2} \times 1200 \mu$A $\times$ 400 nsec $= 240$ pC

$\sim 1500$ million (elementary charges) …(vi)

Overlap Area $A_3 = \frac{1}{2} \times 450 \mu$A $\times$ 150 nsec $= 33.8$ pC

$\sim 200$ million (elementary charges) …(vii)

Total number of charges for double pulse discharge

Total Charge $= (v) + (vi) - (vii)$

$= 318$ pC

$\sim 2000$ million (elementary charges) …(viii)
Figure 2.2.19 shows an envelope of about 20 seconds (1000 cycles) of point plane corona discharge current pulses for a 3.175 mm gap. The envelope was created by first setting the oscilloscope trigger level to +10 V, and then the applied voltage was set to about 3000 V which is 670 V below the onset threshold voltage for TPs. On the oscilloscope, the *infinite persistence* function was started and the voltage was slowly and smoothly raised by hand to approximately 4600 V. The *Stop* button was pressed and the screen display was stored. The heavy traces for voltage and current are the last traces captured by the oscilloscope prior to the stop button being pressed.

![Diagram of Figure 2.2.19](image)

**Figure 2.2.19** Envelope of applied voltage and corona discharge current pulses from the onset of TPs to well-established positive point discharges. Gap = 3.175 mm. Vertical scales: 2 kV/div and 500 µA/div. Horizontal scale: 2 msec/div.

Clearly, patterns are produced by the envelopes of many captures. It is interesting that large TPs and the positive point discharges eventually cover the entire area from onset voltage to extinction voltage especially for the positive point discharges which appear to be erratic for a single capture.

### 2.2.7 Discussion and conclusions of results

The presented results are similar to those described by Comber et al in [57], and by Kuffel and Zaengl in [75] where basically the negative point Trichel pulses occur before the positive point corona discharges in AC power systems. The magnitudes of the TPs are in agreement with previously published literature by being well within the variations shown by both Trichel and Lama to the extent where the point sizes could be checked.
The fluctuations found in the onset of Trichel pulses in Figure 2.2.8 were also found in the pulse trains of many kilohertz (Figure 2.2.10). It is likely that inconsistencies in atmospheric air, such as humidity, air flow, and other particles, interact and influence the timing of space charge build-up and decay within the gap.

The question arises whether the space charge from the TPs affect the positive point discharges and vice versa for the 50 Hz alternating voltage. Comparison of onset threshold voltages and high resolution current pulses to other work was not possible because examples were not found in their literature, apart from low pressure studies (6.65 kPa) by Morrow [66] and by Soria [68] with negative DC voltages. Only Repan [63] included a simulated and a measured Trichel pulse which both are in the same form as those measured in these experiments. Trichel [60] and Lama [61] concentrated mainly on repetition rates and point sizes with varying pressure for established pulse trains.

It may be that the area of the plane electrode can vary the electric field intensity at the point electrode considerably and results for a particular point plane geometry may not be the same for a slightly different point-plane setup. For example, the plane electrode used in these experiments was only 6.35 mm in diameter whereas in the references reviewed the plane size is either not mentioned or assumed infinite. The proximity of the point to ground planes could also influence the conditions of the electric field gradient at the point electrode considerably.

It can be assumed that when only TPs were being detected, no space charge existed in the gap from any positive point discharges. Throughout the experiments, besides the increase in TP frequency from increasing the applied voltage, no noticeable step changes to TP frequency or magnitude was observed when positive point corona discharges commenced.

At higher voltages when the positive point discharges were well-established, such as seen in Figure 2.2.19, the TPs appear larger at the onset and extinction voltages. This is shown by the asterisk * in Figure 2.2.19. A possible explanation follows:

The first pulse of a Trichel pulse train is the largest, and in ideal conditions, when the voltage has reduced to below the onset threshold the continuous train of TPs stop.
However, as seen in Figure 2.2.10(a) TPs can start and stop after a few pulses when the voltage is close to the onset threshold. In Figure 2.2.19 the larger pulses at both ends of the TP envelop are therefore first pulses. The ones at the end are also first pulses, which follow from an extended duration from the last TP of the preceding pulse train, but they have no or very few succeeding pulses. At least, one large pulse should occur at the onset, which is seen in the envelope, and depending on the rate and form of the reducing voltage, there may be enough time for at least one large pulse and possibly a few succeeding TPs as the voltage reduces to below onset levels; this is also seen in the envelope.

The erratic behaviour of the positive point pulses may be caused by ‘the hanging balance between the rates of generation and loss of electrons in the gap’ [70]. It is also possible that the erratic behaviour may come from electron detachment or photoionization that are random and erratic in both time and space.

It is interesting that for a gap of 1.3 mm the negative point and positive point corona onset voltages are the same magnitude except they are of opposite polarity. It is possible that the plasma from the first pulse extends too far out into the gap for the space charge to extinguish the discharge and therefore full conduction occurs for the first pulse. It is also interesting that the locus of positive point onset voltages follow the square root of the gap law while the negative point onset shows a constant difference. As the plane electrode was not of infinite area it may be possible that the point plane geometry has an influence in these results at distances larger than half a diameter of the plane electrode.

The double pulse found on some positive point discharges is of interest as this has not been discussed by other researchers, except for the leading edge of negative point discharges (TPs) where there has been some modelling work done [67] where the first and second steps with several nanoseconds between them, in low pressure oxygen, were described in terms of independent photon and ion feedback mechanisms [74]. Repan [63] discussed for TPs, the first part of the pulse is from ionizing photon radiation and the second part of the current pulse is from positive ions impinging on the surface of the point electrode. Correspondence with Dr. J. Lowke [76] indicated that this process was not possible for positive point discharges because electrons were not released from the positive point under a positive point discharge.
It may be possible that the positive ions generated at the tip of the point electrode could propagate to the plane electrode to cause secondary emission, however, streamer propagation of around 25 mm per 100 nsec has been measured for 1 m gaps [77] which is about 6 times too slow for the streamer head to reach the plane electrode to cause the second pulse.

In the short gaps the increased gas temperature and reduced density may allow faster propagation of the streamer. Nadis [70] describes streamers as a two stage process; “Just after the positive streamer head has contacted the cathode, a region of the cathode voltage drop is formed. The next stage of the discharge development, along the streamer channel, is the propagation of the electric potential wave. As a result, during several tens of nanoseconds the axial distribution of the electric potential becomes nearly uniform.” Naidis goes on to explain that the rate of current growth is dependent on $E_m/N$ where $E_m$ is the mean electric field and $N$ is the gas number density supporting the theory of increased streamer velocity in the discharge gap.

In addition, Namihira et al [78] photographed pulsed streamers from a concentric conductor to an outer cylindrical electrode in atmospheric air with a camera capable of 5 nanoseconds exposure times and showed streamer propagation to be in the order of 1.8 mm/nsec for 30 kV pulses and 3.3 mm/nsec for 20 kV pulses for an outer cylinder of 76 mm in diameter. The impulse current shows a two-step process where low current of 10 A is followed approximately 60 nsec later by high current of 100 A for 30 kV pulses and 40 A for 20 kV pulses. The ratio of these pulses, 10:1 and 4:1, is similar to some of the positive point discharge current pulses such as those in Figure 2.2.17. The second streamer was observed to start from the centre electrode after the first streamer bridged the gap and disappeared half way across the gap. Namihira et al [78] suggested the reason for the second streamer disappearing about half way across the gap was because the electric field was insufficient to sustain ionization.

Communication with Dr. Bruggerman [79] suggests that the double pulses in my experiments are the early stages of streamer to spark transitions, where a slightly higher voltage would cause sustained ionization with resultant spark over. This explanation agrees with the observed nature of the point-plane corona discharges studied here and is an extension of the theory described by Namihira.
2.3  Corona discharges with 0.2 mm SiR over plane electrode

It is of great interest to examine how polymeric insulating materials affect corona discharges and how these materials are affected by corona.

In this experiment a small piece of 0.2 mm thick fibre glass reinforced Silicon Rubber (SiR) insulation manufactured by LAIRD TECHNOLOGIES was fixed to the metal plane electrode with a small amount of silicon oil. The polymer manufacturer gave the test material characteristics as: Thermal operating range from -60°C to 180°C; Thermal resistance of 0.28 °C/W; Thermal conductivity of 1.3 W/m.K; and a working voltage of 1000 Volts. The surface of the material had a fine matt texture.

The SiR was cut into 9 mm squares to facilitate handling. The surface was wiped with a lint free cloth and voids between the plane electrode and the SiR were minimized by applying light pressure to the centre of the SiR. Final adjustments were made to the oscilloscope settings and camera focus then approximately 2 minutes later the experimental apparatus was energized. With the SiR in place the air gap length was:

\[ 6.35 \text{ mm} - 0.20 \text{ mm} = 6.15 \text{ mm}. \]

![Figure 2.3.1](image)

**Figure 2.3.1** Setup showing 0.2 mm thick fibreglass reinforced silicon rubber insulation positioned onto plane electrode prior to energization by applied AC voltage.
2.3.1 Results

The applied voltage was raised until the onset of regular discharge pulses was observed on the oscilloscope. This occurred at approximately 5750 V$_{pk}$. The onset voltages for both positive and negative point discharges were very close in magnitude. Several positive streamers were detected for the slightest increase in applied voltage (less than 1%). The applied voltage and discharge current traces for various applied voltages are shown in Figure 2.3.2.

![Figure 2.3.2](image.png)

**Figure 2.3.2** Typical measured corona discharge current pulses for increasing 50Hz alternating voltage with a 6.35 mm (1/4") point-plane gap and 0.2 mm silicon rubber insulation across the plane electrode. Voltage scale = 2 kV/div, Current scale = 500 µA/div, Time scale = 2 msec/div. Temperature: 23.6 °C, RH: 48%

A 5% increase in voltage to 6010 V$_{pk}$ establishes well-defined pulse trains during both alternate cycles as shown in Figure 2.3.2(b). Positive point discharge current pulses in this figure are larger at onset and become smaller in height at the end of the pulse train. As shown in Figure 2.3.2(c), a further voltage increase of 3% to 6200 V$_{pk}$ significantly increases the frequency of production of negative point discharge current.
pulses and regular pulse height trains become well-established for both polarities of the applied voltage.

In a darkened room, the camera was set to free run asynchronously with 2 second exposures with wide open aperture. Although the apparatus was not visible to the eye during the experiments, the point discharges could be visually seen. Several movies up to 2 minutes in length each were created and analyzed to select the images presented in Figure 2.3.3, except for Figure 2.3.3(c) without SiR, which was taken with an exposure of 1 second.

Figure 2.3.3 (a) Negative point corona discharges with 0.2 mm thick silicon rubber over the plane electrode. (b) Positive and negative point corona discharges with 0.2 mm thick silicon rubber over plane electrode. (c) Positive and negative point corona discharges to metal plane electrode with 6.35 mm (1/4") gap. Insert current scales : 500 µA/div.

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The differences in negative and positive corona discharge onset voltages for with and without SiR are presented in Table 2.2. The absolute magnitudes of the difference between these onset voltages are also provided.

**Table 2.2** Comparison of measured corona discharge onset threshold voltages for an insertion of a 0.2 mm thick piece of silicon rubber insulation over the plane electrode.

<table>
<thead>
<tr>
<th></th>
<th>6.350 mm Gap</th>
<th>6.150 mm Gap</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(no SiR)</td>
<td>(with SiR)</td>
<td></td>
</tr>
<tr>
<td>Neg Onset</td>
<td>5.31 kV</td>
<td>5.75 kV</td>
<td>+ 0.44 kV</td>
</tr>
<tr>
<td>Pos Onset</td>
<td>6.38 kV</td>
<td>5.80 kV</td>
<td>- 0.58 kV</td>
</tr>
<tr>
<td></td>
<td>Difference</td>
<td>1.07 kV</td>
<td>0.05 kV</td>
</tr>
</tbody>
</table>

Figure 2.3.4 presents detail traces of both negative point and positive point discharge current pulses captured by the oscilloscope. All the negative point corona discharge current pulses in Figure 2.3.4 have very fast (< 14 nsec) rise times to singular peaks and with a small inflection in the middle of their tails.

**Figure 2.3.4** Typical measured corona discharge current pulses for a 6.35 mm point-plane gap and 0.2 mm silicon rubber sheet across plane electrode. (a) Negative point corona discharge current pulses. (b) Detail of a typical negative point discharge current pulse. (c) Positive point corona discharge current pulses. (d) Detail of a typical positive point discharge current pulse. Applied voltage = 6010 Vpk.

All the positive point discharge current pulses in the pulse train in Figure 2.3.4 (c) are double peaked pulses as shown in Figure 2.3.4 (d).
The oscilloscope time base was set to *single shot infinite persistence* to obtain the four superimposed positive point discharge current pulses displayed in Figure 2.3.5 (a). Figure 2.3.5 (b) shows both double and single peaked pulses previously captured for bare metal electrodes. Figure 2.3.5 (b) has been vertically scaled down (x 0.4) so that the pulses can be overlapped and their form compared. In Figure 2.3.5 (c) the tails of the pulses are grouped together for clarity. M is designated for metal electrodes and S is designated for the silicon rubber covered plane electrode.

**Figure 2.3.5** Comparison of positive point corona discharge current pulses. (a) With 0.2 mm silicon rubber over plane electrode, and (b) Polished metal plane electrode (no SiR), and (c) Comparison overlay of (a) an (b). The images are vertically aligned at the start of the first pulse.
2.3.1.1 Calculation of total pulse charge $Q$

The total charge per pulse $Q$ was estimated by triangular approximations. The total number of elementary charges for a typical discharge pulse with the 0.2 mm silicon rubber across the plane electrode can then be calculated. Figure 2.3.6 shows the construction lines used in the approximation of a typical large pulse from the group. The total charge per pulse $Q = A_1 + A_2 - A_3$ Coulombs

![Figure 2.3.6](image)

Figure 2.3.6 Construction lines used for estimating the area of a typical large positive-point double pulse with silicon rubber across plane electrode.

Table 2.3 shows the results of the triangular approximations to calculate the total charge $Q$ for the large (1250 µA second peak) double peaked pulse shown in Figure 2.3.6. For the highlighted trace (1000 µA second peak) the estimated total charge $Q$ is 225 pC.

<table>
<thead>
<tr>
<th>Area</th>
<th>pC</th>
<th>Elementary charges</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>154</td>
<td>$960 \times 10^6$</td>
</tr>
<tr>
<td>A2</td>
<td>167</td>
<td>$1000 \times 10^6$</td>
</tr>
<tr>
<td>A3</td>
<td>61</td>
<td>$381 \times 10^6$</td>
</tr>
<tr>
<td>Total Q</td>
<td>260</td>
<td>$1600 \times 10^6$</td>
</tr>
</tbody>
</table>

Table 2.4 Ratio of estimated areas $A_1:A_2$ for positive point discharge current pulses shown in Figure 2.2.18 and Figure 2.3.6.

<table>
<thead>
<tr>
<th>Ratio</th>
<th>6.350 mm Gap (with SiR)</th>
<th>6.350 mm Gap (without SiR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1:A2</td>
<td>0.92</td>
<td>0.47</td>
</tr>
</tbody>
</table>
### Table 2.5

<table>
<thead>
<tr>
<th>Description</th>
<th>5010 V_{pk}</th>
<th>6200 V_{pk}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of positive point pulses</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Magnitude of 1st pulse</td>
<td>850 µA</td>
<td>1100 µA</td>
</tr>
<tr>
<td>Magnitude of 2nd pulse</td>
<td>1400 µA</td>
<td>980 µA</td>
</tr>
<tr>
<td>Largest pulse height</td>
<td>1100 µA</td>
<td>1500 µA</td>
</tr>
<tr>
<td>Smallest pulse height</td>
<td>850 µA</td>
<td>700 µA</td>
</tr>
<tr>
<td>Average Magnitude of 10 pulses</td>
<td>942 µA</td>
<td>1145 µA</td>
</tr>
<tr>
<td>Std Deviation in percent of average</td>
<td>20.1 %</td>
<td>9.4 %</td>
</tr>
</tbody>
</table>

### 2.3.2 Observations and discussion

In Section 2.3 it has been shown that a thin sheet of SiR covering the plane electrode has a considerable effect on the corona (Figure 2.3.3), the corona onset voltages (Table 2.2), and the positive-point corona discharge current pulses (Figure 2.3.5).

The negative point discharge current pulses presented in Figure 2.3.4 (a) and Figure 2.3.4 (b) appear very much like Trichel pulses measured in Section 2.2 without SiR, and those presented in Figure 2.2.10 and Figure 2.2.15. Peak current pulse magnitudes were between 500 µA to 700 µA and about 100 nsec wide at half height for with and without SiR. The TPs also display similar variations in height and spacing for with and without SiR. This similarity is to be expected as the Trichel pulse phenomena is governed by corona at the point electrode on the opposite side of the gap 6.35 mm (1/4”) from the SiR covered plane electrode.

Table 2.2 shows, the negative point corona onset voltage increased from 5.31 kV_{pk} without SiR to 5.75 kV_{pk} with SiR across the plane electrode. The change in onset voltage for negative point corona may be contributed to the polarization of the SiR test material, the distribution of charge on the surface of the sheet of SiR, the size of the SiR sheet, the surface texture of the SiR, and possibly the way the SiR was fixed to the plane electrode. The relative permittivity of glass and SiR [15] are both about 3.6.
For the positive-point corona discharge current pulses, significant changes occurred when SiR was used over the plane electrode:

- There are no single-peaked positive-point pulses with SiR covering the plane electrode. Whereas without SiR, single peaked pulses occurred up to 900 µA, after which double peaked pulses were observed. The double peaked pulses shown in Figure 2.3.4 (c) are fairly evenly spaced in contrast to the positive-point pulses shown in Figure 2.2.16 without SiR.
- For the SiR covered plane electrode, the first peaks are all the same height; whereas without the SiR, the magnitudes of the first peaks appeared random in height. The average heights of the first peaks, for both with SiR and without SiR, are very similar.
- In Figure 2.3.5 (c) it can be seen that the tail from the second peak reduced in a shorter time; 360 nsec for SiR versus 500 nsec for no SiR. The corresponding difference in total charge can be seen in Table 2.4 where the ratios of A₁ and A₂ are compared. For SiR, it can be seen in Figure 2.3.6 that the Area A₁ appears to be quite constant while A₂ varies marginally. For bare metal electrodes both A₁ and A₂ vary considerably in size; this can be seen in Figure 2.3.5.
- Figure 2.3.2 (b) shows established positive-point discharge current pulses with SiR at 6010 V with standard deviation of 20.1 % (Table 2.5). Figure 2.3.2 (c) shows the positive point pulses at 6200 V with standard deviation of 9.4 %. The variations in pulse heights appear to stabilize around 1200 µA by increasing the applied voltage to 6200 V, whereas for established positive point discharges without SiR, and at higher voltages (V⁺onset = 6350 V), the magnitudes of the second peak quickly become much larger than 3000 µA for the slightest increase in applied voltage.

Table 2.6 shows approximations of the amount of charge in one voltage cycle for applied voltage just above corona onset (Figure 2.3.2(a)), and for established corona discharges (Figure 2.3.2(b)). 40 pC was used for all TPs; 260 pC was used for the single pulse, and 225 pC (Average of 10 pulses) was used for well-established positive-point corona pulses.
Table 2.6  *Estimated charge per cycle for Figure 2.3.2(a) and Figure 2.3.2(b).*

<table>
<thead>
<tr>
<th>Number of Neg point pulses</th>
<th>pC</th>
<th>Number of Pos point pulses</th>
<th>pC</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>280</td>
<td>1</td>
<td>260</td>
</tr>
<tr>
<td>58</td>
<td>2320</td>
<td>11</td>
<td>2477</td>
</tr>
</tbody>
</table>

It can be seen from Table 2.6 that there appears to be a balance of charge being transferred across the gap by different types of discharges. The following hypothesis is presented:

Electrons and negative ions from the previous negative point discharge, that were attracted to the positively charged plane electrode, land on the surface of the SiR and remain there on the surface without completing conduction into the metal plane electrode.

During the next alternate half cycle, when the point becomes positively charged and the plane becomes negatively charged, negative charge will exist on both sides of the SiR. The residual negative charge left on the surface of the SiR, plus the increasing negative charge on the plane metal electrode, has the effect of increasing the electric field strength in the gap. Because this additional negative charge is in the gap it enhances the electric field at the positive point to the extent that positive-point corona occurred with applied voltage of 580 V lower than without SiR (Table 2.2). If the electric field strength at the point is the same for the onset of positive-point corona, for with and without SiR, then 580 V must have been across the thickness of the SiR prior to the onset of positive point discharges.

The smaller second peak of the pulse with SiR can be explained by the limited distributed surface charge available to each positive streamer. Each positive streamer sources electrons from a different location off the SiR surface. As each discharge reduces the electron surface density in one location, the next discharge pulls electrons from another electron abundant location. This may also be linked to the more regular nature of these pulses with SiR and also explains why the corona appears over the large area of the SiR surface seen in Figure 2.3.3(b); whereas in Figure 2.3.3(c) electrons are readily available from the centre of the metal plane electrode (see asterisk). The abundant availability of these electrons may cause variations of residual
space charge and cause the large variations in magnitude and timing of positive point discharges without the SiR across the plane electrode.

It was noticed in Figure 2.3.2 (c) that the number of positive-point discharges were close to the number in Figure 2.3.2 (b) although the TP rate was nearly twice that shown in Figure 2.3.2(b). It is possible that the electron surface density saturates and the excess electrons leak around the edges of the SiR to conduct into the metal plane electrode. This seems to occur from when the total charge reached about 2477 pC.

It is therefore conceivable that charge may accumulate on the surfaces of insulators near discharge sites and promote positive-point discharges.

It is also conceivable that positive ions from positive streamers could also be trapped onto the SiR surface; due to higher energy levels these ions would have a detrimental affect to the SiR surface, but as negative point discharging occurs at lower voltages in AC systems than for positive point discharges, negative ions and electrons cross the gap initially to accumulate on the SiR surface.
2.4 Breakdown of silicon rubber under corona discharges

From the unenergized state as shown in Figure 2.4.1 the applied voltage was increased to 6200 $V_{pk}$. At this voltage both negative and positive discharges were being observed as in Figure 2.3.3 (b). Discharges were being monitored at this level for approximately 20 seconds after which the electrical insulating properties of the SiR broke down and arcing commenced. The event was captured by the camera (Figure 2.4.2). The camera frame transfer rate was 25 Hz.

![Figure 2.4.1](image1)  
**Figure 2.4.1**  Experimental setup showing 0.2 mm thick fibre glass reinforced silicon rubber insulation over the plane electrode prior to energization. Air gap = 6.15 mm.

![Figure 2.4.2](image2)  
**Figure 2.4.2**  Breakdown streamers occurred approximately 20 seconds after establishing discharges at 6200 $V_{pk}$. 


2.4.1 Examination

Figure 2.4.3 is a photograph taken by a digital camera fitted to a microscope and shows the difference between a typical unused point and the point after the spark-over shown in Figure 2.4.2. A visual examination shows that the point is damaged. The tip of the point has vaporized and a considerable amount of material is missing.

![New and After spark-over](image)

**Figure 2.4.3** Microscope photograph showing the difference between a typical unused point and the point shown in Figure 2.4.2 after the spark-over.

Figure 2.4.4 shows the side of the SiR that was in contact with the metal plane electrode. When the SiR was examined with a graduated microscope a tunnel approximately 50 µm in diameter was seen through the SiR. A brown heat-affected area approximately 1.5 mm wide and 1 mm in height, and missing material up to 25 µm deep surrounds the tunnel.

![Tunnel and 500 µm](image)

**Figure 2.4.4** Microscope photograph of the side of the SiR that was in contact with the metal plane electrode. A 50 µm diameter tunnel and brown affected area of the failed 0.2 mm SiR is clearly seen.
Figure 2.4.5 shows a microscopic photograph of the side of the SiR that was in contact with the corona discharge. This is the location where the arcs appear to terminate in Figure 2.4.2. This location is on the centre axis of the discharge.

There is a white chalky appearance on the surface surrounding the damaged area. The periphery of the heat affected substrate is tan in colour which becomes blacker towards the centre of the affected area. What appears to be the rim of a broken glass bubble can also be seen in the figure.

![Silica glass rim Black area Tan area](image)

**Figure 2.4.5** Microscope photograph of the SiR that was in contact with the air. The location is on the centre axis of the discharge gap opposite the point electrode.

The sample was prepared for the scanning electron microscope (SEM) and during the preparation the crusty silica layer seen in the centre of the affected area in Figure 2.4.5 was removed. Figure 2.4.6 shows the tunnel through the material, and exposed glass fibres from the fibre glass reinforcing. The fibre glass reinforcing is missing from the across the entire crater.

![Tunnel Glass fibers Void](image)

**Figure 2.4.6** SEM image of the affected area shown in Figure 2.4.5 with the crusty layer of silica removed.
**Figure 2.4.7** A close up of the position indicated by ‘Glass fibres’ in Figure 2.4.6 showing one of the exposed glass fibres and the SiR polymer.

**Figure 2.4.8** A close up image of the centre of Figure 2.4.6 showing the tunnel entrance (arrowed). The dotted line shows the rim of a crater around the tunnel with wax like material at the bottom of the well. A granular surface texture can be seen in the upper RHS of the image.
After SEM the sample was subject to dispersive X-ray spectroscopy (EDS) which is provided as an additional function of the scanning electron microscope. Figure 2.4.9 shows the results of EDS.

![Energy dispersive X-ray spectrum](image)

**Figure 2.4.9** Energy dispersive X-ray spectrum from centre of the affected area shown in Figure 2.4.6.

The peak on the far left side of the spectrum is carbon C. The next peak is oxygen O. The next peak is aluminium Al, and the largest peak is silicon Si. The next two peaks are calcium Ca followed by two small peaks of chromium Cr and then there are two very small peaks related to iron Fe. Usually, only peaks above twice the background noise are considered.

### 2.4.2 Observations and discussion

The subsequent arcing following the breakdown has consumed some of the tip from the pointed electrode leaving a very slightly larger gap and a larger tip radius. This clearly explains the changed discharge voltage and current characteristics that occurred after a flashover in previous experiments that always required the point to be changed and the experiment repeated. After a flashover, the onset voltage is always higher due to this larger gap and the current pulses are much larger due the larger tip radius [60] [61]. The degree of damage is attributed to the limited current available from the
A power supply under short circuit conditions (30 mA) and the short duration that the arcing was sustained (10 msec max).

Polydimethlsiloxane degrades thermally into basic components with applied heat from discharges [29] [23] [21]. Kim et al [38] showed that chemical changes to the surface of SiR by discharges, caused weight loss with reduction in surface density of CH$_3$ groups and further crosslinking of SiR (PDMS) backbone chains.

The reduction of volume from crosslinking can cause micro cracks to appear in the surface [29] [44] [39]. Similar surface texture can be seen in the bright region at the top right in Figure 2.4.8. Figure 2.4.10 from [31] is an SEM image that shows plate-like structures on the surface of SiR after application of corona discharges that could be the early stages of the granular effect seen in the top right hand side of Figure 2.4.8. Prior to discharges the surface was smooth and homogenous. Figure 1.28 shows a cross section of a freshly cut piece of SiR for comparison.

Furthermore, it may be possible that the boundaries of these plate-like structures contain the increased surface silica SiO$_2$ and hydrophilic OH groups that can be found on the surfaces of aged SiR insulators [22] [31].

Most of the transparent material that formed the rim of what may have been a bubble of the rim in Figure 2.4.5 would have come from melted fibre glass reinforcement and a portion would have come from the silicon and oxygen from the base material.

![Image](https://example.com/image.png)

**Figure 2.4.10** Surface texture after the application of corona discharges to the surface of SiR.
Figure 2.4.7 shows the discharge vaporized a small area of SiR leaving exposed glass fibres. The fibres that melted to form the bubble must have exceeded the melting temperature of Silica (1650 ±75 °C).

Figure 2.4.8 shows a pool of a solidified compound near the tunnel entrance. This area could have been the hottest region because of the depth of the crater and possibly it was in close proximity to the arc plasma column.

Figure 2.4.5 shows tan and blackened areas within the surface layer of the material. This is most likely gradual carbonisation by the loss of hydrogen from the methyl groups. In testing flashover resilience of PDMS samples [21] it was shown that carbon was always found in the track left by a flashover which lowered the insulation level in that area. Carbon is intentionally placed over the surface of the sample for the SEM and therefore can be ignored in the analysis although carbon can also come from the methyl groups in the structure of the SiR substrate material including silicon, and oxygen (dimethylsiloxane). Other sources of carbon might have come from carbon dioxide in the air, from the chrome steel point, and from the polished metal plane electrode which can include up to 4 % interstitial carbon.

The aluminium is most likely to be from ATH filler [21] [23] [22]. As calcium is present in the sample this suggests that calcium carbonate is present as filler as well as the aluminium as ATH. In addition to condensed silica, the ATH and calcium carbonate contributed to the whitish powdery surface that surrounded the affected area. This area was brightly illuminated by discharges prior to breakdown.

It is most probable that the chromium Cr and iron Fe is the missing material from the tip of the pointed electrode (chrome plated steel) that was carried across the gap in the plasma. The finding of these traces of metal on the surface of the SiR is important as it indicates that real insulators that suffer flashover between the metal fittings may also have traces of metal from the fittings deposited onto the surface of the insulator. These metal deposits could cause localization of discharges to further degrade the surface and weaken the overall insulating properties of the insulator.
2.5 Effect of smoke in the gap

Transmission line outages due to bushfires [56] and concerns about smoke entering high voltage switchboards prompted an investigation to ascertain the effects of smoke within a point-plane gap stressed under AC voltage.

Several smoke sources were trialled: A cigarette, a mosquito coil, and an incense stick. The smoke from the cigarette and mosquito coil both proved too inconsistent and uncontrollable because the smoke plume often changed in size, was relatively large compared to the gap, and continuously moved about even in a shielded enclosure. The patchouli incense stick provided a very consistent plume and was able to be positioned horizontally so the plume would eventually pass through the gap as it burned at a rate of approximately one half cm.min\(^{-1}\) providing the opportunity to record any discharge activity. The smoke source was positioned 30 mm vertically below the point plane gap shown in Figure 2.5.1.

![Figure 2.5.1](image.png)

**Figure 2.5.1** Setup showing pointed electrode and 10 mm wide copper plane electrode with a 3.2 mm (1/8”) gap.

The digital camera responded best to light reflected by the smoke. A 50 W quartz halogen lamp was positioned behind the camera and 250 mm away from the gap. To explore the nature of any effects over a complete voltage cycle, the camera was set to free run non-synchronously at 25 frames per second for 20 seconds at time to produce each film clip. This facilitated the capture of a series of images that were taken progressively at slightly different phase angles relative to the power system.
frequency. The film clips were then reviewed for any events. Corona could be seen only very faintly due to the short exposure settings required to photograph the smoke.

The voltage and current measurement circuitry, instrumentation, and voltage source were the same as those used in previous experiments. The plane electrode was substituted for a piece of annealed transformer winding conductor 12 mm wide and 2 mm thick copper (Figure 2.5.1) which was needed to be curved slightly away from above the point to provide a smooth laminar flow of smoke through the gap. The copper conductor was selected because it had a smooth radius instead of 90 degree edges and it was easy to bend. A new point provided Trichel pulses with a peak amplitude of around 600 µA which are shown in Figure 2.5.2.

![Figure 2.5.2 Trichel pulses from the point-plane gap in Figure 2.5.1.](image)

The gap was set to 3.2 mm using a standard feeler gauge. Two experiments were then conducted:

1. In the first experiment the applied voltage was set to just below the corona onset threshold voltage. This was achieved by slowly raising the applied voltage until discharge pulses were detected (~ 3670 V_{pk}). The voltage was then carefully reduced until no discharges were detected (~ 3660 V_{pk}). The oscilloscope was armed for a single capture on the detection of the first current pulse greater than 100 µA while the smoke trail moved toward and eventually into the gap.

2. In the second experiment the applied voltage was set to obtain only Trichel pulses with no positive point discharges. Then the smoke plume was introduced into the gap. The voltage was set to approximately half the incremental voltage between Trichel pulse onset and positive point discharge onset voltage which was 3690 V_{pk}. The oscilloscope was armed for a single capture trigger level of 800 µA to detect the first current pulse that was larger than the established Trichel pulses.
2.5.1 Results for smoke induced discharges

Video monitoring at 25 frames per second recorded the following events as smoke entered a non discharging stressed gap.

![Figure 2.5.3](image.png)

**Figure 2.5.3** Visible effects of a smoke-induced negative point discharge. (a) Laminar flow of smoke as the plume enters the gap with no discharges. (b) The onset of discharges affects the laminar flow. (c) Slight increase in plume width after one second. (25.0 °C, 61% RH).

Figure 2.5.3 (a) shows the setup with a laminar flow just prior to the smoke reaching the point electrode with applied voltage of 3660 V. The smoke streams upwards in natural air. It also moves about horizontally within the gap. Sometimes it flows close to the point and sometimes outside the gap. As the source material burns, the plume moves further into the gap. Figures 2.5.3 (b) and (c) both show a dark indentation in the smoke in front of the point electrode during discharge activity.

Figure 2.5.4 shows the first current pulses recorded when the smoke entered the gap. Figure 2.5.5 is an expanded view of the small section indicated by the bracket in Figure 2.5.4 displayed at 200 microseconds per division and shows what appears to be the random nature of the pulses in both height and time between pulses. The pulses occurred when the point was negatively charged. There are a few small initial current pulses less than 200 µA can be seen at the onset. Pulses rapidly increased in magnitude over the next half millisecond to approximately 420 µA. This was followed by a pause where there was no discharge activity for approximately 1 millisecond. After the pause, large pulses appeared up to 1700 µA in magnitude. It can be seen in 1 second envelope in Figure 2.5.4 that the pulse heights changed with the form of the applied voltage.
Figure 2.5.4 The initial current pulses detected as smoke enters the gap.

Figure 2.5.5 Expanded section of current pulses of the smoke induced discharge.

During the setting up of a useable smoke plume with various gaps the following frame (Figure 2.5.6) was recorded by the camera as the onset threshold voltage was being established and shows what appears to be a distortion in the smoke plume immediately in front of the point electrode in a 6.35 mm gap. The indent in the plume appears to focus toward the discharging point.

Figure 2.5.6 Distortion of a smoke plume in a point-plane gap during the initial stages of a discharge.
2.5.2 Results for smoke entering a discharging gap

Simultaneous with current, video monitoring at 25 frames per second recorded the following event during the second experiment as smoke entered the gap with established discharges occurring. It can be seen that the discharge affects the laminar flow of the smoke plume.

![Figure 2.5.7](image)

Figure 2.5.7 A photograph showing the visible effects of smoke entering the gap of a negative point discharge.

The oscilloscope display mode was set to infinite persistence to create simultaneous envelopes of both applied voltage and Trichel pulses to observe any spurious discharge events. This technique was used to ensure applied voltages were below discharge onset levels prior to smoke entering the gap. In Figure 2.5.8 the dark pulses shown are the last acquisition and the background shows all other pulses over a two second period (100 cycles).

![Figure 2.5.8](image)

Figure 2.5.8 A two second envelope of negative point discharges at 3690 V_{pk} prior to smoke entering the discharge gap.
Figure 2.5.9 shows what appears to be random discharges up to 3000 µA superimposed onto the background envelope of Trichel pulses as the smoke entered the gap.

![Figure 2.5.9](Image)

**Figure 2.5.9** Envelope of large current pulses superimposed on a background of a negative point discharges when smoke entered the gap. Gap = 3.2 mm, Applied voltage = 3690 V$_{pk}$.

An expansion of one of the larger pulses from the centre of the screen in Figure 2.5.9 reveals double peaked pulses. A typical double peaked pulse is presented as Figure 2.5.10. The first pulse marked as ‘1’ is the height of a normally occurring Trichel pulse. The second pulse marked as ‘2’ is close to four times larger than the largest pulses recorded during the previous experiment where smoke entered a stressed gap. The second peak occurred approximately 45 nanoseconds after the first peak. There is a minimum current of approximately 240 µA between them.

![Figure 2.5.10](Image)

**Figure 2.5.10** A typical large double current pulse. (1) Trichel pulse. (2) Second pulse from smoke in the discharging gap. Gap = 3.2 mm, Applied voltage = 3690 V$_{pk}$.
The total number of elementary charges for each pulse was estimated by method of triangular approximations as detailed in Figure 2.5.11. The results are presented in Table 2.7.

**Calculation of Charge Q per double pulse**

Total charge \( Q \) = Area of (1) plus Area of (2). Where Area of (2) has two triangular approximations to define the pulse so that:

\[
\text{Total Area} = A_1 + A_{21} + A_{22}
\]

**Table 2.7**  
Number of elementary charges for the three areas detailed in Figure 2.5.11 of a typical double current pulse caused from smoke within a point-plane gap.

<table>
<thead>
<tr>
<th>Area</th>
<th>pC</th>
<th>Elementary charges</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_1 )</td>
<td>18</td>
<td>( 112 \times 10^6 )</td>
</tr>
<tr>
<td>( A_{21} )</td>
<td>41</td>
<td>( 253 \times 10^6 )</td>
</tr>
<tr>
<td>( A_{22} )</td>
<td>81</td>
<td>( 505 \times 10^6 )</td>
</tr>
<tr>
<td><strong>Total Q</strong></td>
<td>140</td>
<td>( 870 \times 10^6 )</td>
</tr>
</tbody>
</table>
During both experiments, after a few seconds, the tip of the pointed electrode became contaminated from smoke condensate which resulted in very erratic discharges. Figure 2.5.12 shows a light colour condensate built up on the surface of the shank of the pointed electrode but it is the darker material at the tip of the point that causes the erratic discharge behaviour. When the tip was cleaned by wiping it with a clean sheet of paper the discharges reverted to those exhibited at the start of the experiments. The smeared material appears as an oily condensate, amber in colour and quite sticky. No further analysis was performed on the residue.

**Figure 2.5.12** A photograph showing condensate build-up on the tip electrode prior to cleaning.

Figure 2.5.13 presents a one second envelope of Trichel pulses from the cleaned tip at the end of these experiments. When compared with the Trichel pulses in Figure 2.5.8 it is clear that minimal, if any at all, damage was sustained to the tip during these experiments. Note that Figure 2.5.8 has a horizontal time scale of 1 msec/div and Figure 2.5.13 has a horizontal time scale of 500 µsec/div.

**Figure 2.5.13** A one second envelope of established Trichel pulses after the point was wiped clean at the end of the experiments. Gap = 3.2 mm, Applied Voltage 3690 V.
2.5.3 Observations and discussion of results

The gas channel in the middle of the plume travels vertically faster than the peripheral smoke gases which were in contact with the surrounding still air. As the resolution of the camera was not sufficiently high enough to resolve individual smoke particles estimating a position change from consecutive photo frames was too difficult to provide a reasonable estimate of smoke velocity.

The smoke-induced discharges appear random in nature and did not exhibit the regular pulse characteristics of a negative point-plane gap. In Figure 2.5.4 the one millisecond pause may be attributed to the fact that the plume moves in and out of the gap lowering the onset threshold voltage only while smoke is in the gap and surrounding the tip of the point electrode.

The electric field did not cause any noticeable effects to the smoke plume until discharging occurred. In Figure 2.5.4 there are no regular Trichel pulses although the maximum heights are similar in size to Trichel pulses. This is possibly due to the lack of electron capturing oxygen and changing conditions such as the density and composition of the gas surrounding the tip. Charging of dust particles will also alter the space charge and change the corona. The larger pulses may well be negative streamers triggered by the smoke, similar to the large current pulses due to positive streamers; hence their erratic behaviour. Accumulating condensate from the smoke on the surface of the point (Figure 2.5.12) may also contribute to the erratic behaviour of the larger current pulses.

For the second experiment where smoke entered a discharging gap there were bursts of double pulses within a series of Trichel pulses. These bursts can be clearly seen in Figure 2.5.9. Figure 2.5.10 shows a typical double pulse that looks as though the larger pulse (2) was triggered by the smaller pulse (1) which is similar in size to the already established Trichel pulses. It appears that the air ionized at the tip to start a Trichel pulse and then approximately 45 nanoseconds later (Figure 2.5.10) the smoke in the gap ionized. Due to their erratic behaviour, these larger secondary pulses may also be negative streamers triggered by the smoke. The double pulse consistently coexisted with the existence of an air gap between the tip and the smoke such as shown in Figure 2.5.6.
Three possible theories to cause the second ionization with the smoke are:

1. Collision ionization where electrons from the first pulse have attained enough kinetic energy to ionize smoke molecules as they traverse the gap.
2. Field induced ionization where the advancing negatively charged ion cloud generated by the small pulse (1) increased the electric field strength in the gap high enough for smoke molecules to ionise.
3. Photoionization similar to that described in [67] where photons from excited air molecules cause further ionization. In this case photons from the first discharge ionized smoke molecules.

The plume is also hot and is therefore expanded and less dense than the surrounding air and it is known that lower density gases independently favour early discharge onset voltages [60] [80] [66]. Therefore the electric field required to ionize hot smoke is less than that required for production of Trichel pulses.

The form of the second pulse is more symmetrical than the Trichel pulse. This is attributed to the much quicker decay time of 60 nanoseconds (Figure 2.5.11) versus 140 nanoseconds for a small to 180 nanoseconds for a large TP (Figure 2.2.15). The shorter decay shows that ions were swept from the gap more quickly for the second pulse than for TPs. A reason for this shorter time may be that the second discharge occurred closer to the plane electrode. Overall time for the double pulse is about 150 nsec which is similar to a standard TP. Figure 2.5.14 shows an overlap of a Trichel pulse (scale: x2) onto a double pulse to show the overall duration of the pulses are similar.

![Figure 2.5.14](image)

*Figure 2.5.14* A typical Trichel pulse overlaid onto a double pulse from smoke in a discharging gap. TP scale: 500 µA/div. Double pulse scale: 1000 µA/div. Horizontal scales: 100 nsec/div.
It is also interesting that the total charge Q in the first pulse A₁ (18 pC) was about half that of the first part of the second pulse A₂₁ (41 pC) and this is half the charge in the decay part A₂₂ (81 pC) of the pulse (Table 2.7). This binomial multiplication may be coincidence, or it may be possible that the A₁ charges cause a two for one multiplication to obtain the second peak followed by another two for one multiplication for the tail part of the current pulse.

The calculated rate of current rise for pulse ‘1’ is 12.5 uA/nsec which is slow when compared to similarly calculated rise rates of 45.3 uA/nsec for Trichel pulses and 45.0 uA/nsec for pulse ‘2’ where these values are suspected to be the rate limit of the measuring system. The small difference of 0.3 uA/nsec between the measurements was most likely due to inexact estimations of the triangles used to calculate the pulse areas.

### 2.5.4 Summary

An experiment to investigate the effects of smoke entering a point-plane gap with and without discharges has been done. It is found that smoke causes the early onset of discharges only when the smoke in the gap enveloped the tip of the pointed electrode. It was also found that double peaked current pulses occurred when smoke entered a discharging gap and these discharge current pulses were up to four times the magnitude of Trichel pulses from the same point and gap. The envelope of Trichel pulses over 100’s of AC voltage cycles shows that the magnitude of the current pulses is voltage dependant.

### 2.6 Conclusion

In this chapter corona discharges with point-plane gaps with spacing up to 16 mm were investigated using 50 Hz AC applied voltage. Corona discharges were also investigated with 0.2 mm thick SiR over the plane electrode and the effects of smoke entering the gap was also explored. In the next chapter (Chapter Three) corona discharges from water drops between metal electrodes, and corona discharges from between water drops on the surface of SiR in a radial electric field are investigated.
Chapter Three

WATER DROP CORONA DISCHARGES

3.1 Introduction

In Chapter One many authors identified water drop corona as a major cause of deterioration to the surface of silicone rubber high voltage insulation. Previous researchers, including Moreno [29], Gorur [81], Braunsberger et al [82], and Philips et al [46], confirm water drop corona discharges degrade the surface of high voltage SiR composite insulators. In this chapter water drop corona discharges are further reviewed. Several experiments involving various sized water drops between metal electrodes, and water drop to water drop corona discharges on surface samples of silicone rubber with radial electric fields provide further insights into the movement and behaviour of water drop corona discharges.

A literature review of electrified water drops

3.1.1 Isolated water drops in an electric field

Water is polar and the shape of a water droplet is influenced by an electric field. A water drop elongates and contracts in the direction of the electric field. If the surface charge on the drop is high enough the drop becomes unstable and it disintegrates into smaller droplets. This instability phenomena was first described by Lord Rayleigh [83] in 1882 where he defined the maximum charge a water drop can hold before it becomes unstable: For a spherical drop, the total surface charge $Q$ to render it unstable was defined as follows:

$$ V = \frac{Q}{a_0} = (16a_0T)^{1/2} $$

Where:

- $Q$ is the charge in Coulombs
- $a_0$ is the surface area of the drop (cm$^2$)
- $T$ is the surface tension (CGS units)

For example, for a 1 mm diameter drop with $T = 81$ (C.G.S.) the potential in electrostatic units is equal to 20 V. The following description is quoted from Lord
Rayleigh [83] with reference to a water drop becoming unstable: “Under these circumstances the liquid is thrown out in fine jets, whose fineness, however, has a limit.” Further works included the analytical derivation of the polar elongation of the drop using Laplace’s series and included harmonic vibration modes.

Latham and Roxburgh [84] studied the disintegration of pairs of water drops in the early 1960’s and derived a numerical formula for the elongation of the drops as a function of their separation distance and background electric field. If the drops were less than one diameter apart, the discharging jet would penetrate the air film separating the drops thereby promoting their coalescence. Latham concluded by stating that the drops can have an appreciable amount of charge on them even if the background field is weak.

### 3.1.2 The Taylor cone and cone jet

Sir Geoffrey Taylor [85] in 1964 reviewed many previous works on electrified water drop distortion and disintegration and found that the water drop surface does indeed become unstable in a localized electric field at Rayleigh’s criteria for instability. Taylor’s experiments showed that the surface of the elongated drop in an electric field produced a cone shape with an angle of approximately 49.3 degrees prior to ejecting a fine jet of liquid from the conical apex. Taylor’s work proved that the surface of a water drop can exist in equilibrium at this angle and it is not a complex dynamic phenomenon of drop instability. This phenomenon is known as a ‘Taylor cone jet’.

![Figure 3.1.1](image)  
**Figure 3.1.1** Electrohydrodynamic atomization of a fluid via a Taylor cone jet.
Figure 3.1.1 from [86] shows an image of a Taylor cone jet formed in DC electric field and shows negatively charged nanodroplets forming some distance away from the Taylor cone fluid jet.

An interesting outcome from Taylor’s review is that the drop becomes unstable when the length is 1.9 times its equatorial diameter and this result was shown to be accurate to within 1 % in laboratory experiments for distilled water. The electric potential of an isolated water drop in an electric field can be estimated by observing and calculating the elongation of the isolated drop in the background electric field. If the drop disintegrates, then the charge on the drop exceeded Rayleigh’s criteria for drop stability at that location.

### 3.1.3 Distortion of water surfaces by electric fields

The distortion of a water surface by a perpendicular alternating electric field, with frequency varied in the range 20 Hz to 300 Hz, was studied by Robinson et al [87] [88] during the development of a novel ozone generator using a 6 mm wide water channel as an electrode. It was shown that the breakdown voltage was dependent on the frequency of the applied electric field.

For higher frequencies, the entire surface bulged toward the upper electrode. The height of the water surface rose 1.9 mm at 300 Hz, and 3.0 mm at 20 Hz, before exhibiting sharply pointed cones which were observed approximately 12 mm apart. A spark was found to always be accompanied by the appearance of a distinct conical projection from the top of the raised water surface (Taylor cone) and that the breakdown voltage was independent of polarity. Once sparking occurred, the regular cone shape was lost. No corona was observed visually or was detected in the current before the conical peak occurred. The instant of sparking was assumed to be the peak electric field strength. Although the breakdown field increased with increasing frequency, the instant of sparking remained in a constant position slightly lagging the applied voltage peak.

It was also shown that the breakdown voltage was independent of water drop resistivity over the range tested, and the same magnitude of breakdown voltage was observed for tap water with resistivity of 35-40 Ωm as for distilled water with
resistivity of 440-12000 \( \Omega \) m. At all frequencies tested (200 Hz to 300 Hz) the breakdown voltage was less than expected in air over metal [88].

### 3.1.4 Acoustic emission from water drop discharges

Water drops on high voltage transmission lines were studied by Roero and Teich [32] to determine the acoustic emission from water drop discharges following complaints of noisy power lines after cessation of rain. Roero and Teich [32] thought that the acoustic signals from the discharges could be resolved and used to provide an indication of the size of the water drop and surface condition.

![Figure 3.1.2](image)

**Figure 3.1.2** Water drop resonant frequency for various water drop radii.

Figure 3.1.2 from [32] shows the measured resonant frequencies for water drops and shows the bigger the water drop the lower the resonant frequency. For example: On high voltage transmission lines a 0.60 mm radius drop has a resonant frequency of 120 Hz, and a water drop of 1.27 mm radius has a resonant frequency of 80 Hz. It was also shown that small amplitudes of electric fields produced higher frequency resonances. Figure 3.1.2 shows that water drops between 3 mm and 6 mm in diameter will resonate at the supply frequency of 50 Hz. Noise emission and time taken for the drops to dry was also monitored and charts were produced for audible noise levels on both hydrophobic and hydrophilic surfaces. It was shown the more hydrophobic the surface the longer the dry-out period.

Figure 3.1.3 shows typical dry-out times are 12 minutes for hydrophilic surfaces and 42 minutes for a hydrophobic surfaces. It is possible that water drop discharges on
good hydrophobic insulators will occur for a longer time (~ 36 minutes) than on degraded insulator surfaces (~ 8 minutes). Sound emissions were coincident with an observed discharge at short distances.

Figure 3.1.3 Decay of sound level after cessation of rain for an aluminum tube with different surface treatments and coatings.

### 3.1.5 Water drops in electric fields perpendicular to a surface

Distortion of stationary water drops in perpendicular DC electric fields have been studied by Sugimoto et al [89]. It was shown that the Taylor cone peak formations, shown in Figure 3.1.4 at time instances T1, T2, T3, and T4, coincided with Trichel pulse groups observed in the current oscillograms shown in Figure 3.1.5.

Figure 3.1.4 A water drop under the influence of an DC electric field at 17 kV. Discharge current pulses were detected at T1, T2, T3, and T4. Gap from top of drop to top electrode without applied voltage = 2.0 mm. Corona discharge inception voltage ~ 17 kV.<sub>dc</sub>. 
The water cones tended to return to the initial ellipsoidal surface with a decrease in height after emission of fine droplets. The loss of fluid from the drop during the discharge resulted in the drop decreasing in size. As the drop decreased in size the gap between the drop surface and the metal plane electrode increased and increasingly higher voltages were required for discharge inception. The first pulse was about 200 \(\mu A\) in height and less than 1 microsecond in width.

Roero [90] also studied water drops in a DC fields and showed that the instability of a water drop in a perpendicular electric field was dependent on drop size, surface condition, and electric field strength. It was also shown that as insulator surfaces age and become less hydrophobic, the size of the water drops increase and the gaps between them decrease which increases the electric field strength between them which lowers their instability voltages. The area of surface damage from the water drop discharges was found to increase and spread with continuous discharge activity.

3.1.6 Water drops in electric fields parallel to a surface

Krivda and Birtwhistle [91] [92] have experimented with coalescing water droplets on a flat silicon rubber insulator surface with an alternating electric field parallel to the SiR surface and showed the drop can wobble at harmonic and sub-harmonic (25Hz) vibrations of the applied alternating voltage.
During clean fog experiments, individual drops formed onto the surface of SiR. The drops vibrated and were often found to coalesce into larger drops at the positive and negative peaks of the applied voltage. As drops coalesced into larger drops they moved away from the electrodes into the lower field region while new drops were being formed in the high field region. The larger drops formed a curved line approximately 9 mm away from the electrodes. Water drop size, wetting angle, purity, and surface tension were stated to be contributing factors.

It was shown that the larger and flatter the water drops the less distance existed between them. As the distance between the water drops decreased, the strength of the electric field between the drops increased for fixed applied voltage.

Krivda and Birtwhistle [91] [92] also experimented with a single water drop on the surface of a sample of SiR insulation in a parallel 50 Hz alternating electric field. Small discharges were observed at the SiR-air-drop triple junction interface at the base of the drop during their experiments. Upon removal of the drop, spots of carbon and surface damage were observed on the SiR surface in the form of a ring where the drop was located.

Zhu et al [93] [33] studied corona discharges from water drops with conductivities of 2.0 µS/cm (ion exchange water), 800 µS/cm (salt water), and 20 mS/cm (sea water) on the surfaces of cylindrical test samples of SiR to simulate the sheath region between the weather sheds of real insulators, with a 60 Hz alternating electric field parallel to the cylindrical surface. Drops sizes ranged from 30 µl to 100 µl. Discharge current was measured with a 50 Ω series resistor.

Using a high speed camera, the behavior of water drops was observed and simultaneously recorded with the corona discharge current. They found that the water drops vibrated and elongated in the direction of the electric field and the drop surface tended to pull towards the positive electrode. The reason for the attraction to the positive electrode was that the drop must have been negatively charged at the time.

Figure 3.1.6 from [33] shows the distortion of a charged drop at 23 kV just prior to the drop discharging. The time instances shown on the images correspond to those shown in the 60 Hz waveform.
Several corona pulses were shown over several milliseconds for each light emission from the discharge. The first pulse was higher in magnitude than the succeeding pulses and was approximately 2 mA in magnitude. The following repetitive pulses displayed varying magnitudes from about 200 µA to 1000 µA. The current pulses did not appear the same as the well-defined groups of pulses shown in Figure 3.1.5 for a perpendicular electric field.

It was suggested that the region at the SiR-air-drop triple junction interface had the highest electric field intensity due to their different relative permittivities. This triple junction location for discharge activity agrees with the findings of Krivda and Birtwhistle in [91] and [92].

It was also shown by Shaowa et al [30] in a similar experiment that corona occurs at the tip of a distorted water drop and that this corona destroys the hydrophobicity of the polymeric insulator surface, and that this loss of hydrophobicity causes further drop elongation. For their experiments, the discharge inception field strength occurred between 10 kV/cm and 15 kV/cm when the water drops were about 3.5 mm apart, and about 6 kV/cm when the drops were 2 mm to 3 mm apart. In a single water drop experiment between circular electrodes, Phillips et al [43] calculated the electric field gradient at the drop surface to be about 12 kV/cm which is in the range 10 kV/cm to
15 kV/cm calculated by Shaowa et al. Shaowa et al [30] concluded that the electric field strength should be limited to 5 kV/cm at end fittings to improve long life performance for polymeric composite insulators.

Using a digital video camera at 25 frames per second, Braunsberger et al [82] showed the stages of two water drops on SiR in an increasing parallel electric field between two electrodes 50 mm apart. Figure 3.1.7 is from [82] and shows these stages.

![Figure 3.1.7](image)

Figure 3.1.7 Two drops in a parallel electric field (a) Drops at rest between two metal plate electrodes 50 mm apart. (b) Increasing the applied voltage to approximately 14 kVrms distorts the two drops in the direction of the applied electric field. (c) Increasing the applied voltage further causes the drops to burst and split into smaller drops followed by flashover.

Braunsberger et al [82] also measured the partial discharge pulses from a single 80 µl water drop on the surface of SiR at 14.8 kV. Figure 3.1.8 is from [82] and shows the accumulation of discharge pulses that occurred during 1 minute of discharges. Note the symmetry of the discharges for both positive and negative half cycles.

![Figure 3.1.8](image)

Figure 3.1.8 Phase-resolved diagram of PD activity during one minute while applying voltage of 14.8 kV on a single water drop of 80 µl on SiR. Electrode gap = 50 mm.
3.1.7 Theoretical models of electric fields about water drops

Que and Sebo [94] developed a computer model that shows the electric field distortion due to the presence of a water drop on a horizontal surface of SiR using COULOMB electric field modeling software. Their models produced equipotential contours and shows comparative electric field distributions: these are reproduced in Figure 3.1.9.

Figure 3.1.9 Electric field distortion due to the presence of a water drop on a surface of SiR. (a) Equipotential contours for a perpendicular field. (b) Equipotential contours for a field parallel to the surface. É field lines shown dotted; Numbers show equipotential contours.

Figure 3.1.9 (a) shows the effect of a drop in an electric field perpendicular to the SiR surface such as for a drop adhered to the top or bottom of a weather shed, and Figure 3.1.9 (b) shows the electric field distortion for a drop in a field parallel to the SiR surface simulating a drop on the vertical cylindrical sheath part of an insulator.

The results show the distortion of the electric field in the presence of a water drop and that the highest electric field gradient for the perpendicular field was at the top of the drop arrowed in Figure 3.1.9 (a). This location is where Taylor cones can be seen to form in Figure 3.1.4.

For the field parallel to the surface it can be seen in Figure 3.1.9 (b) that the highest electric field gradient is at the circumferential triple junction interface where the surface of the drop meets the SiR surface (arrowed). Discharges at this triple location have been observed by Krivda and Birtwhistle [91] [92], Braunsberger et al [82], Zhu et al [33], and Phillips [43].
Braunsberger et al [82] also produced a simple mathematical model of the electric field about a water drop on an insulator surface for both parallel (horizontal) and vertical (perpendicular) applied electric fields as the first part of a larger experiment in an attempt to correlate partial discharge with loss of hydrophobicity. A high resolution video camera at 25 Hz was used to show the water drop behavior in an electric field but this produced insufficient information to show the various oscillatory movements of the drop.

In 2004, Langemann created a mathematical model of a droplet moving in a parallel electric field [95]. The deformation of the droplet was calculated together with the total force acting on the whole droplet. This work was done on a horizontal plane and excludes adhesive forces. The shapes produced agreed with shapes of water droplets described and shown in references [87] [26] and [91] of actual water drops. A visual graphical representation provided the force distribution and electric field strength at the surface of a water drop.

No modeling was done in [95] for a water droplet on a vertical surface although mention was made that asymmetrical shapes should be expected in positions other than the general horizontal position. The comment was made that there appeared to be a lack of experimental data to support the models.

### 3.1.8 Characteristics of water drops in an electric field

Research described in this review provides results about many characteristics of electrified water drops. Some of the most interesting of these are summarised below:

- The dynamics of the water drops on a surface of SiR in an alternating electric field can distort the drop to produce dynamic shapes such as sideways wobbling. Other modes of harmonic and sub-harmonic vibrations of the applied frequency are also possible [92] [91].

- For each individual drop size a fundamental resonant frequency exists [32].

- Application of an electric field causes an isolated water drop to elongate up to 1.9 times its equatorial diameter. Further increasing the electric field creates a
Taylor cone with an angle of 49.3 degrees that jets fluid from the drop [85], [84].

- Surface tension reduction is proportional to the square of the applied voltage [96].
- Surface tension changes only slightly with conductivity [96].
- Surface tension changes with temperature which also changes the drop to SiR contact angle [97].
- Appreciable charge can be on isolated drops. This charge causes the surface of the drop to wobble in an alternating electric field [33].
- Charge can accumulate on a drop until the drop stability limit is reached then the drop disintegrates into smaller drops.[83]
- Charged drops evaporate slower than uncharged isolated drops. Typical values of charge could be in the order of $1 \times 10^{-10}$ Coulombs [98] (100 pC).
- For drops in a field perpendicular to the surface, Taylor cones are produced at the top of the drop [89] [88].
- For drops in a field parallel to the surface, the highest electric field gradient is at the SiR-drop-air triple junction interface [82] [91] [92] [33] [43].
- Discharges can occur between drops on hydrophobic surfaces and at the triple junction for hydrophilic surfaces [26].

### 3.1.9 Conclusion

Numerical modelling for water drops, so far, has been with electric fields parallel to the surface and with the electric fields perpendicular to the surface, simulating idealised conditions. Although the models provide critical background information on where discharges might occur, in reality the drops do not behave as ideal shapes; they wobble, coalesce, and move about in alternating electric fields. At this stage, there has been no thorough studies made of these phenomena, and there appears to be a lack of experimental data to support further modeling. Discharges that can transport charge from water drop to water drop can also distort these idealized electric fields.
Much work has been done on the testing of real insulators that confirms that surface degradation is consistent with discharges on wet insulators; some small scale experiments have shown static water drop discharges at the triple junction can also severely damage SiR insulator surfaces, but there is very little information available on this recently discovered phenomenon. No models have been specifically produced to study triple junction type discharges, or to study the interaction between discharges from wet metal fittings and water drops.

Unlike Trichel pulses and streamers, there has been very little research done on water drop corona discharge current pulses which may be significantly different to the current pulses from dry type discharges involving only metal electrodes. Therefore, there are also opportunities to further knowledge on some of the fundamentals of water drop corona especially on silicone rubber insulator surfaces.

To provide further insights into the behaviour and movement of water drops and the electrical discharges from water drops on the surfaces of silicone rubber insulation, it was decided to set up two experiments: The first experiment involves electrified water drops of various sizes and gaps with metal electrodes to simulate water drop discharges from a metal fitting; and the second involves a series of experiments to determine how water drops behave in non linear electric fields to better represent those that exist about real insulators. These experiments are described in the following sections of this chapter.
Experimental Work

3.2 Water drop to metal electrode corona discharges

This experiment is designed to study the behaviour of water drops in contact with a metal electrode; such as a wet metal fitting at one end of a SiR composite insulator. To maintain the precision of measurements for further comparative and analysis purposes the apparatus used the same power supply, measuring circuit, and insulated micrometer as the plane electrode experiments in Chapter Two.

3.2.1 Experimental setup

The experimental setup is shown in Figure 3.2.1, and Figure 3.2.2 shows the electrical circuit diagram. In Figure 3.2.1 the drop is held by a horizontal steel pin prepared with 1000 grit emery. It has a small upward bend at the end to hold the drop. The drops were salt water (1% salt by weight).

![Figure 3.2.1](image)

Figure 3.2.1 Experimental apparatus showing a 16 µl water drop on a wire electrode. The high voltage AC supply is connected to the plane electrode. Ambient: 31°C, 30% RH.

Each drop was hand placed for each experiment by successively picking up several small drops with a hooked copper wire applicator and then by wiping the drop upwards against the side of the electrode. The hooked wire consistently picked up drops of similar sizes. The final volume was built up by adding smaller drops to the drop already on the wire electrode. Drops ranged from approximately 1 µl to 16 µl.
The volume of each drop was approximated by overlaying circles onto video images and the equivalent spheroidal volume calculated. All dimensions were scaled to the diameter of the plane electrode (precision ground to 6.35 mm (1/4”)) from enlarged prints using a ruler. Considering the small camera angle error it is estimated that the measurement of the drop volume was accurate to ± 10% for drops greater than 6 μL. For smaller drops, the surface distortion at the wire-drop interface made the estimation more difficult and although extra attention was invested, a wider error (up to ± 20%) for the estimated volume for the smallest of drops must be expected.

The video camera image transfer rate was 30 frames per second. The exposure time was initially set to 12.5 milliseconds to cover the 10 millisecond half cycle and allow time for the image to transfer to the PC. Trials were conducted and the lens aperture was varied to allow small sparks to be observed as well as try to maintain a clear overview of the position of the drop within the gap without video detector saturation. The variations in tone are due to various aperture settings followed by basic image enhancements such as brightness and contrast to expose more clearly some of the more interesting characteristics. The camera was allowed to free run to ensure sequential information was captured over the entire 50 Hz waveform. During the thirty or so individual trials and experiments some videos missed the entire critical event while others revealed high quality information. A selection of the best images is presented in Figures 3.2.3 to 3.2.10.

![Figure 3.2.2](image_url)  
**Figure 3.2.2** Electrical circuit showing the location of the water drop and measuring points for the applied voltage V1 from the voltage divider and circuit current measured as voltage V2 across the 1 kΩ shunt resistor.
3.2.2 Images of water drops with metal electrodes

(a) A water drop of approximately 7.6 µl volume is initially hanging on the wire electrode with no applied voltage. The surface of the drop bulges slightly into the gap.

(b) Application of the voltage causes the water drop to stretch towards the plane electrode narrowing the gap. The drop wobbles slightly as it is suspended at an angle from the wire electrode.

(c) Further increasing the voltage to 4.2 kV$_{pk}$ causes the drop to stretch further towards the plane electrode. The drop wobbles with notable surface vibration. This is at the maximum voltage before the water drop leaves the wire electrode.

(d) Slightly further increasing the voltage to 4.4 kV$_{pk}$ causes the drop to lose its form and slips off the wire electrode. It begins to fall through the gap.

(e) The drop has cleared the gap without a spark, leaving the wire electrode slightly wetted.

Images (c), (d), and (e) are sequential video frames.

Figure 3.2.3 A 7.6 µl water drop under the influence of a 50 Hz electric field. Camera frame rate: 30 Hz, Shutter: 12.5 msec., 31°C, 30 % RH.
Figure 3.2.4 Successive images of a 6.0 µl water drop under the influence of a 50 Hz electric field. Camera frame rate: 30 Hz, Shutter: 12.5 msec., Ambient: 31ºC, 30 % RH.

(a) Discharge onset of a water drop of approximately 6 µl at applied voltage of 2.9 kV \(_{pk}\) causes the drop to wing towards the plane electrode narrowing the gap to approximately 4 mm. The drop wobbles as it suspends from the wire electrode.

(b) Slightly further increasing the voltage causes the drop to slip off the wire electrode, and jump the gap. It adheres to the plane electrode.

Images (b), (c), and (d) are sequential video frames.

(c) Final stages of corona discharge activity. Full conductive breakdown of the gap did not occur.

(d) The drop has jumped across the gap leaving the wire electrode wet. The transferred drop wobbles influenced by the 50 Hz alternating electric field with no discharges being detected.
It is remarkable that the water drop shown in Figure 3.2.4 transferred across the gap without causing full conduction breakdown to occur. To investigate if this was repeatable, another experiment was performed on the next day. Figure 3.2.5 shows the results of this other experiment with a similar sized water drop of approximately 6.0 µl in ambient conditions of 31ºC and 43 % RH jumping the gap again without causing full conduction at the approximately the same voltage (2.9 kV<sub>pk</sub>) as previously shown in Figure 3.2.4. This repeatability provided confidence of this result.

(a) Discharge onset of a water drop of approximately 6 µl at 2.9 kV<sub>pk</sub> causes the drop to stretch towards the plane electrode narrowing the gap to approximately 4 mm. The drop wobbles as it suspends from the wire electrode.

(b) Slightly further increasing the voltage causes the drop to lose its form and it slips off the wire electrode, jumps the gap, and adheres to the plane electrode without initiating full conductive breakdown of the gap.

Images (b) and (c) are sequential video frames.

(c) The drop has jumped across the gap leaving the wire electrode slightly wet. The transferred drop wobbles influenced by the 50 Hz alternating electric field with no discharges being detected.

Figure 3.2.5 Successive images of a 6.0 µl water drop under the influence of a 50 Hz electric field Camera frame rate: 30 Hz, Shutter: 12.5 msec., Ambient: 31ºC, 30 % RH.
(a) A water drop of approximately 3 µl is initially suspended on the wire electrode with no applied voltage.

(b) Application of alternating voltage causes the drop to elongate horizontally towards the plane electrode narrowing the gap. The drop vibrates axially as it suspends from the wire electrode. The onset of discharge current pulses are being detected.

Images (b), (c), and (d) are sequential video frames.

(c) A slight further increase in applied voltage causes the drop to be engulfed in electrical discharges and the formation of a heated channel can be seen.

(d) The drop has transferred to the plane electrode and a full conducting power arc is also established. Note the arc shape produced by the hot air in the channel rising.

Figure 3.2.6 A 3.0 µl water drop under the influence of a 50 Hz electric field. Camera frame rate: 30 Hz, Shutter: 12.5 msec., Ambient: 31°C, 30 % RH.
(a) A water drop of approximately 2.3 µl is initially suspended on the wire electrode with no applied voltage.

(b) Application of voltage causes the drop to elongate horizontally towards the plane electrode narrowing the gap to approximately 6.7 mm. The drop vibrates horizontally as it suspends from the wire electrode. Discharge current pulses are being detected.

(c) Increasing the applied voltage to approximately 5 kV\textsubscript{pk} dramatically increases stretching, decreases the gap to 6.3 mm, and increases discharge intensity. Images (c), (d), and (e) are sequential video frames.

(d) Without any further increase in voltage the drop stretches out with discharges commencing being clearly visible.

(e) The drop is seen engulfed with discharges as the drop disintegrates in the gap prior to conduction current beginning to flow between the electrodes.

Figure 3.2.7 A 2.3 µl salt water drop (1% wt) under the influence of a 50 Hz electric field. Camera frame rate: 30 Hz, Shutter: 12.5 msec., Ambient: 31°C, 30 % RH
Figure 3.2.8 A 1.5 µl water drop under the influence of a 50 Hz electric field. Camera frame rate: 30 Hz, Shutter: 12.5 msec., Ambient: 31°C, 30 % RH.

(a) A water drop of approximately 1.5 µl sits on the wire electrode with no applied voltage.

(b) Application of voltage causes the drop to elongate and vibrate horizontally back and forth with axial direction towards the centre of the plane electrode. The elongation and vibration narrows the gap to approximately 3.5 mm. Discharge currents are being detected.

(c) Further increasing the voltage causes the drop to slip off the wire electrode into the gap. The next frame was completely white from arcing in the gap.
Figure 3.2.9 shows a water drop that was initially 1.0 µl. As the drop evaporated the voltage needed to be increased to continue to observe negative water drop to metal plane discharge activity. Eventually a voltage was reached where a single transient sparks were observed.

![Figure 3.2.9](image1.png)

**Figure 3.2.9** A transient spark is observed to interact with an evaporating water drop with original volume of approximately 1.0 µl. Camera frame rate: 30 Hz, Shutter: 12.5 msec., Ambient: 31°C, 30 % RH.

![Figure 3.2.10](image2.png)

**Figure 3.2.10** Transient sparks observed between a wetted wire electrode and a metal plane electrode under the influence of a 50 Hz electric field. Camera frame rate: 30 Hz, Shutter: 12.5 msec., Ambient: 31°C, 30 % RH.
3.2.3 Water drop to metal electrode discharge current pulses

The water-drop-to-metal discharges are characterised by current pulse bursts consisting of a large initial pulse followed by a rapid series of pulses that successively increase in both magnitude and time interval and their form is found to be very similar to the groups of current pulses shown in Figure 3.2.5 by Sugimoto et al [99] during experiments with water drops in a vertical electric field using DC voltage.

Control of the AC voltage to sustain a water drop discharge prior to the drop breaking away from the wire electrode was difficult for small gaps due to the proximity of the drop to the plane electrode. The control of applied voltage to sustain water drop to metal discharges was easiest with gaps of approximately 7 mm and with the smaller sized drops. Figure 3.2.11 shows the current pulses captured by the oscilloscope during such an experiment with an evaporating 1.5 µL salt (1% wt) water drop.

![Figure 3.2.11](image)

Figure 3.2.11 Groups of current pulses from a salt water drop of approximately 1.5 µL. Reduced gap ~ 7 mm. (a) First pulse burst detected, and (b) established discharging drop.
Figure 3.2.12 shows several bursts of current pulses for a smaller drop and slightly smaller gap, and Figure 3.2.13 shows a burst of current pulses in detail and includes a general trend of the pulse peaks.

Figure 3.2.12 Bursts of current pulses from a discharging salt water drop to a metal plane electrode. Vol ~ 2.5 µL Reduced gap ~ 6.5 mm.

Figure 3.2.13 Detail of a typical water drop to metal electrode current pulse burst for a drop of approximately 1.5 µL. Reduced gap ~ 7 mm.

Figure 3.2.14 Typical small current pulses for the wetted electrode prior to the spark shown in Figure 3.2.9. Gap ~ 7 mm.

All bursts of current pulses for all drop sizes investigated were found to appear after the voltage peak in the second quadrant of the 50 Hz voltage cycle as seen in Figure
3.2.11 while the drop is negatively charged and the plane electrode is positively charged.

Voltage and current recordings for a spark breakdown of a gap of approximately 7 mm are shown in Figure 3.2.15. At approximately 1.2 milliseconds into the recording a dip in the supply voltage is clearly seen as the current pulse exceeds the 2000 µA input range of the oscilloscope. The dip in voltage is followed by a recovery of the voltage followed by another spark breakdown and then another and another. Sparking can be seen to continue during the next half cycle of opposite polarity. It was usually observed that the initial spark breakdown of the gap always occurred while the drop was negatively charged and the plane electrode positively charged as shown below.

![Figure 3.2.15](image)

**Figure 3.2.15** Current and voltage waveforms of a spark breakdown of a salt water drop to metal plane discharge for a drop of approximately 1.5 µL. The drop was discharging with a reduced gap of approximately 7 mm prior to sparking.

### 3.2.4 Observations and discussion

The drops were attracted to the plane electrode on both positive and negative half cycles of the applied voltage. This implies the polarity of charge on the drop reverses every half cycle to always maintain the attractive force. As the voltage is further increased the force of attraction increases and causes the drop to elongate narrowing the gap which further increases the attractive force between the drop and the plane electrode.

For all but the largest of drop sizes (7.6 µL) the drop started to vibrate and discharging commenced before the drop fell from the wire into the gap. As the drop left the wire under electrostatic attraction it would carry with it some quantity of charge.
The total force on the drop is the combination of the applied electric force in the horizontal direction and the vertical downward force due to gravity. A study of the images revealed the drop necks down and breaks near the wire electrode rather than the whole drop slipping off the wire which would have left the wire dry. Because the drops are always observed to leave the wire electrode wet, the force of gravity plus the electrostatic attractive force must be balanced by the surface tension of the liquid.

In Figure 3.2.7 (d) the drop is seen elongated. In the next image (Figure 3.2.7(e)) the drop is disintegrating in the gap. Latham [84] predicted water drops would disintegrate in an increasing electric field once the charge on the drop reached the Reliegh stability limit which was shown by drop elongated to 1.9 times the original spherical diameter of an isolated drop at rest. Figure 3.2.16(a) shows an enlargement of the disintegrating drop from Figure 3.2.7(d) and shows the drop elongation as it begins to disintegrate.

![Figure 3.2.16](image1.png)

**Figure 3.2.16** An enlarged view of the disintegrating water drop shown in Figure 3.2.7(d). (a) The 1.9 times Rayleigh criteria for drop disintegration in an electric field. (b) Measurement of the wavelength of the discharge spirals. Also shown is a hemispherical shaped region at the discharge site (1), and jets of water emanating from the disintegrating drop (2) and (3).
Indeed Figure 3.2.16 (a) shows the 1.9 times elongation stability criteria is fairly accurate even in these experiments. In Figure 3.2.16 (b) a hemispherical dome shape is identified and water jets are seen emerging as the drop begins to disintegrate. Spiral streamers with a pitch of approximately 1.6 mm can be seen bridging the gap. The diameter of the spiral is about the same diameter as the hemispherical dome shown as 1 which is also about the same diameter as the wire electrode. Rayleigh [83], and Latham and Roxburgh [84] reported violent surface vibrations prior to the cone jet forming under DC applied voltage. It may be possible that surface activity prior to the cone jet forming causes the spinning effect of the streamer. The rotating frequency of the spiralling is uncertain as numerous similar events have occurred within the exposure time. The speed of rotation is much too fast for it to be 50 Hz induced.

Analysis of the photographic images provides a means to approximate the reduced gap distance when the onset of discharging commences. As the drops vibrate axially when they are discharging the gap is also changing. In the images it can be seen that the location of the discharging site appears as a blurred region on the drop surface.

Figure 3.2.8 (b) shows a 1.5 µL discharging drop vibrating producing an unclear boundary while Figure 3.2.6 (b) shows a 3.0 µL discharging drop elongated in the electric field which appears almost stationary. The reduced gap measurements presented in Table 3.1 are therefore approximate measurements estimated from photographic images of the blurred boundaries of discharging water drops. It may be possible that the drop surface vibrates with frequencies other than harmonics of the applied voltage as the current bursts did not appear to be regular on the millisecond time scales studied.

**Table 3.1 Reduced gaps and discharge voltages for drops ranging from 0.1 µl (wetted electrodes) to 7.6 µL.**

<table>
<thead>
<tr>
<th>Reduced gap [mm]</th>
<th>Voltage [kVpk]</th>
<th>Size (ul)</th>
<th>Drop Transfer</th>
<th>Flashover</th>
<th>Ave Field Strength [kVpk/mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>5.0</td>
<td>0.1</td>
<td>N</td>
<td>N</td>
<td>1.3</td>
</tr>
<tr>
<td>7.0</td>
<td>5.8</td>
<td>1.0</td>
<td>N</td>
<td>N</td>
<td>0.8</td>
</tr>
<tr>
<td>3.4</td>
<td>2.4</td>
<td>1.5</td>
<td>Disintegrated</td>
<td>Y</td>
<td>0.7</td>
</tr>
<tr>
<td>6.6</td>
<td>4.8</td>
<td>2.3</td>
<td>Disintegrated</td>
<td>Y</td>
<td>0.7</td>
</tr>
<tr>
<td>6.3</td>
<td>4.4</td>
<td>3.0</td>
<td>Y</td>
<td>Y</td>
<td>0.7</td>
</tr>
<tr>
<td>4.1</td>
<td>3.0</td>
<td>6.0</td>
<td>Y</td>
<td>N</td>
<td>0.7</td>
</tr>
<tr>
<td>6.0</td>
<td>3.8</td>
<td>7.6</td>
<td>N</td>
<td>N</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Average: 0.8  Std deviation: 0.2
It was noticed that after leaving the wire electrode, some drops disintegrated in the gap, some transferred to the plane electrode, and some resulted in a flashover (FO).

Not all video clips captured the moment prior to the drop slipping off the electrode. Figure 3.2.17 is produced from Table 3.1 and shows an approximation from the initial and reduced gap for discharge onset for a range of drop sizes plotted against applied voltage and shows the instability voltages were close if not slightly less than the negative point-plane corona discharge onset voltages using metal electrodes. This lower inception voltage for water drops was also mentioned by Robinson et al [88].

Figure 3.2.17 Water drop to metal electrode gap versus applied voltage for several gaps for drops ranging in size 0.1 µL (wetted electrodes) to 7.6 µL. Corona discharge onset voltages V- and V+ for point-plane metal electrodes are shown for comparison.

Figure 3.2.18 shows the electric field gradient for all available data that included the critical moment which was calculated by simply dividing the applied voltage (kV) by the reduced gap measurement (mm).

To compare these results with other researchers it is important to understand the differences in their experimental setups. From Figure 3.2.18 it can be seen that, except for very small drop volumes which are in fact wetted electrodes, the average electric field gradient of about 0.7 kV/mm for the onset of water drop corona discharges agrees favourably with data researched by Moreno and Gorur [29] which is shown as a band in Figure 3.2.18 from 0.5 kV/mm to 0.7 kV/mm.
Shaowa [30] estimated a discharge onset field gradient of 0.6 kV/mm for drops 2 mm to 3 mm apart for drops on real insulators. From Figure 3.2.18 it can be seen that the recommendation by Shaowa in [30] for the maximum electric field gradient to be limited to 0.5 kV/mm to prevent water drop discharges seems reasonable.

For a 20 µl drop between fixed parallel plates on a section of SiR insulator, Philips et al [43] showed that the drop was stable up to a calculated field strength of 0.58 kV/mm. Further increasing the voltage to 0.68 kV/mm caused the drop to abruptly change shape and discharge current was then detected. Although the drop volume of 20 µl is off scale in Figure 3.2.18 the calculated electric field gradient of 0.68 kV/mm for drop instability by Philips et al is also in close agreement with the results of these experiments.

### 3.2.5 Conclusion

In this section single water drops with metal electrodes were studied which provided information about drop elongation and discharge current pulse groups for water drop to metal discharges over a range of gaps many times the diameter of the drop under test. The next section also involves experimental work; to further understand the movement of water drops, and to try to identify the location of water drop discharges, on the surface of SiR in non-linear electric fields.
**Experimental Work**

### 3.3 Water drop to water drop corona discharges

These experiments have been designed to study the behaviour of water drops and to examine the corona discharge current pulses that occur for water drops in a radial electric field on a 0.2 mm thick sheet of SiR. The setup is designed to simulate parts of an insulator that are adjacent to the high voltage metal end fitting where highly non-linear electric fields exist.

#### 3.3.1 Experimental Apparatus

Figure 3.3.1 and Figure 3.3.2 show the experimental apparatus. The circular electrode was made by smoothing the sharp inner edges of a 17.5 mm ID stainless steel washer with 1000 grit emery. A 3 mm wide copper flexible braid was silver soldered to the outer edge for connection to the high voltage supply. The flexible lead permitted the outer circular electrode to be lifted to change the SiR sheet between experiments.

![Figure 3.3.1 Section view of experimental apparatus showing high voltage power supply and current measurement circuitry.](image)

Each sheet of SiR was prepared by using a drawing compass to draw a circle 38 mm in diameter which was used as a guide to concentrically align the electrodes. The hole pierced by the drawing compass was used for the centre electrode. The apparatus was illuminated with a 50 Watt quartz halogen lamp on a stand positioned at various
angles and distances from the apparatus during the experiments. The drops used in these experiments contained salt 1% by weight.

**Figure 3.3.2** Plan view of experimental apparatus showing two isolated water drops.

The apparatus was tested by placing small drops about 2 mm in diameter onto the surface of the SiR. The drops were sized not to exceed the 2 mm height of the outer electrode. The drops were observed via the video camera as the 50 Hz alternating voltage was applied. The positions of the drops were initially at one third radius, half radius, and two thirds radius from the centre electrode. These positions can be used as a guide as to where the drops are in relation to the conductors.

The main aim of these experiments was to study the movement of water drops, and the locations of the discharges with various drop configurations. Thirty experiments were conducted of which every frame from each video was carefully examined for discharge activity.
3.3.2 Water drop elongation in a radial electric field

Figure 3.3.3 shows two drops placed on the apparatus. In (a) the drop on the left side is positioned with its centre at approximately half the inside radius of the outer electrode (~ 4.4 mm from the centre of the wire electrode), and the drop on the right side is positioned approximately at one third radius from the centre of the wire electrode. The drops were approximately 2 mm diameter when hand placed from a wire hook onto the SiR. The drops reduce in size due to evaporation, sometimes lasting only 5 to 10 minutes. The rate of evaporation is dependent on the charge on the drop and the conditions at the drop surface-to-air interface which includes temperature, pressure, humidity, and air velocity.

Figure 3.3.3 Two small water drops subject to 50 Hz alternating electric field. Ambient: 16.3 °C, 40% RH.
3.3.3 The movement of water drops in a radial electric field

In Figure 3.3.4 one drop is placed against the centre conductor and the other is placed to create a gap of approximately 2 mm between the drops. The voltage is raised until discharge current pulses are detected and then held steady (~ 4 kV\textsubscript{pk-pk}). Figure 3.3.4 shows selected video frames of the movement of these water drops with 14.3 milliseconds of open shutter time.

![Figure 3.3.4](image)

**Figure 3.3.4** Behavior of a water drop in contact with the centre electrode and an isolated water drop in a steady AC electric field on the surface of SiR (a) A water drop against the central conductor and an isolated water drop with zero applied voltage. (b) Increasing the applied voltage to approximately 2 kV\textsubscript{pk} causes discharges to occur between the water drops. (c) Discharges between the drops begin the coalescence process. (d) The two drops coalesce to form one drop. (e), (f), (g) and (h) Coulomb forces act to draw the drop toward the outer electrode. (i) Radial movement of the drop ceases when the circuit breaks from the centre electrode. Time stamp = 18.88 seconds. Ambient: 16.3 °C, 40% RH.
3.3.4 Surface geometries of water drops in a radial electric field

Two water drops were placed on the surface of the SiR as shown in Figure 3.3.5. One drop is placed against the centre conductor and the other is placed 90 degrees radially to it at approximately 2 mm away from the centre conductor. The insert is a reflection from the 50 Watt quartz halogen lamp which is used to show drop surface movements during the application of alternating voltage. Discharges from the SiR-drop-air triple junction interface can be seen arrowed in Figures 3.3.5 (c) and (d).

Figure 3.3.5 Surface distortion and vibration of two water drops on SiR insulation with increasing applied alternating voltage. (a) Zero applied voltage, (b) Surface wobbles reflect a triangular shape locus at approximately 3 kVpk (c) Surface vibration is simple linear oscillatory motion with the detection of discharges (arrowed) at approximately 5.0 kVpk (d) Further increasing the voltage to approximately 5.2 kVpk (e) Flashover (f) conduction current (g) Cooling (h) Stable. Open shutter time: 150 msec., Ambient: 21 °C, 64 % RH.
3.3.5 Water drop discharges for an isolated drop between a wetted inner electrode and dry outer electrode

In Figure 3.3.6 a small water drop was positioned against the central conducting electrode and an isolated drop of approximated 2 mm diameter was positioned to create a gap of approximately one millimetre between drops. Increasing the applied voltage produces repeatable water drop to water drop, and water drop to metal type discharges as shown in Figure 3.3.6. Discharges between drops are not always observed in the same frame as the discharges that are indicated with arrows.

![Figure 3.3.6](image)

**Figure 3.3.6** Discharges between water drops and discharges between water drops and metal outer electrode. (a) Zero applied voltage. (b) Negative point discharge from outer drop to metal outer electrode. (c) Discharges between drops and outer electrode. (d) Increasing the applied voltage to approximately 5 kV\textsubscript{pk} intensifies discharge activity. (e), (f), and (g) Positive streamers between metal outer electrode and the isolated water drop. (h) Conduction current flows. Open shutter time: 200 msecs. Ambient: 18 °C, 47 % RH.
3.3.6 *Water drop discharges between an isolated drop and wetted electrodes with the isolated drop close to outer wetted electrode*

To provide only water drop to water drop corona discharge current pulses, a water drop was placed against the central conducting electrode and another was placed against the inside surface of the outer conducting electrode then an isolated drop was placed as shown in Figure 3.3.7(a).

**Figure 3.3.7** An isolated water drop between wetted electrodes. (a) Zero applied voltage. (b) Inner and isolated water drop stretch and elongate closing the gap between them. Discharge onset is detected. (c) and (d) A slight increase in voltage causes intense discharges to occur between the wetted electrodes via the isolated drop. (e) and (f) The isolated drop disintegrates and conduction current flows boiling the water. (g) and (h) Cooling after removal of applied voltage. Open shutter time: 150 msecs. Ambient: 21 °C , 64 % RH.
3.3.7 Water drop discharges between an isolated drop and wetted electrodes with the isolated drop close to the inner wetted electrode

A water drop was placed against the central conducting electrode and another was placed against the inside surface of the outer conducting electrode (shown dotted) then an isolated drop was placed close to the inner drop as shown in Figure 3.3.8 (a). Then the applied voltage was increased until discharges were detected.

![Figure 3.3.8](image)

Figure 3.3.8 An isolated water drop between wetted electrodes. (a) Zero applied voltage. (b) The isolated water drop elongates and discharges are detected. (c) to (e) Discharges between water drops. (f) Discharging after 8 minutes. (g) evaporation caused discharging to decrease in intensity. (h) A slight increase in voltage causes disintegration resulting in a flashover. Open shutter time: 0.2 sec. Ambient: 18 °C, 47 % RH.
3.3.8 Dry-band type arcing

In Figures 3.3.5 to 3.3.8 it is shown that a flashover usually occurs after the drop disintegrated. This flashover usually causes conduction current to flow which concludes the experiment. However, in some experiments the flashover occurred followed by a different mode of discharging, rather than the full conduction current. This later mode of discharge appears similar to dry band arcing, where multiple discharges appear across a wide band with hydrophilic surfaces. Figure 3.3.9 shows the result of two water drops disintegrating followed by dry band type arcing.

![Dry band arcing following water drop disintegration](image)

Figure 3.3.9 Dry band arcing following water drop disintegration.

In Figure 3.3.9(a) water drops were placed onto the SiR surface immediately following a previous similar experiment and shows the loss of hydrophobicity (arrowed) caused from the previous experiment, prior to energization. Loss of hydrophobicity can be observed at the discharging locations arrowed in Figure 3.3.9 (b) prior to the drop disintegrating. The white arrow in Figure 3.3.9 (b) shows a discharge initiating from the centre metal electrode. In Figure 3.3.9 (c) the isolated drop can be seen skating to the outer wetted electrode. In Figure 3.3.9 (d) the inner
drop touching the centre electrode begins to disintegrate; it looks as though it is starting to boil (>100 °C). In Figure 3.3.9 (e) fluid connects the inner and outer electrodes, and in Figure 3.3.9 (f) arcing commences at two locations. The arcing lasted for about 100 to 200 milliseconds then quickly stopped once the gaps between evaporating drops exceeded the discharge threshold voltage (Figure 3.3.9 (h)). The drops continued to evaporate during the next 14 seconds to Figure 3.3.9 (i).

### 3.3.9 Current pulses and observations

The applied voltage was held steady and the oscilloscope manually triggered to capture current pulses; the representative water drop images that are referred to in this section were taken over several cycles during the experiment. Figure 3.3.10 shows an envelope of approximately 1 second of the applied voltage and current pulses recorded during the experiment shown in Figure 3.3.6. It can be seen in Figure 3.3.9 that large discharges up to 2000 µA occurred during the positive half cycle, while the outer electrode was positively charged; and discharges of less than 100 µA occurred during the negative half cycle while the outer electrode was negatively charged.

![Figure 3.3.10](image)

**Figure 3.3.10** 1 second envelope of current pulses recorded during the water drop discharge experiment shown in Figure 3.3.6.

Figure 3.3.11 shows current pulses recorded about the time image (b) in Figure 3.3.7 was taken. Figure 3.3.7 (b) shows the inner and isolated drops elongated in the electric field with the tips of the drops formed similar to Taylor cones with the apex of the cones touching the SiR surface and pointing toward each other; Figure 3.3.11 shows the discharge current pulses detected for both half cycles of the applied voltage.
Figure 3.3.11  Current pulses observed during the water drop discharge experiment shown in Figure 3.3.7.

Figure 3.3.12 was taken about the same time as image 3.3.13(a) was taken and shows a single-shot acquisition of a group of pulses similar to the water drop to metal discharges shown in Figure 3.2.11(b), except they occurred during the negative half cycle of the applied voltage.

Figure 3.3.12  First current pulses recorded for the experiment shown in Figure 3.3.13.

In Figure 3.3.13 it can be seen that a point is formed by the water from the wet outer electrode. From water drop to metal discharge experiments in Section 2 of this chapter it is known that these groups of current pulses occurred when the water drop was negatively charged which means the discharge must have come from a drop attached to the outer electrode. The location marked by the arrow shows a likely location for this discharge.
Figure 3.3.13 An isolated drop between wetted inner and outer electrodes. (a) At 1 minute (b) Maximum distortion of isolated drop prior to flashover. (c) First streamers commence as the isolated drop and inner drop coalesce.

The question arises why there are multiple pulses in this discharge when previous water drop to water drop experiments show single pulses… It may be that the anode was the metal wire electrode rather than the isolated and inner drop. Figure 3.3.13(c) shows a streamer bridging the metal electrodes by going over the inner drops. This should be taken as evidence that the inner drops may have had little involvement in the initial discharge shown in Figure 3.3.12 taken at the beginning of the experiment.

**Increasing the applied voltage**

Figure 3.3.14 shows envelopes of approximately 2 seconds for discharge current pulses recorded during a similar experiment shown in Figure 3.3.8 with two drops.

The applied voltage was raised until discharge current pulses were observed on the oscilloscope; then the voltage was held constant while the oscilloscope created an envelope of the current pulses. This envelope image was saved, then the applied voltage was raised further, held steady, and another envelope created and saved. This process continued until flashover occurred at about 3.4 kV.

The images shown on the left were taken from the video during the experiment. Although the images were taken to observe water drop movement and drop distortion, and are slightly over exposed to see the discharges (arrowed) clearly, they are presented here to match the envelopes of the recorded current pulses.
Figure 3.3.14 Envelopes of approximately 1 second duration of current pulses recorded during the water drop discharge experiment shown on the left. (a) 2.2 kV (b) 2.4 kV (c) 2.6 kV (d) 3.0 kV.
In Figures 3.3.8 (c) and (f) positive point type discharges can be seen at the triple junction (arrowed) which could account for the increased occurrence of discharges during the negative half cycle when compared to Figure 3.3.6 where no discharges at the triple junction can be seen; this does not mean that there were none, only that none can be seen in Figure 3.3.7. Figure 3.3.9 shows some discharges less than 100 µA during the negative half cycle of the applied voltage.

Positive point discharges can be seen from the metal outer electrode in Figure 3.3.15. In the image a discharge can also be seen at the triple junction from the isolated drop. It appears that negative charge accumulated on the drop surface has caused a high enough field gradient for positive point discharges to occur from the metal electrode.

![Figure 3.3.15](image)

**Figure 3.3.15** A two drop experiment showing positive point discharges from the outer electrode and a small discharge at the triple junction of the isolated drop.

Discharges occurring when the centre electrode was negative can be seen in Figure 3.3.8(g) and these are similar to the discharges shown arrowed in Figures 3.3.6 (b) and (c). In Figure 3.3.8 the discharges between the centre drop and the isolated drop appear to be slightly above the surface of the SiR whereas the positive point type discharges seen at the triple junction are on the surface of the SIR.

Figure 3.3.16 shows current pulses recorded for the experiment shown in Figure 3.3.5 where the only discharges found were at the triple junction shown arrowed in Figures 3.3.5 (c) and (d) on page 138.
Figure 3.3.16 Water drop discharge current pulses recorded during the experiment shown in Figure 3.3.5 involving a wetted centre electrode and an isolated drop. (a) Envelope from below onset to first pulses detected at about 4.9 kV. (b) Envelope as voltage was gradually increased from 4.9 kV to 5.2 kV.

Because the isolated drop is in the form of a Taylor cone, discharges are also expected to be occurring at the apex of the cone. Significant surface distortion can also been seen on the drop wetting the centre electrode providing an insight into the forces exerted by the electric field on water drops. The current pulses were singular in nature and occurred prior to the applied voltage peak; they did not appear in bursts or groups like the water drop to metal discharge current pulses in Figure 3.2.11 and Figure 3.2.12, which occurred after the peak voltage.

Comparing Figures 3.3.16 (a) and 3.3.16 (b) shows the discharge onset voltage (V1) does not change with increasing voltage, however, the onset voltages (V2 to V3) show the opposite polarity onset voltage increases with applied voltage. This phenomenon may be caused by the surface shape changing as the drop stiffens in the electric field, or could have something to do with accumulated charge on the isolated drop.
3.3.10 Charge transfer during coalescence of water drops

This experiment was aimed at obtaining the current trace during water drop coalescence. An isolated water drop was positioned between wetted electrodes and the applied voltage increased until discharges were detected (Figures 3.3.17 (a) and (b)).

![Figure 3.3.17](image)

**Figure 3.3.17** Water drop coalescence. (a) and (b) Discharges between water drops. (c) Drop to drop coalescence. (d) Intense discharge activity is detected between the coalesced drops and the wetted outer electrode. Open shutter time: 100 milliseconds. Time stamp: 1 min: 17.60 sec.

The oscilloscope trigger level was then increased to a level slightly above the trigger threshold for these initial discharges (~ 200 µA). The oscilloscope was armed for a single capture and then the applied voltage was slightly further increased. Figure 3.3.18 shows the current trace captured when the isolated water drop coalesced with the water drop attached to the centre electrode. After the drops coalesced the current pulses became larger (up to 1000 µA); this can be seen in the right hand side on Figure 3.3.18(a). The total charge transferred was approximately $4 \times 10^{-9}$ Coulombs.

![Figure 3.3.18](image)

**Figure 3.3.18** The measured current that occurred during water drop coalescence shown in Figure 3.3.17(c). (a) 1 msec/div. (b) Detail of coalescence pulse at 20 µsec/div.
3.3.11 Water drop to water drop discharge current pulses

In these experiments, current pulses from water-drop to water-drop discharges ranged in magnitude from about 100 µA to 1200 µA. Figure 3.3.19 shows a typical large current pulse from the experiment shown in Figure 3.3.10, and Figure 3.3.20 shows a typical small current pulse measured during the experiment shown in Figure 3.3.10.

![Figure 3.3.19](image)

**Figure 3.3.19** A typical large water drop to water drop discharge current pulse.

![Figure 3.3.20](image)

**Figure 3.3.20** A typical small water drop to water drop discharge current pulse.
3.3.12 Estimation of pulse charge $Q$

The total charge $Q$ per pulse is estimated by triangular approximation of the current pulse. Figures 3.3.21 and 3.3.22 each show the construction of two triangles A1 and A2 used in estimating the total charge $Q$ per pulse.

**Figure 3.3.21** Total charge $Q$ calculation using triangular method of approximation for a typical large water drop discharge current pulse.

![Figure 3.3.21](image1)

<table>
<thead>
<tr>
<th>Area</th>
<th>pC</th>
<th>Elementary charges</th>
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<td>115</td>
<td>$720 \times 10^6$</td>
</tr>
<tr>
<td>A2</td>
<td>72</td>
<td>$450 \times 10^6$</td>
</tr>
<tr>
<td>Total Q</td>
<td>187</td>
<td>$1200 \times 10^6$</td>
</tr>
</tbody>
</table>

**Figure 3.3.22** Total charge $Q$ calculation using triangular method of approximation for a typical small water drop discharge current pulse.

![Figure 3.3.22](image2)

<table>
<thead>
<tr>
<th>Area</th>
<th>pC</th>
<th>Elementary charges</th>
</tr>
</thead>
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<td>$332 \times 10^6$</td>
</tr>
<tr>
<td>A2</td>
<td>10</td>
<td>$62 \times 10^6$</td>
</tr>
<tr>
<td>Total Q</td>
<td>63</td>
<td>$394 \times 10^6$</td>
</tr>
</tbody>
</table>
3.3.13 Comparison of discharge current pulses

Water drop to water drop corona discharge current pulses are different to current pulses produced by metal electrodes. Figure 3.3.23 shows a comparison between the two types. The metal point discharge was recorded during testing of the circular water drop apparatus without water drops. In these experiments the water drop discharge current pulses all had a slightly slower rise time, an extended peak (approximately 40 nsec for the typical larger pulses) with a slight inflexion, followed by a tail that clearly extends up to 5 times that of a metal electrode corona discharge current pulse.

![Water drop discharge current pulses](image)

**Figure 3.3.23** A comparison between water drop discharge current pulses and pulses from discharges between metal point-plane electrodes.

In a very recently published paper by Bruggermann et al [100] a current pulse from a water surface glow discharge was shown that also exhibited a similar extended tail. The extended tail shown in [100] was a continuation from an initial large current pulse (1A) to a steady state glow regime with current limited to about 300 mA, in contrast to the smaller (up to 1200 µA) single pulses found in these experiments with tail currents continuously reducing over several hundreds of nanoseconds.

Conceptually, the extended tail found in these experiments must be from a decaying process of electron conduction into the gap unique to the presence of the water.
3.3.14 Summary

For the water drop to metal discharges, the discharge current pulses appeared in groups after the peak voltage of the applied waveform, and the water drop to water drop discharges appeared as single pulses with an extended tail.

In addition, it was observed that the water drops can elongate, vibrate, and produce complex shapes when they are stressed by electric fields on the surface of SiR. While their ability to move, or skate, across the surface is related to the hydrophobicity, the amount of surface charge on the drop, and the electric field strength. Table 3.2 summarises some fundamental characteristics of the electrified water drops observed during the experiments in this section.

Table 3.2 Observed movements and discharge characteristics of water drops on a silicone rubber surface in a radial electric field.

<table>
<thead>
<tr>
<th>Inner electrode</th>
<th>Radial position of drop from centre electrode</th>
<th>Outer electrode</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1/3</td>
<td>1/2</td>
<td>2/3</td>
</tr>
<tr>
<td>Dry</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Dry</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Wet</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wet (small drop)</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wet</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wet</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Wet</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Wet (at 90°)</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It is of interest how the water drop discharges advance on the surface of the SiR and the relation to loss of surface hydrophobicity. From the observations studied in the experiments in this section, an interpretation of the fundamental steps of the water
drop advancing on the surface of SiR is as follows:

- Applying an alternating electric field to a water drop causes evenly distributed surface charge to divide and localizes on the surface of the drop and causes the drop surface to distort and wobble.
- Increasing the applied voltage causes the wobbling to become less and the drop appears to stiffen in the electric field.
- Further increasing the applied voltage causes localized instability on the drop surface. In the highest field region a Taylor cone protrudes from the drop surface onto the surface of the SiR; the discharge from the pointed tip sprays charged nano droplets across the surface of the SiR (Figures 3.3.7 (a) and (b), and Figures 3.3.17 (a) and (b).
- Extra charge may also be added to or subtracted from the surface of the drop, for example; from a nearby discharge, or by the drop collecting charge directly from the surface of the silicone rubber insulator.

The electrical forces exerted on the drop are also balanced by the surface tension of the drop, and the difference in surface energy between the drop and the SiR.

### 3.4 Conclusion

In this chapter water drop corona discharges were reviewed. This review was followed by experiments with single water drops between metal electrodes, and then by experiments with water drops on the surface of samples of silicone rubber insulation in a radial electric field. From these experiments it was discovered that the peak water drop discharge current pulses ranged in size from 100 µA to 1000 µA, and that the water drop discharges have some special additional features when compared to discharges between metal electrodes. From the study of the results of the experiments in this chapter four classes of water drop discharges have been observed:

1. Water drop to metal electrode type discharges.
2. Water drop to water drop discharges.
3. Triple junction type discharges; which appear to move across the surface of the SiR away from the triple junction.
4. Dry band arcing type discharges.
The water drop experiments presented in this chapter have provided new insights into
the fundamental shapes that water drops can form on the surface of SiR in a radial
electric field, and have provided further insights into the locations of where
discharges from water drops are likely to occur and how discharges can occur on real
insulators.

The images from the digital camera have provided information on the behaviour of
water drops in alternating electric fields, and on the surfaces of SiR. The camera also
has provided images of the corona from both dry and wet corona discharge
experiments. The corona from the discharges is known to be produced by light of
discrete wavelengths emitted from gas molecules and atoms that get involved in the
discharge. Therefore, to complete this study of the corona discharge phenomena,
further scientific investigation of the visible and ultra violet light emitted from the
discharge site is therefore necessary. Chapter 4 presents a study of the atomic and
molecular emission spectra from both dry and wet discharges.
Chapter Four

SPECTROSCOPIC STUDIES OF CORONA DISCHARGES

4.1 Introduction

In this thesis corona has been observed to occur from metal electrodes and from water drops. Although others have suggested that water drop corona is the cause of insulator degradation, the precise mechanism by which the degradation occurs remains unexplored. It is therefore of interest to determine the free radicals that are produced at the surface of insulators by water drop corona. In this chapter spectra of the ultraviolet and visible light emitted by these discharges are measured and active species present are identified from the spectra.

Before the spectral studies are described, previous spectral works about discharges in gases are reviewed. Fundamental data about the relevant properties of air and other molecules which may become involved in an electrical discharge are also reviewed. In addition, a summary of chemical reactions and emission spectra for corona discharges is presented.

A literature review on atomic emission spectra from corona discharges

4.1.1 Emission principles

In a discharge, gases in the high field region are subject to inelastic collisions from high speed electrons. Energy transferred to molecules in the air by these electrons causes excitation, dissociation, and ionization. Energy is released as the molecule or atom cools. This may be in the form of photons which are unique to each type of atom or molecule. Energy can be also reduced by quenching such as via collisional de-excitation with other electrons and molecules [59].

The electromagnetic radiation emitted in the visible and ultra violet part of the spectrum comes from fast changes in electron orbit configurations. The Born-
Opperheimer approximation and Franck-Condon principle assumes the heavier nuclei do not move during the very fast electronic transitions; hence, electronic transitions are drawn vertically on potential energy diagrams [101], and as illustrated in Figure 4.1.1.

4.1.2 Nomenclature

The nomenclature for the excited states of molecules and atoms has been enshrined in history and unlikely to change in the near future. For diatomic molecules, X is used for the ground state, A is used for the first excited state, B for the second, and so on; for example, the designation (A-X) is used for the transition from the first excited A state to the ground X state.

For each excited state there are vibrational modes; \( \nu = 0 \) is used for the lowest vibrational state, \( \nu = 1 \) for the first vibrational state, \( \nu = 2 \) for the next, and so on; \( \nu' \) is used for vibrational functions associated with the lowest excited state, and \( \nu'' \) is used for vibrational functions associated with the higher order excited state. The change is written \((\nu', \nu'')\). For example, the designation A→X(0→2) is used to show the electronic transition of electrons from their second vibrational mode in the first (A) excited state to the lowest vibrational mode in the ground (X) state of the molecule. Figure 4.1.1 has been drawn to show this example. \( D_0 \) is the dissociation energy required to separate the molecule into two atoms.

Figure 4.1.1 An example of a potential energy diagram for a diatomic molecule showing a 2.5 eV energy emission (arrowed) from the electronic transition A-X(0-2) .
In the case of nitrogen $\text{N}_2$, C-B(0-0) designates the electronic transition from the lowest vibrational level in the excited C state to the lowest vibrational level in the excited B state. For nitrogen, the energy emitted from the transition C-B(0-0) has a wavelength of about 337.1 nm. This line at 337.1 nm is often simply referred to as $\text{N}_2(0,0)$. The intensity of the radiation from a given transition is proportional to the square of the transition moment integral [101].

A potential energy diagram for oxygen $\text{O}_2$ is shown in Figure 4.1.2. Figure 4.1.2 is adapted from [101] and shows the ground state X, the first excited state A, and the second excited state. Energy in units of cm$^{-1}$ is on the left and in eV on the right. Oxygen also has three underlying ground states which are termed $a$ for the first excited X state, and $b$ for the second excited ground state. Electronic transitions are forbidden between the $a$, and $b$ excited states.

![Figure 4.1.2 Potential energy diagram for the oxygen molecule.](image)

In Figure 4.1.2 it can be seen that the oxygen molecule can dissociate into two excited oxygen atoms at about 5.16 eV energy ($\sim$2.58 eV each). The ($^3\text{P}$) and ($^1\text{D}$) relate to the configuration of the electron orbits for each oxygen atom. Further details of the electron configurations and associated orbits can be found in [101] and related texts. Excited oxygen atoms are also referred to as O* where the * denotes the excited state of the atom or molecule.
The name ‘band’ comes from the appearance of the bands of lines produced on photographic films by early spectrometers. A group of bands with $\Delta \nu = 0$ is called a sequence, for example; (0-0), (1-1), (2-2), etc., and a group of bands connected to the same vibrational level is called a progression, for example; (3-1), (2-1), (1-1), and (0-1).

The first positive system and second positive system of nitrogen both refer to the observed band systems produced by the excited state of the $N_2$ molecule. The first negative systems for nitrogen and oxygen refer to the observed band systems for the ions $N_2^+$ and $O_2^+$.

For hydrogen atom H, the lines $H_\alpha$, $H_\beta$, and so on, are in order of increasing energy. These lines were named by Johann Balmer who discovered an empirical formula to predict the Balmer series for the hydrogen atom in 1885.

### 4.1.3 Atomic emission spectra from corona discharges

Most of the radiation emitted from a corona discharge is in the ultra violet (UV) part of the electromagnetic spectrum for photons with wavelengths from 240 nm (5.13 eV) to 480 nm (2.57 eV). The visible portion of the electromagnetic spectrum lies for photons with wavelengths between 380 nm (3.26 eV) for violet and 780 nm (1.59 eV) for the far red [102].

Figure 4.1.3(a) shows a typical atomic emission spectra in the range 200 nm to 460 nm and Figure 4.1.3(b) 460 nm to 1100 nm for streamer corona (SC), transient spark (TS), and glow discharges (GD) for a 4 mm gap in air from a very recent (2007) publication by Machala et al [103]. The experiments utilized a pulsed (kHz) DC spark discharge chamber. The spectra were recorded with an OceanOptics 2000 spectrometer. The streamer corona SC is similar to the experiments done in Chapter Two for discharges in relatively dry air. The transient sparks TS are similar to the sparks shown in Figures 3.2.9 and 3.2.10 of Chapter Three, and a glow discharge GD is a sustained higher current discharge (> 1 mA) such as that which occurs in a fluorescent tubes or a sodium vapour lamps. Figure 4.1.3 is referenced in Section 4.2. The Y axis is arbitrary units (a.u.) of intensity. Figure 4.1.3 is referenced throughout Section 4.2 where the gases that get involved in corona discharges are reviewed.
Figure 4.1.3 Atomic emission spectra for three types of electrical discharges in atmospheric air. Fig. (a) Spectrum in the range 200 nm to 460 nm. Fig. (b) Spectrum in the range 460 nm to 1100 nm. SC – Streamer corona, TS – Transient sparks, GD – Glow discharge.

Fig. (a) Typical emission spectra of DC discharges in UV region (corrected for the spectrometer’s spectral response). Gap: 4 mm; SC: 26 kHz, $I_{\text{max}} = 25$ mA; TS: 1 kHz, $I_{\text{max}} = 1.5$ A; GD: $I = 6$ mA.

Fig. (b) Typical emission spectra of DC discharges in vis–NIR region (corrected for the spectrometer’s spectral response). Gap: 4 mm; SC: 26 kHz, $I_{\text{max}} = 25$ mA; TS: 1 kHz, $I_{\text{max}} = 1.5$ A; GD: $I = 6$ mA.
4.1.4 Data for air and other materials

The atomic emission spectra are produced by the gases involved in the discharge and the gases most likely to be involved in atmospheric air are those in the high voltage field gradients surrounding the pointed electrode. Apart from the metal vapor at the surface of the metal electrode the atmosphere about a point electrode consists mainly of nitrogen (78%), oxygen (21%), argon (0.9%), and smaller quantities of other gases include carbon dioxide (0.03%), krypton, xenon, neon, helium, and moisture.

Table 4.1 shows a collection of properties taken from the CRC Handbook of Chemistry and Physics [25] of the most common gases in atmospheric air which might be expected to be involved in a corona discharge. The first section (grey background), in order of decreasing abundance, lists gases found in atmospheric air at sea level. This is followed in Table 4.1 by a list of atoms (tan background) that are produced by dissociation of molecules contained in atmospheric air. Na⁺ and Cl⁻ ions occur in salty water and so sodium and chlorine are both included. Next (red background) are well known recombination byproducts from a gas discharge in air. Since this research is related to the degradation of SiR, data for silicon compounds and fragments of SiR (blue background) are included in Table 4.1. The electrical property of polarizability is included for comparison. Note that Na has a very high polarizability (24.11x10^{-24} cm^2), and that CO₂ also has a relatively high polarizability when compared to N₂, O₂, and H₂O.

In Table 4.1 all energy units have been converted to electron volts (eV) for the purpose of energy comparisons. For example; N₂ has thermal bond dissociation energy of 945 kJ/mol at 298 °K which is equal to electrical energy units of 9.79 eV. This is the minimum equivalent kinetic energy required to dissociate a nitrogen molecule into two nitrogen atoms. If more than 15.58 eV of kinetic energy is transferred to a N₂ molecule then the nitrogen will ionize. Similarly, only 5.16 eV of kinetic energy is required to be transferred to the oxygen molecule O₂ to dissociate it into two oxygen atoms O + O and 12.07 eV is required to ionize O₂ to produce O₂⁺.
Table 4.1 Properties of selected elements and compounds associated with corona discharges.

Grey – gases present at sea level
Tan – atoms produced by dissociation of atmospheric air molecules
Yellow – Sodium and chlorine associated with salt (NaCl)
Red – recombination byproducts for corona discharges in air
Blue – gas degradation byproducts of silicone rubber

Information for Table 4.1 was sourced from Ref [25].

Electronegativity is the interesting property of atoms and molecules that enables them to gain an electron to become a stable negative ion (Column 8 in Table 4.1) and is quantified by the Pauling scale. Electron Affinity is more useful (Column 7) as it defines the energy released when the atom or molecule X gains an electron in the following reaction:

\[ X + e^- \rightarrow X^- \]
This occurs in a corona discharge when the oxygen in the gap gains free electrons following the first avalanche process [66]. Nitrogen becomes unstable with the addition of an electron, in contrast to the oxygen ion which has a lower preferred state than the neutral oxygen, so the oxygen easily becomes negatively ionized which encourages the development of the space charge cloud that reduces the electric field intensity at the tip of the point electrode during the production of Trichel pulses.

It is interesting to note that Cl, Cl\textsubscript{2}, OH, and CO\textsubscript{2} all have an electron affinity greater than O or O\textsubscript{2}. It would therefore be expected that if these atoms and molecules are present in the discharge then they would also capture electrons and contribute to the development of negative space charge similar to oxygen.

An input of energy is also required to remove the electron from the negative ion as shown in the following reverse equation:

\[
X^- \rightarrow X + e^- 
\]

This process must occur when a mobile oxygen ion gives up its electron at the positive plane electrode (anode) after traversing the drift zone in the discharge gap.

### 4.1.5 Dissociation of molecules by electron impact

Not all the energy from the high velocity electrons in the high field region of corona discharges causes the dissociation of gas molecules. In a study of the efficiency of the dissociation of air molecules for industrial processes, using an electron beam, Eletskii and Smirnov [104] found that the type of gas mixtures can have a dramatic effect on the dissociation process efficiency. The process efficiency was defined as the ratio of energy introduced into the system to the amount of energy to produce the atoms by the dissociation process.

In [104] 100% CO\textsubscript{2} required approximately 68 eV of energy to dissociate one molecule of CO\textsubscript{2} to yield CO + ½O\textsubscript{2}. A CO\textsubscript{2}:He (40:10) mixture required an average electron input energy of approximately 113 eV. The optimum dissociation yield for CO\textsubscript{2} was 61% when the gas was prior heated to 3200 °K at 1 atmosphere pressure. For nitrogen in the discharge, at 300 °K the average input energy required was 370 eV, and 100 eV at 4900 °K which shows energy can be gradually added to the...
molecule by heat to assist dissociation efficiency. For oxygen in the discharge, the highest dissociation efficiency was 23% with a mixture of 21% oxygen (same % as in air) and 79% helium. For low gas pressures (0.1 to 10 Torr) 100% dissociation of oxygen was achieved at 3600 °K without any electrical discharges.

During heating, the gaining of energy for molecular dissociation proceeds via the increase of vibrational energy levels within the molecule. Besides the electric discharge and gas heating other causes of dissociation were also examined in [104], including UV radiation, and focused electron beam excitation. The most effective process for dissociation was shown to be by photon excitation when the surrounding gases are transparent and provide little attenuation to the critical dissociation wavelengths. The second highest efficiency for dissociation of air molecules was found to be heating by passing the gas over a hot plate.

4.2 Gases involved in corona discharges

4.2.1 Nitrogen and oxides of nitrogen

Nitrogen undergoes excitation, dissociation, and ionization by electron impacts within an electrical discharge. Ono and Oda (2002) [105] studied NO formation in a pulsed spark discharge in a N\textsubscript{2}/O\textsubscript{2}/Ar mixture of various relative concentrations, at atmospheric pressure with a tunable KrF excimer laser that produced light with wavelengths of 248 nm. NO (X,3) and O\textsubscript{2} (X,6) were measured by fluorescence as byproducts of the spark discharge. O\textsubscript{2} (X,6) was found to be excited through B-X (0,6) transition fluorescing with emissions at around 300 nm. Ono and Oda concluded that the NO production mainly came from collisions of excited nitrogen molecules with excited oxygen:

\[ \text{N}_2^* + \text{O}^* \rightarrow \text{N}_2 + \text{O}_2^* \]

Neither NO (X,3) nor O\textsubscript{2} (X,6) was produced with below 9% oxygen concentration. Both NO (X,3) and O\textsubscript{2} (X,6) increased in concentration linearly with O\textsubscript{2} concentration once the O\textsubscript{2} exceeded the 9% threshold.

In 2000, Rambo et al [106] used 248.6 nm, ultra short (200 x 10\textsuperscript{15} sec) laser pulses to produce ionization of atmospheric air during experiments aimed at producing laser-
induced lightning. The repetition rate of the laser pulses was 10 Hz. Their experiments were conducted in a cylindrical chamber with configurable gaps up to 42 cm between two circular plane electrodes of 15 cm diameter, each with a hole in the centre. One end of the cylinder was used for the laser and the other end of the cylinder was used for monitoring the emission spectra. Their spectroscope had a wavelength response ranging from 300 nm to 900 nm. Voltages of up to 200 kV DC were applied to the apparatus. From studies in air, Rambo et al [106] found that the N\textsubscript{2} molecule could be ionized and exist in the plasma prior to it dissociating into two nitrogen atoms.

From Table 4.1, dissociation of N\textsubscript{2} requires 9.79 eV of energy whereas 15.58 eV of energy is required to ionize N\textsubscript{2}. In [106] this excess energy was shown to be carried by the ionized molecule for some time (µsecs). Radiation emitted from de-exciting N\textsubscript{2}\textsuperscript{+} is illustrated in Figure 4.1.3 between 375 nm and 400 nm.

In [106], Table 2 and Table 3 both include a collection of over sixty spectral lines for negative-point corona discharges in air, and from laser induced discharges in; air, O\textsubscript{2}, and N\textsubscript{2}. More than 80 % of the laser induced discharge spectra align with those of the point type air discharge.

Hallsten et al (2004) [107] irradiated nitrogen in a closed target chamber with less than 1 ppm moisture and oxygen impurities with a 4.3 MeV proton (H\textsuperscript{+}) beam. The experimental pressure was varied in four steps up to 0.325 MPa at which the protons were presumed to have had a range of approximately 7.4 cm into the gas mixture. Emission spectra were recorded by a Mechelle spectrometer with a response ranging from 200 nm to 1060 nm. No electric field was applied. Measured spectra included a strong O line at 557.7 nm rather than at 777 nm for electrically initiated discharges in air (Figure 4.1.3). Also, in the closed chamber NO\textgamma (NO A-X; indicated by lines 200 nm to 300 nm) increased exponentially over 10’s of minutes as the O and NO\textbeta (NO B-X; indicated by lines 300 nm to 330 nm) decreased together. Hallsten suggested that the O was being consumed to make NO\textgamma.

Apart from the fact that there was no N\textsubscript{2}\textsuperscript{+} in the examined spectra, and the O at 557.7 nm the recorded atomic emission spectra from proton (H\textsuperscript{+}) irradiation is remarkably similar to that for electric corona discharges in air where the atomic emission is
mainly from de-exciting N\textsubscript{2} molecules. Since there was no applied electric field in the discharge chamber, no electric field driven electron avalanche would have occurred inside the chamber. It may be possible that N\textsubscript{2}\textsuperscript{+} ions are only produced in an electric discharge.

In a study of the air discharge spectra during vacuum pump-down trials of a discharge chamber, Hrachova [108] in 2003, with applied DC voltage, found that the intensity of the O line from the discharge at 777 nm was not affected by the concentration of impurities and was always a feature in their spectra.

However, the O\textsubscript{2} (B-X) band from 760 nm to 770 nm increased in intensity for increasing oxygen purity. For nitrogen the N\textsubscript{2}(C) bands disappeared with reduction of impurities and N\textsubscript{2}\textsuperscript{+} at 391.4 nm increased in intensity with increasing purity.

4.2.2 Oxygen

In 1996 spectroscopic studies were made by Hrachova and Kanka [109] of glow discharges in pure oxygen at a pressure of 130 Pa with a sustained current of 30 mA\textsubscript{dc} in a 30 mm diameter 700 mm long glass U tube with Pyrex (borosilicate) windows fitted at each end. Experiments were made with oxygen from two different commercial suppliers. In addition 5% argon or 1% nitrogen was added to the oxygen and the results were then compared.

In [109] spectroscopic studies of the glow discharge in the purest of oxygen gave rise to only three spectral lines in the range 440 nm to 700 nm. The lines had wavelengths of 441.6 nm, 615 nm, and 645.5 nm and all three lines were identified to be from atomic oxygen. The line at 615 nm was slightly more intense than the other two lines. For above 700 nm the atmospheric A-bands of molecular oxygen O\textsubscript{2} at 759.4 nm and 761.9 nm were persistent in their experiments.

Their results show obvious changes in the atomic emission spectra with the slightest addition of nitrogen or argon. With 1% nitrogen added the first positive system of nitrogen N\textsubscript{2} developed simultaneously with the first negative system of oxygen O\textsubscript{2}\textsuperscript{+} in the range 499 nm to 853 nm. The developing of the first negative system of oxygen O\textsubscript{2}\textsuperscript{+} was observed as a result of the presence of any impurities whose energetic levels lie near to those of oxygen.
4.2.2.1 Ozone

One of the most noticeable effects from an electrical discharge in air is the production of ozone. Ozone is a pale blue highly reactive gas in which three oxygen atoms combine to form one ozone molecule. The ozone molecule is made from a double-bonded pair of oxygen atoms, and a weakly bonded third oxygen atom. Thermal bond energy of the double oxygen bond is 5.13 eV where as the bonding energy of the third oxygen atom to O$_2$ is only 1.05 eV [110]. The weak bond means that an oxygen radical can be easily released and this makes ozone a very reactive oxidizing agent.

Oxygen does not need to be ionized to form ozone although some ionization is necessary to produce a corona discharge. From Table 4.1 only 5.13 eV of dissociation energy is required to be transferred to the oxygen molecule to produce two oxygen atoms. The following reaction shows production of excited oxygen O$^*$ by electron impact:

$$e^- + O_2 \rightarrow O^* + O^* + e^-$$

Each O$^*$ then combines with O$_2$ as an exothermic reaction, to produce an ozone molecule by the equation:

$$O^* + O_2 \rightarrow O_3, \Delta h = 2.99 \text{ eV}$$

Upon dissociation of the ozone molecule the single oxygen leaves as O$^*$. If two single oxygen atoms recombine to form O$_2$ then 5.13 eV of formation energy is released [110].

4.2.2.2 Sodium and ozone

Sodium and ozone are often both available as products from a salt water discharge therefore it is of interest to understand how they react. Sodium and ozone reactions have been studied since 1938 [111]. The process was then described as a possible two step reaction that occurs in the sodium layer in the upper atmosphere:

$$Na + O_3 \rightarrow NaO + O_2$$

$$NaO + O \rightarrow Na + O_2$$

Experiments to date have found the reaction of sodium and ozone ends only with NaO [111]. Sodium in a discharge produces two intense spectral lines known as the sodium D line (D for double) at about 589 nm which are in the yellow region of the visible
spectrum and is shown by the following energy equation:

\[ \text{Na}(3^2\text{P}) \rightarrow \text{Na} (3^2\text{S}) + h\nu \text{ (589 nm)} \]

### 4.2.3 Discharges in humid gases

If an electric discharge occurs in a humid gas, an OH band may be observed in the discharge emission spectra [112]. This appears as a broad band and can be seen as OH (A-X) in Figure 4.1.3 in the range 275 nm to 320 nm. H₂O can be dissociated into OH and H; and then the OH can be dissociated to O and H. By 1999 it was well known that the OH radical is an effective removal agent of atmospheric pollutants such as NOx and SOx [112].

In a pulsed corona plasma Shin et al [112] detected the OH(A-X) and O(^1\text{D}) emission spectra when wet nitrogen gas was introduced their discharge chamber. They proposed that OH is also produced by O(^1\text{D}) reacting directly with H₂O such that:

\[ \text{O}(^1\text{D}) + \text{H}_2\text{O} \rightarrow 2 \text{OH} \]

The reaction of nitrogen oxides with the OH radical is also known to make nitric acid when water is present [7] and this reaction can be represented by the following equation:

\[ \text{NO}_2 + \text{OH} \rightarrow \text{HNO}_3 \]

Shin et al [112] also showed that for moisture in nitrogen gas, which was obtained by bubbling nitrogen through water and then by mixing it with pure nitrogen, that OH emission intensity at 308 nm was dependent on the concentration of moisture in the gas mixture. The intensity of OH emission was shown to rise quickly from zero, with zero percent H₂O, to about 80% intensity with 20% wet gas. The intensity of the OH band slowly increased to a maximum with approximately 50 % wet gas. The intensity of the OH band showed no significant change with wet gas between 50 % and 100 % mixture. The 308 nm line peak was used monitor OH because it does not overlap with nitrogen bands in this part of the spectrum.

During diagnostics of atmospheric pressure air plasmas Laux et al. [113] in 2002 using an 50 kW inductively coupled plasma torch also detected OH at approximately 309 nm. Various amounts of H₂O or H₂ was added to the air. Oxygen lines at 777.3
nm oxygen lines were clearly detected. Comparative computer modelling with SPECAIR© [114] showed a best fit solution for the rotational temperature of the OH molecule in their discharge of 2200 ± 50 K which is an indication of the reactivity of the OH radical. It was also reported in [113] that there appeared to be an overlap of NOγ and N₂⁺ second positive system in the spectra showing that nitrogen oxides were being formed in their discharge. When hydrogen gas was added to the air discharge, the H₀ line at 486.1 nm became prominently noticeable, whereas with air alone no line at 486.1 nm was detected.

Comparing the atomic emission spectra from discharges with air and SF₆, Fujii et al [115] observed a region about 308 nm that did not always appear in their experiments and that the nitrogen spectra also seemed to alter.

From the above literature the region around 308 nm observed in the spectrum is affected by the presence of OH in the discharge, for this reason, the variations in [115] around the 308 nm were most likely due to small amounts of moisture in the SF₆ gas and changes in humidity during air discharge experiments.

SPECAIR©

SPECAIR© is an accurate computer simulator that theoretically calculates the emission and absorption spectra in the range 80 nm to 5.5 µm for user-entered combinations of the common gases found in air. The current version of SPECAIR© models 37 molecular electronic transitions of NO, N₂, N⁺₂, O₂, CN, OH, NH, C₂, and CO. The SPECAIR© code is based on the NonEQuilibrium Air Radiation (NEQAIR) code [116] that was originally developed by NASA in 1985 [117].

4.2.4 Hydrogen peroxide production from underwater electric discharges

Commercially produced hydrogen peroxide is manufactured by placing an insulated point electrode underwater. The resultant discharge creates a bubble in the water and produces H₂O₂ and OH radicals.

In 2007, Nikiforov and Leys [118] used two water tanks separated by a 5 mm long 1 mm diameter capillary tube to investigate H₂O₂ production efficiency. The discharges
were produced in the capillary tube. H$_2$O$_2$ and OH radicals were produced in the tube by the application of AC voltage. Various capillary tube diameters and lengths were trailed. A maximum yield of 3.48 molecules of H$_2$O$_2$ per electron was achieved in a 5 mm diameter tube. Detection of OH was by a photo multiplier fitted to one end of the tank in line with the axis of the capillary tube; the photomultiplier had a filter with a window set from 280 nm to 400 nm.

Lukes et al [119] studied Hydrogen Peroxide and Ozone production in a hybrid reactor during water purification experiments. The reactor consisted of multiple point discharges directed down towards the water surface as well as an underwater point discharge at the bottom of the reactor. In a closed head space ozone levels reached a limit of approximately 3000 ppm irrespective of the input power. Dissolved H$_2$O$_2$ concentrations were found to be independent of the air discharges. Dissolved O$_3$ from the air discharges was considered to destroy dissolved H$_2$O$_2$. When the water was alkaline, the H$_2$O$_2$ concentration depended on the rate at which H$_2$O$_2$ destroying ozone could transfer from the discharge zone through the surface and into the liquid.

4.2.5 Spectra from discharges on wet insulation

Blackmore [120] observed salt water dry band discharges and described them as starting with a faint blue light, and as dry band discharge intensity increased, yellow and orange light was emitted at the root of the discharge.

Otsubo et al [121] studied corona discharge emission spectra occurring on the surface of polymer insulator materials, including SiR, during salt fog aging tests. Spectra were observed using a photo-multiplier and CCD Camera. Results showed that corona discharges emit mainly ultra violet light from O$_2^+$ and from the first and second positive band systems of nitrogen. For dry band discharges, the spectral components showed yellow light with wavelengths of 590 nm and also included the yellow-red portion of the spectrum with wavelengths up to 800 nm. On a one millisecond time scale the current pulses detected by the photomultiplier were observed to be coincident in time with the partial discharge current pulses.

Otsubo et al [121] suggested that the high electrical energy due to partial discharges probably causes the Si-CH$_3$ bond to break in silicone rubber resulting in
hydrophobicity loss. Although some spectral data was presented, no explanation of the mechanism for the emitted light or surface degradation was presented.

Galofaro et al [122] studied an arcing problem on silicone insulated solar arrays in the presence of moisture. During the arcing, the emitted light was analyzed using a spectroscope. Electrical discharges were found to occur at a silicone-metal-water triple junction line interface. During these experiments negative DC voltage was adjusted to produce 1 spark per second. Included in the experimental apparatus was a mass spectrometer that scanned for gas numbers 1 to 150 with a scan rate of 1.0 scans per minute.

Besides the presence of the OH band from 302 nm to 309 nm, and strong Hα line at 656.3 nm and Hβ line at 486 nm, a SiH band at 387 nm, and a CH band at 432 nm were clearly observed in the atomic emission spectra. O++ was also occasionally observed in the atomic mass spectra.

Interestingly, the OH bands could be detected for 8 to 10 microseconds after the discharge ceased at distances up to 2 cm from a tiny arc. It was reasoned that OH was produced by a twostep dissociative molecular ion recombination process where firstly H₂O is ionized by electron impact then the H₂O⁺ dissociates into H* and OH* by another electron-combining impact. This process was also suggested by Shin et al [112].

In 2005, spectroscopic studies were made by Jaworek et al [123] of electrical discharges that take place during an electrospraying process using high voltage DC. Spectra were measured over the range 200 nm to 600 nm. For water only, the spectra included the OH indicators at 308.9 nm, 306.4 nm, and 282.9 nm as well as OH⁺ at 356.5 nm. Both 486.1 nm and 434.1 nm from gaseous hydrogen (Balmer series) were also detected in the spectra. NOγ was also detected indicating that nitrogen oxides were being produced in the discharge.

In electrospraying, the negative corona was observed over the whole surface of the fluid cone jet, and including its breakup whereas previous reports [123] state visible corona begins from the point at which the jet breaks up. It was also suggested in [123] that space charge formed by large droplets lower the electric field at the liquid
jet and suppresses the corona current. With 3% Potassium Iodide KI by mass in the solution, KI* lines at 496.5 nm and 511.2 nm were detected as well as I⁺ at 511.2 nm and 521.9 nm, in addition to Fe₂⁺ at 430.66 nm. With 3% CuSO₄ by mass in the solution, lines of trace elements of Fe, Cu, and Na were identified in the spectra. This shows that dissolved materials can also be dissociated by a discharge involving water.

Interestingly, Jaworek et al [124] during another study with discharges in electrostatic static precipitators with dry fly ash, recorded spectra of Na, Si, Fe, and Mo from the fly ash covered electrode. The spectral lines were mainly between the visible wavelengths of 550 nm and 600 nm. This shows that dry materials can also be dissociated by electrical discharges.

4.2.6 Carbon oxides

Using an atomic mass spectrometer Naidis [70] and Skalny et al [125] confirmed previous reports that CO₂⁻ and CO₃⁻ ions as well as O₂⁻, O₃⁻, O⁻, NO₂⁻, NO₃⁻ ions were produced by a point plane discharge in dry air. A hole in the plane electrode allowed connection to the mass spectrometer. The tip radius was 0.1 mm separated from a gold plated brass plane electrode.

Experiments were conducted with atmospheric air over the range 5 kPa to 27 kPa. It was confirmed that CO₃⁻ was the dominant ion in dry air discharges. It was suggested that O₃⁻ and O⁻ react with CO₂ to produce CO₃⁻. The concentration of CO₃⁻ was found to rapidly decrease with presence of moisture. For discharges in humid air, it was suggested that the CO₃⁻ ions formed clusters with the water molecules.

According to Blaze Laboratories [126], the high concentration of CO₂ in the electrical discharges is caused by accumulation of CO₂ at the point electrode by the dielectrophoretic force effect which acts on polarisable gases in highly non-linear electric fields. It can be seen in Table 4.1, that CO₂ has the highest polarizability of the majority of the gases in air. Carbon from CO₂ from air may possibly contribute to the surface carbon deposited by the process of tracking.
4.3 Summary of possible reactions and emission spectra

Based on reviewed papers in the previous section, a summary of known reactions that may occur in an electrical discharge are presented below: Where it is shown, the transferred energy relates to kinetic energy absorbed by the atom or molecule during the associated reaction. The energy comes from collisions with electrons accelerating in the electric field in the discharge gap. Reactions (1) to (6) involve oxygen, (7) to (11) involve nitrogen, and (12) to (16) involve water.

(1) \( e^- + O_2 \rightarrow O_2^- \) (Energy transferred < 5.16 eV)
(2) \( e^- + O_2 \rightarrow O^* + O^- \) (5.16 eV < Energy transferred < 12.7 eV)
(3) \( e^- + O_2 \rightarrow O^* + O^* + e^- \) (5.16 eV < Energy transferred < 12.07 eV)
(4) \( e^- + O_2 \rightarrow O_2^+ + e^- + e^- \) (Energy transferred > 12.7 eV)
(5) \( e^- + O \rightarrow O^+ + e^- + e^- \) (Energy transfer > 13.62 eV)
(6) \( O^* + O^* \rightarrow O_2^+ + e^- \) [59]

(7) \( e^- + N_2 \rightarrow N_2^* + e^- \) (Energy transferred < 9.79 eV)
(8) \( e^- + N_2 \rightarrow N^* + N^* + e^- \) (9.79 eV < Energy transferred < 15.58 eV)
(9) \( e^- + N \rightarrow N^+ + e^- + e^- \) (Energy transferred > 14.53 eV)
(10) \( e^- + N_2 \rightarrow N_2^+ + e^- + e^- \) (Energy transferred > 15.58 eV)
(11) \( N^* + N^* \rightarrow N_2^+ + e^- \) [59]

(12) \( e^- + H_2O \rightarrow H + OH^- \) (Energy transferred ~ 5.15 eV)
(13) \( e^- + H_2O \rightarrow H + OH + e^- \) (Energy transferred > 5.15 eV)
(14) \( e^- + OH \rightarrow H + O + e^- \) (Energy transferred > 4.46 eV)
(15) \( e^- + H_2O \rightarrow H_2O^+ + e^- + e^- \) (Energy transferred > 12.62 eV)
(16) \( e^- + H_2O^+ \rightarrow H^+ + OH^+ \) [122]
Table 4.2 presents some known by-product reactions that may occur in a corona discharge.

Table 4.2  Known chemical by-product reactions that can occur in corona discharges

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Reference</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_2 + UV &lt; 244,\text{nm} \rightarrow O^* + O^*$</td>
<td>[110]</td>
<td>Production of atomic oxygen by UV light</td>
</tr>
<tr>
<td>$O^* + O_2 \rightarrow O_3$</td>
<td>[110] [119]</td>
<td>Ozone from discharges</td>
</tr>
<tr>
<td>$O_3 + \text{Visible light} \rightarrow O_2 + O^*$</td>
<td>[110]</td>
<td>Reaction by sunlight</td>
</tr>
<tr>
<td>$O^* + O^* \rightarrow O_2 + \Delta h$</td>
<td>[110]</td>
<td>Reverse reaction</td>
</tr>
<tr>
<td>$N_2 + O_2 + \text{heat} \rightarrow 2\text{NO(g)}$</td>
<td>[127]</td>
<td>Production of NO</td>
</tr>
<tr>
<td>$NO + O_3 \rightarrow NO_2 + O_2$</td>
<td>[128]</td>
<td>Production of NO$_2$ with ozone</td>
</tr>
<tr>
<td>$NO_2 + O^* \rightarrow NO + O_2$</td>
<td>[127]</td>
<td>Molecular oxygen preferred</td>
</tr>
<tr>
<td>$NO_2 + UV \rightarrow NO + O_2$</td>
<td>[128]</td>
<td>Ozone production</td>
</tr>
<tr>
<td>$O^* + O_2 \rightarrow O_3$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2\text{NO}_2 + H_2O \rightarrow \text{HNO}_2 + \text{HNO}_3$</td>
<td>[7]</td>
<td>Minor source of nitric acid</td>
</tr>
<tr>
<td>$\text{NO}_2 + O_3 \rightarrow \text{NO}_3 + O_2$</td>
<td></td>
<td>Ozone produces acid precursor</td>
</tr>
<tr>
<td>$\text{NO}_3 + XH \rightarrow \text{HNO}_3 + X$</td>
<td></td>
<td>Production of nitric acid (X=polymer)</td>
</tr>
<tr>
<td>$\text{H}_2\text{O} + O^* \rightarrow \text{H}_2\text{O}_2$</td>
<td>[119] [118]</td>
<td>Production of hydrogen peroxide – a powerful oxidizing agent</td>
</tr>
<tr>
<td>$N_2 + UV &lt; 128,\text{nm} \rightarrow N^* + N^*$</td>
<td>[25]</td>
<td>Dissociation requires high energy (eg fast ion collision)</td>
</tr>
<tr>
<td>$\text{NaO} + O(3^3\text{P}) \rightarrow \text{Na}(3^3\text{P}) + O_2$</td>
<td>[111]</td>
<td>Sodium from salt and oxygen</td>
</tr>
<tr>
<td>$O^- + \text{CO}_2 \rightarrow \text{CO}_3^-$</td>
<td>[70] [125]</td>
<td>Production of CO$_3^-$</td>
</tr>
<tr>
<td>$O_3^- + \text{CO}_2 \rightarrow \text{CO}_3^- + O_2$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3 presents a collection of spectral components of corona discharges. The collection includes observed spectra for dry and salt water discharges on real insulators. Table 4.4 presents a few known effects of UV light on SiR/PDMS.
Table 4.3  A collection of observed atomic emission spectra from corona discharges

<table>
<thead>
<tr>
<th>Observed Emission lines/bands (nm)</th>
<th>Atomic Species</th>
<th>Ref</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>230nm - 400nm</td>
<td>Excited N\textsubscript{2}</td>
<td>[115]</td>
<td>Atmospheric pressure. Point-plane corona discharge in air, 15 mm gap, DC voltage</td>
</tr>
<tr>
<td>337nm</td>
<td>Excited N\textsubscript{2}</td>
<td>[54] [106]</td>
<td>Many other references. Largest most prominent peak in an air discharge</td>
</tr>
<tr>
<td>300nm - 500nm</td>
<td>Sodium D lines</td>
<td>[42] [121]</td>
<td>Observed in salt fog tests with real insulators, AC 60 Hz</td>
</tr>
<tr>
<td>260nm – 295nm</td>
<td>NO\textsubscript{y}</td>
<td>[105]</td>
<td>Atmospheric pressure, N2/O2/Ar mixtures, 17 kV DC pulses at 5 Hz, 130 A</td>
</tr>
<tr>
<td>200nm – 1100nm</td>
<td>O,N</td>
<td>[106]</td>
<td>Atmospheric pressure, Laser (248.6nm) pulsed</td>
</tr>
<tr>
<td>300nm - 850nm</td>
<td>N\textsubscript{2} (385nm-380nm), N\textsuperscript{2} (385nm-400nm), O\textsubscript{2} (775nm-775nm), O (774.4nm and 844.7nm), OH (310nm-320nm)</td>
<td>[108]</td>
<td>Low pressures to near vacuum (300Pa to 66Pa) for; nitrogen with impurities, and for oxygen with impurities in a discharge tube. Currents up to 40 mA.</td>
</tr>
<tr>
<td>400nm - 800nm</td>
<td>Oxygen (O, O\textsuperscript{+}, O\textsuperscript{++})</td>
<td>[129]</td>
<td>Grotian Diagram for various states of atomic oxygen in the visible spectrum</td>
</tr>
<tr>
<td>557.7nm</td>
<td>Excited Oxygen atoms</td>
<td>[130]</td>
<td>Pale Green Aurora due to electric current at globe poles</td>
</tr>
<tr>
<td>630nm and 636.4nm</td>
<td>Excited Oxygen atoms</td>
<td>[130]</td>
<td>Deep Red Aurora due to electric current at globe poles</td>
</tr>
<tr>
<td>656.3nm and 488nm</td>
<td>Hydrogen H\textalpha\ and H\textbeta\</td>
<td>[122]</td>
<td>Arcing in presence of moisture</td>
</tr>
<tr>
<td>Blue</td>
<td>Water Drop Discharge</td>
<td>[131]</td>
<td>Water drop to water drop glow discharge (I &gt; 1 mA)</td>
</tr>
<tr>
<td>302nm-309nm</td>
<td>OH</td>
<td>[122] [123]</td>
<td>Water vapour indicator in an electrical discharge</td>
</tr>
<tr>
<td>Yellow/orange</td>
<td>Salt Water Arc</td>
<td>[131] [121]</td>
<td>Discharge involving salt (NaCl) water</td>
</tr>
<tr>
<td>599nm,589nm</td>
<td>Sodium 'D' lines</td>
<td>[121]</td>
<td>Discharge involving salt (NaCl) water</td>
</tr>
<tr>
<td>530nm-800nm</td>
<td>Dry band arcing</td>
<td>[121]</td>
<td>With salt (NaCl) water (I &gt; 1 mA)</td>
</tr>
<tr>
<td>387nm</td>
<td>Si-H</td>
<td>[122]</td>
<td>Arcing on SiR at low pressure</td>
</tr>
<tr>
<td>432 nm</td>
<td>C-H</td>
<td>[122]</td>
<td>Arcing on SiR at low pressure</td>
</tr>
<tr>
<td>550 nm – 600 nm</td>
<td>Elements in fly ash</td>
<td>[124]</td>
<td>Solid elements on the plane electrode were detected in the discharge spectra</td>
</tr>
<tr>
<td>290 nm – 800 nm</td>
<td>Elements in electrospraying</td>
<td>[123]</td>
<td>Cu, K, I and other elements dissolved in a water solution were detected in the spectra</td>
</tr>
</tbody>
</table>

Table 4.4  Effects of UV light on SiR/PDMS

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Source</th>
<th>Ref</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>172 nm</td>
<td>Xe Laser</td>
<td>[24]</td>
<td>Xe excimer laser reduced carbon and increased SiO\textsubscript{2} in PDMS surface</td>
</tr>
<tr>
<td>290 nm – 400 nm</td>
<td>Xe lamp</td>
<td>[23]</td>
<td>Broad range UV was found to cause permanent loss of hydrophobicity for SiR/PDMS</td>
</tr>
<tr>
<td>355 nm</td>
<td>Nd:YAG laser</td>
<td>[28]</td>
<td>Effectively melts SiR/PDMS and reduced hydrophobicity; without producing SiO\textsubscript{2}.</td>
</tr>
<tr>
<td>Less than 300 nm</td>
<td>Silicone Rubber degradation</td>
<td>[132]</td>
<td>Manufacturer claims this radiation is absorbed by the atmosphere</td>
</tr>
</tbody>
</table>
Experimental work

4.5 Spectroscopic studies of corona discharges

4.5.1 Introduction

It was shown in the literature review in Chapter Three that water drop discharges cause degradation to the surface of polymer insulators. It is therefore of interest to examine the emission spectra of surface discharges, such as water drop corona, to ascertain whether such spectra will provide information about the nature of the degradation of the surface of the insulation.

There is no available information on the development of emission spectra from negative point corona onset to streamer for 50 Hz alternating voltages. Knowing the stages of development of the discharge emission spectra may provide further insights into the active species that may interact with and cause deterioration of the surface of polymeric insulators and their metal fittings.

This section describes experiments done to explore the spectrum of electrical corona discharges in atmospheric air and from water drops on the surface of SiR. The first study is of the corona emitted from the tip of a point electrode at an angle that was considered to be representative of the radiation endured by insulation close to metal end fittings of insulators. The second experiment attempts to examine the light emitted from the surface of the SiR insulation over the plane metal electrode shown in Section 2.3. The third experiment is made on water drop to water drop discharges to identify conditions in the space immediately above the surface of the SiR insulation between discharging water drops. In all experiments, the emphasis was on identification of active species that might provide insights into the mechanisms of degradation of the insulator surfaces by corona discharges.

In this chapter, SPECAIR© along with the reviewed material, are used to identify the most commonly known molecular band systems. The NIST© atomic emission spectra data base is also used to verify the identity of radiating atoms within the corona associated with the electrical discharges.
4.5.1 Spectrometer configuration and experimental setup

A HR4000 Ocean Optics spectrometer was custom fitted with a 25 micron width entrance slit and a composite grating and a window filter to span the 200 nm to 1150 nm range. The configured spectrometer has a linear resolution of 0.25 nm per pixel and a sensitivity of 100 photons per count. The spectrometer plugs directly into portable PC using SPECTRASUITE© operating software. The numeric output files were transferred into GRAPHER© presentation software. Calibration was achieved with the use of a mercury-argon calibration light source. Details of the calibration are shown in Section 4.5.6.

The light from the discharge was collected by a single, 1 mm diameter, polished bare ended optical fibre 2 m in length, with transmission qualities suitable for both UV and visible light. The transmission attenuation of the optical fibre for the range 200 nm to 1100 nm is shown in Section 4.5.6. The bare end of the fibre was positioned between clamps fitted with soft nylon jaws. Careful positioning was required to ensure the end of the fibre did not affect the shape of the discharge. Also, to reduce the possibility of the discharge plasma from affecting the polished end of the fibre, a minimum distance of 1 mm from the discharge plasma was selected for the experiments. The final location for the fibre was decided after reviewing video files taken during testing.

The spectrometer was set for consecutive scans. There is an optimal balance between getting enough light onto the CCD detector to provide reasonable resolution and the speed of scanning. If the integration time is set too long then the CCD detector can saturate, clipping the data. If the integration time is set too short then the smaller peaks in the spectra were buried in electrical noise.

For point-plane discharges, an integration time setting of 100 milliseconds was found to provide the quickest scan times without the corona saturating the CCD detector. An integration time of one second was used to record the spectra from corona on the surface of the SiR covered plane electrode, and an integration time of two seconds (2 seconds of exposure on the CCD detector) was found to raise the electrical noise levels significantly and the largest spectral peaks saturated the detector.
4.5.2 *Measured spectra of point-plane corona discharges in air*

In a darkened room the applied voltage was smoothly increased until discharges were detected. The voltage was then reduced to slightly below the corona discharge onset threshold. The spectrometer was set to scan automatically and the applied voltage was smoothly increased until an audible spark was heard. Figure 4.5.1 shows a typical spectrum of the corona produced, prior to sparking, for a negative point discharges (Trichel pulses) in air.

![Atomic emission spectrum produced by a point-plane corona discharge for wavelengths in the range 200 nm to 1150 nm. Gap = 8.3 mm, V_{app} = 6.35 kV_{pk}.](image)

**Figure 4.5.1** Atomic emission spectrum produced by a point-plane corona discharge for wavelengths in the range 200 nm to 1150 nm. Gap = 8.3 mm, V_{app} = 6.35 kV_{pk}.

Figure 4.5.1 shows that most of the radiation produced by the corona is in the UV region of the electromagnetic spectrum. There are no distinguishable peaks from 430 nm to 1150 nm nor any peaks below 295 nm.

Figure 4.5.2 shows 14 consecutive spectra with a 100 msec integration times for equally increasing voltage steps for wavelengths in the range 280 nm to 440 nm. Vibrational transitions are shown in parentheses. A SPECAIR© simulated N\textsubscript{2} second positive band system is also shown for comparison and identification purposes.
All temperature parameters were set to 4000 K to produce simulated spectra for identification of known molecular band systems. N\textsubscript{2} was set to 0.78, and O\textsubscript{2} was set to 0.21 for the simulated air. Small amounts of O, N, and OH made up the balance. A 1 nm trapezoid (default) slit function was used for all SPECAIR\textsuperscript{©} simulations.

According to the reviewed literature the six most notable peaks are from the second positive system of N\textsubscript{2}. No oxygen lines can be seen in the spectra.

Figures 4.5.3 to 4.5.7 shows the results in detail for the ten largest peaks in the consecutive spectra. Peak voltages are included in Figure 4.5.3. Unless off scale, the spectrum of sparking is included for comparison. A clear view of the 6 most notable peaks are shown in Figures 4.5.8 to 4.5.10. Apart from N\textsubscript{2}\textsuperscript{+} (B-X) transition at 391.4 nm, all the emission is from N\textsubscript{2} (C to B) excited states, these are also known as the Second Positive System of nitrogen (SPS). The magnitude of the N\textsubscript{2}\textsuperscript{+} peak is approximately 5% of the magnitude of the N\textsubscript{2} (0-0) peak at 337.1 nm.
Figure 4.5.3  Atomic emission spectrum produced by point-plane corona discharges in atmospheric air up to sparking for wavelengths in the range 334 nm to 340 nm. Gap = 8.3 mm. \( V_{\text{onset}} = 6.3 \text{ kV}_{\text{pk}}, V^+_{\text{onset}} \approx 8.0 \text{ kV}_{\text{pk}} \).
Figure 4.5.4  Atomic emission spectrum produced by point-plane corona discharges in atmospheric air for wavelengths in the range 350 nm to 362 nm from onset up to sparking. Gap = 8.3 mm.

Figure 4.5.5  Atomic emission spectrum produced by point-plane corona discharges in atmospheric air for wavelengths in the range 308 nm to 320 nm from onset up to sparking. Gap = 8.3 mm.
Figure 4.5.6 Atomic emission spectra produced by point-plane corona discharges in atmospheric air for wavelengths in the range 370 nm to 383 nm from onset up to sparking. Gap = 8.3 mm.

Figure 4.5.7 Atomic emission spectrum produced by point-plane corona discharges in atmospheric air for wavelengths in the range 385 nm to 410 nm from onset up to sparking. Gap = 8.3 mm.
Figure 4.5.8  Atomic emission spectrum produced by point-plane transient spark discharges in atmospheric air.

Figure 4.5.8 shows a spectrum of a typical spark discharge overlaid onto the corona discharge spectra (blue spectra) from Figure 4.5.2 for the range 200 nm to 1150 nm. OH bands in the 300 nm to 310 nm region cannot be seen in either spectrum. The background intensity of the spark discharge has increased significantly in the visible region. Many distinguishable lines have clearly exceeded the range of the spectrometer. Sparks and arcs can involve metal elements and the spectrum becomes very complex due to the high temperatures involved. As this current work focuses on small low current discharges, no detailed investigation was done on the spark spectra.

4.5.2.1  Intensity of corona with applied AC voltage

Figure 4.5.9 presents overlaid spectra showing the rapid growth of radiation from the N$_2$(0-0) and N$_2$(0-1) electronic transitions for the C-B band. These transitions seem to appear in pairs: (0-0) and (0-1), (1-0) and (0-2), (1-3) and (1-2), and so on.

The six largest peaks were summed for each scan to see how the intensity of the corona relates to applied AC voltage, and then the relative intensity of these peaks up to spark-over are presented in Figures 4.5.10 and 4.5.11 respectively.
Figure 4.5.9 Fourteen consecutive scans showing the trend for the six largest peaks in the spectra for applied voltage from onset to prior to sparking.

Because the applied voltage was increased at a constant rate (smoothly by hand) scan number is also proportional to $V_{\text{app}} - V_{\text{on}}$. Figure 4.5.10 shows when the intensities of the six most dominant peaks are summed and plotted against scan number and curve fit applied, it is seen that the trend of the intensity of the corona discharges follows very closely to a square law.
Figure 4.5.11 shows that the contribution of some lines increase and others decrease after spark-over which implies some later radiative emission may be occurring for the 376.2 and 316.7 lines.

![Graph showing relative intensities of lines after spark-over.](image)

**Figure 4.5.11** Relative intensities of the six most dominant lines as a function of the sum of the six intensities up to and including the first scan after spark-over.

TPs only are responsible for the emission lines for scans 2 to 7 as positive discharges did not occur up to this level. Both Trichel pulses and positive point streamers occur in Scans 7 to 14. Sparking occurs in scan 15.

It is interesting that the 337.1 nm and 357.7 nm lines reduced slightly and the 353 nm and 375.5 nm increased several scans before spark over. It appears it may be possible that detection of the streamer to spark transition may be able to be monitored automatically by comparing the ratio of these spectral lines.

All measured spectra so far have been from corona at the point of a metal electrode.
4.5.3 Spectra of light from SiR insulated plane electrode

A small 9 mm square piece of SiR 0.2 mm thick was adhered to a circular plane electrode 12 mm in diameter with a small amount of silicone oil in an experiment similar to that described in Section 2.2.3. The optical fiber was directed toward the centre of the corona at an angle of 45° approximately 1.6 mm away from the corona as shown in Figure 4.5.12. In a darkened room the applied voltage was smoothly increased until discharges were detected.

Figure 4.5.12 Setup showing position of optical fiber during both positive and negative point corona. Gap = 5 mm, Applied voltage ~ 6 kV\(_{\text{pk}}\). Plate electrode is behind the SiR on the right.
First results at 100 milliseconds integration times showed no interesting features in the spectra although the entire base line was raised significantly. The integration times were increased in steps of 100 milliseconds to try to expose the spectrometer to more light.

Averages of 2, 4, and 8 were tried, and integration times were further increased, but to no avail. Figure 4.5.13 shows fifteen consecutive scans at 1 second integration times. The floor of the chart has been lifted to see only the highest of peaks. The spectrum does not show any obvious consistencies although some N\textsubscript{2}(0-0) at 337.1 nm can been seen. Because of the difficulty to resolve the corona spectra on the surface of the SiR, it was concluded that broad band light is mostly responsible for the illumination over the surface. The spectra was also compared with that of methane to see if any C, H, or C-H could be found, formed from the degradation of the SiR/PDMS but nothing consistent could be seen. Perhaps a spectrometer of much higher resolution that is not subject to inherent electrical noise is required to further investigate the broadband light detected in this experiment.

Figure 4.5.13 Atomic emission spectrum produced when the optical fibre was directed toward the surface of silicone rubber insulated plane electrode. Gap = 6.15 mm, Applied voltage $\sim 6 \text{ kV}_{\text{pk}}$. 
4.5.4 Spectra of water drop to water drop discharges

In this experiment emission spectra were obtained by directing the polished end of the optical fiber between water drops on the surface of a sheet of silicone rubber insulation as shown in Figure 4.5.14. The spectrometer was set for 100 milliseconds integration time between scans. The water drops contained 1% by weight of NaCl (salt).

![Spectrum of Water drop to Water drop Corona discharge](image)

**Figure 4.5.14** Emission spectrum for water drop to water drop discharges. Insert shows three water drops on the surface of silicone rubber and the position of the UV transparent optical fiber to the HR4000 Spectrometer. Water drops contain 1% wt salt. Integration time = 100 msecs.

Figure 4.5.15 shows the spectrum of a water-drop to water-drop discharge of the type shown in Figure 3.3.8. The water drop to water drop spectrum is overlaid with a spectrum obtained from a previous point-plane experiment at 30.3 °C and 43% RH. This spark spectrum was used because the 337.1 nm peak was very close to the maximum resolution of 16,000 counts obtainable from the spectrometer. When the spectra were compared, they were found to be significantly different in the range 305 nm to 340 nm. The spectra were then normalized for further examination by scaling up the water drop discharge spectra to match the higher resolution spark spectra at the $N_2(0-0)$ 337.1 nm peak to provide Figure 4.5.16.
Figure 4.5.15 Emission spectra over the range 220 nm to 430 nm for a water drop to water drop discharge and for a metal point to metal plane transient spark discharge.

Figure 4.5.16 A comparison between emission spectra normalized to the 337.1 nm peak shows the differences in UV emitted radiation ((A) – (B)) between water drop to water drop discharges (A) and metal point-plane discharges (B).
There is a notable increase in the ratio of intensity in the range 314 nm to 317 nm and a significant increase from 310 nm to 311 nm. The peaks that appear in the spectra between 307 nm and 309 nm relate uniquely to the water drop discharges. The difference peak at 336 nm exposes the formation of NH(A-X) in the wet discharges [100].

Using SPECAIR© simulation software, the mole fraction of OH in the discharge was adjusted to obtain the family of curves shown in Figure 4.5.17. A mole fraction of OH equivalent to $8 \times 10^{-8}$ produced similar results to those measured in Figure 4.5.3. Laux et al [113] estimated an OH rotational temperature of 2250 K for a similar spectra.

![Figure 4.5.17](image)

**Figure 4.5.17** A simulation of discharge spectra in 78% nitrogen and 21% oxygen at atmospheric pressure for various amounts (relative mole fractions) of OH added to the mixture.

In Figure 4.5.14, in the range 500 nm to 840 nm, there are three distinct peaks in the water drop spectra that are not in the spectra of point-plane discharges using metal electrodes. Figure 4.5.18 shows the range 500 nm to 840 nm in detail and clearly shows a peak at about 589.3 which is the sodium D lines at 589.0 nm and 589.6 nm from the salt (NaCl); H$_{\alpha}$ at 656 nm and O* at 777 nm. The peak from O* at 777 nm is really made up of three lines very close to each other; they emit slightly different energies due to their electron spins. Hydrogen also has two slightly different configurations at about 656 nm as shown in Table 4.5. Table 4.5 is from the NIST© atomic spectra data base [133] and also shows that the excited oxygen atoms contain 9.146 eV energy after photons with wavelengths of 777 nm are emitted.
Because the H\textsubscript{α} and O* were not in the dry air discharge spectra it is deduced that these species come from H\textsubscript{2}O dissociated into O + OH, and then from a further dissociation of OH into O* and H\textsubscript{α} as seen in the spectra. In Figure 4.5.5 the first positive system of nitrogen can also be seen to appear with the water drop discharges. Table 4.5 from [133] shows the before and after energy levels for the active species O, H, and Na identified in the water drop to water drop corona discharge spectra.

![Emission spectra](image)

**Figure 4.5.18** Emission spectra over the range 500 nm to 840 nm for a water drop to water drop discharge. Water drops contained 1% wt NaCl (salt).

**Table 4.5 Data for O*, H\textsubscript{α} and O* from NIST\textsuperscript{©} atomic spectra database**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>777.194</td>
<td>870</td>
<td>9.1469096</td>
<td>10.74031</td>
<td>2s\textsuperscript{2}p\textsuperscript{3}s\textsuperscript{3}p - 2s\textsuperscript{2}p\textsuperscript{3}s\textsuperscript{3}p</td>
<td>s2p3s3p - s2p3s3p</td>
</tr>
<tr>
<td>O</td>
<td>777.417</td>
<td>810</td>
<td>9.1469096</td>
<td>10.740475</td>
<td>2s\textsuperscript{2}p\textsuperscript{3}s\textsuperscript{3}p - 2s\textsuperscript{2}p\textsuperscript{3}s\textsuperscript{3}p</td>
<td>s2p3s3p - s2p3s3p</td>
</tr>
<tr>
<td>O</td>
<td>777.539</td>
<td>750</td>
<td>9.1469096</td>
<td>10.740224</td>
<td>2s\textsuperscript{2}p\textsuperscript{3}s\textsuperscript{3}p - 2s\textsuperscript{2}p\textsuperscript{3}s\textsuperscript{3}p</td>
<td>s2p3s3p - s2p3s3p</td>
</tr>
<tr>
<td>H\textsubscript{α}</td>
<td>656.272</td>
<td>120</td>
<td>10.1988101</td>
<td>12.0875066</td>
<td>2s - 3p</td>
<td>3s - 3p</td>
</tr>
<tr>
<td>H\textsubscript{α}</td>
<td>656.285</td>
<td>180</td>
<td>10.1988101</td>
<td>12.0875110</td>
<td>2s - 3p</td>
<td>3s - 3p</td>
</tr>
<tr>
<td>Na</td>
<td>588.9950</td>
<td>80000</td>
<td>0.0</td>
<td>2.1044293</td>
<td>2p63s - 2p63p</td>
<td>2p63p - 2p63p</td>
</tr>
<tr>
<td>Na</td>
<td>589.5924</td>
<td>40000</td>
<td>0.0</td>
<td>2.1022973</td>
<td>2p63s - 2p63p</td>
<td>2p63p - 2p63p</td>
</tr>
</tbody>
</table>

Figure 4.5.19 shows a series of consecutive water-drop to water-drop corona discharge spectra taken with 100 milliseconds scans. It can be seen in Figure 4.5.19 that active sodium from dissociated NaCl (salt) radiated some time (within 200 msecs) after the 337.1 nm N\textsubscript{2} peak.
Figure 4.5.19 Five 100 millisecond consecutive spectral scans of a water drop to water drop corona discharge showing late radiative emission of Na D lines at 589.0 and 589.6 nm.

Figure 4.5.20 shows a typical water drop corona discharge spectrum overlaid onto a spectrum taken of the sun at 11:50 am in Brisbane on 19th January 2009. The spectrometer was aimed directly at the sun without the use of the 2 m optical fibre.

Figure 4.5.20 A typical spectrum of a water-drop to water-drop corona discharge overlaid onto a solar spectrum. The water-drop to water-drop spectrum was taken with 100 milliseconds integration time. The solar spectrum was taken with the spectrometer aimed directly at the sun on a fine day with 10 microseconds integration time. RH = 59%, Time of day: Noon, Location: Brisbane, Date: 19/1/2009.
4.5.5 Spectroscope calibration measurements

An Ocean Optics HG-1 mercury-argon calibrated light source was used to determine the error in the measured wavelength data from the spectrometer. The calibration source was connected via the same UV-Vis fiber optic cable that was used in all the discharge experiments. Figure 4.5.21 shows six spectra calibration calculations in the range 290 nm to 828 nm. Table 4.6 shows the results from using the calibration source and shows the calculated average and standard deviation values of the error.

From Table 4.6 it appears that there is a linear offset error of approximately 0.8 nm over the measured range 290 nm to 828 nm. Data was corrected by subtracting 0.8 nm from the measured wavelength for all general work, or by subtracting the actual error closest to the target wavelength for detailed work.
Table 4.6  Error in measured wavelength determined using a calibrated mercury-argon calibration light source.

<table>
<thead>
<tr>
<th>ID</th>
<th>Actual (nm)</th>
<th>Measured (nm)</th>
<th>Error (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>296.728</td>
<td>297.6</td>
<td>0.87</td>
</tr>
<tr>
<td>B</td>
<td>313.155</td>
<td>313.9</td>
<td>0.75</td>
</tr>
<tr>
<td>C</td>
<td>738.393</td>
<td>739.2</td>
<td>0.81</td>
</tr>
<tr>
<td>D</td>
<td>750.387</td>
<td>751.3</td>
<td>0.91</td>
</tr>
<tr>
<td>E</td>
<td>811.531</td>
<td>812.2</td>
<td>0.67</td>
</tr>
<tr>
<td>F</td>
<td>826.452</td>
<td>827.3</td>
<td>0.85</td>
</tr>
<tr>
<td>Ave</td>
<td></td>
<td></td>
<td>0.81</td>
</tr>
<tr>
<td>Std Dev</td>
<td></td>
<td></td>
<td>0.09</td>
</tr>
</tbody>
</table>

No processing of data could be done during rapid acquisition modes by the spectrometer, so averaging and base line noise reduction calculations were performed on the raw data afterwards using Microsoft XL©.

**Relative magnitude error**

Figure 4.5.22 shows the relative transmission from the manufacturer [134] of the 2m optical fiber used in all the spectroscopic studies in this chapter. It can be seen in Figure 4.5.22 that a 5% relative error is to be expected in the range 250 nm to 440 nm, and approximately a 10% relative error from 300 nm to 800 nm. The transmission of the fiber is less than 50% for photons with wavelengths of about 950 nm.

**Figure 4.5.22**  Relative transmission in percent of the UV/Visible optical fibre used for the spectroscopic studies.
4.6 Discussion

All the significant peaks in the dry corona discharge spectrum were within the range 250 nm to 440 nm. Figure 4.5.21 shows the relative transmission chart which was provided with a calibration certificate by the manufacturer for the fibre used in these experiments. For these limits it can be seen that that a maximum of 5% relative error is therefore expected from the measured results in the range 250 nm to 440 nm. Because the six most prominent peaks are from 315 nm to 380 nm the maximum relative error between these peaks would be less than 5%.

For dry air point plane discharges with both negative point Trichel pulses and positive point streamers, no obvious oxygen lines could be seen in the spectra; only lines of N<sub>2</sub>* and N<sub>2</sub>+ could be seen. Oxygen must therefore be active in the following ways in dry air corona discharges:

- Oxygen dissociates into atomic oxygen. The oxygen atoms carry their portion of the dissociation energy (no emission). Oxygen can also ionize prior to dissociation.
- Away from the plasma, oxygen O and O2 attract free electrons and become negative ions; these ions are attracted by the electric field towards the positively-charged plane electrode.
- Slightly further away from the ionization zone atomic oxygen forms: ozone with oxygen molecules, CO<sub>3</sub> with CO<sub>2</sub> molecules, and negative ion clusters with water.
- Energy is released at the plane electrode producing broad band light which includes some active N<sub>2</sub> emission indicating that the surface of the plane electrode is not immune from active species of oxygen or nitrogen.

An interpretation of the ionization process which occurs near the tip of a pointed metal electrode is shown in Figure 4.6.1. To create a free electron, any molecule or atom will do for this example:
Figure 4.6.1 An interpretation of the ionization process near the tip of a pointed metal electrode: 1. No applied electric field. 2. Applying an electric field causes crowding of electrons at the tip surface which causes electron orbits to distort in nearby gas atoms and molecules. 3. An electron is pulled clear from its orbit by the electric field. 4. The free electron accelerates away from the negatively charged point electrode by repulsion.

Once an electron is freed, it gains kinetic energy in the electric field to cause further ionization, dissociation, and excitation of molecules. The positive ion conducts an electron from off the surface of the tip electrode to neutralize.

An interpretation of the process for O$_3$ production in the discharge gap is shown below in Figure 4.6.2 which also shows the various states of oxygen in the discharge gap. In Figure 4.6.2 the colour shading depicts the strength of the electric field; deep red is the region of highest field gradient which is against the tip electrode. The process shown involves two free electrons generated by the ionization process described above, and three O$_2$ molecules, to make two O$_3$ molecules.

In 1 an oxygen molecule captures a low speed electron to form an oxygen ion O$_2^-$. In 2 an oxygen molecule is dissociated by a high speed electron; one of the dissociated oxygen atoms captures the electron to form O$^-$, the other oxygen atom is in the excited state O*. In 3 and 4 ozone O$_3^-$ is formed but from slightly different ways.
Figure 4.6.2 An interpretation of the formation of ozone in a dry point-plane discharge gap showing the conduction process of the electrons. The high field region next to the tip of the pointed electrode is coloured deep red.

The ozone ions neutralize by giving up their electrons at the plane metal electrode after drifting across the gap under the influence of the electric field. Once neutralized, the ozone molecule can drift out of the discharge gap. Oxygen $O_2^-$ and $O^-$ can also reach the plane metal electrode and neutralize without forming ozone.

For water drop to water drop discharges that contain 1% wt salt, the spectra included additional lines from the presence of OH, as well as lines from $\text{H}_\alpha$, $\text{O}^*$ and $\text{Na}^*$ were clearly detected. Upon detailed spectral comparison, NH was also shown to be formed in the water drop discharges.

The water drop to water drop atomic emission spectra shows elements dissolved in the fluid of the drop as evidenced by the detection of the sodium D lines. Besides the detection of the sodium from the salt, this phenomenon may be used to determine other dissolved elements on real insulator surfaces to identify various types of surface pollution. With the 2 m bare ended optical fibre input into the spectrometer this could be done in situ on in-service energized insulators.
NOγ was observed only with higher energy sparks. For sparking, many lines from excited and ionized oxygen, nitrogen, and other elements and compounds including NOγ were distinguishable in the discharge spectrum. No emission from NO could be seen in the spectra for negative point (Trichel pulses), positive point streamer type discharges, nor from water drop discharges.

The extended tail in the water drop to water drop discharge current pulse is consistent with the presence of water in the discharge which produces the OH radical, excited O, H, and NH, in addition to N₂⁺ and N₂⁺.

### 4.6.1 Damage to SiR/PDMS by corona discharges

It was suggested in [26] that a photon may be able to cleave a hydrogen atom from a -CH₃ group of SiR/PDMS and that the photon energy associated with this cleavage would need to have a wavelength around 354 nm. It can be seen in Figure 4.3.4 that the peak electromagnetic radiation from N₂(C-B)(1-2) transition is at 353.7 nm which supports this theory. Interestingly, the laser used for patterning SiR/PDMS in [28], and used for etching of SiO₂ in [27] by exciting the Si-O bond in the backbone of SiR/PDMS, has a wavelength of 355 nm, which is close to the energy required to cleave the hydrogen from the -CH₃ group, however, no chemical change was done to the SiR/PDMS by the laser.

Chemical analysis of corona-affected and service-aged insulators consistently show a significant increase of O/Si (1 to 3.5), therefore, active oxygen in addition to UV light produced by the discharge, is required to cause chemical changes to the surface of SiR/PDMS. These changes may occur by the systematic breakdown of the methyl group starting with breaking the hydrogen to carbon bonds, and then by breaking the carbon to silicon bond. It may also be possible that the 353.7 nm energy, and possibly other electromagnetic radiation from N₂ electronic transitions, excites the backbone of the SiR/PDMS and allows active oxygen to directly enter the carbon to silicon bond.

Radiation from electronic transitions is not the only source of energy in a discharge that may interact with the surface of an insulator. The accelerating free electrons gain kinetic energy, and the atoms and molecules in a discharge are also excited to high energy levels which could impart into the surface of the SiR/PDMS. For example; the
total energy associated with the $\text{N}_2^+$ molecule is at least 15.58 eV. Table 4.1 shows that energies 3.5 eV to 8.28 eV should break down the silicone rubber methyl structure. Once the C-Si bond is broken it is then possible for the active atomic oxygen, coincidently produced by the discharge, to bond to the silicon atom to initiate the formation of SiO$_2$.

### 4.6.2 Damage to SiR/PDMS insulators by water drop discharges

Surface damage to SiR insulators was found to occur for both wet and dry discharges. For wet discharges OH groups can be formed on the surface which may cause further crosslinking and shrinkage, which would explain the cracks and splits found in the SiR sheath of insulators during salt fog ageing tests by Philips et al [43]. As seen in Figure 4.5.3, OH radicals are created by water drop discharges. The Taylor cone discharge on the surface of the SiR/PDMS would spray OH radicals and charged nanodroplets directly across the insulator surface enhancing the opportunity for chemical changes to occur.

Figure 4.6.3 shows a comparison between surfaces of a new silicone rubber sheathed composite insulator and a cleaned wet silicone rubber insulator that has been aged for several thousand hours previously in a salt fog chamber. The aged insulator was cleaned with tap water, allowed to dry, then LMW silicone oil (50 cSt) was applied to the surface with a cloth. Tap water was sprayed onto the surface then the insulator was energized. The loss of hydrophobicity from the discharges is quite evident.

![Figure 4.6.3](image_url)  
**Figure 4.6.3** A comparison between surfaces of a new silicone rubber sheathed composite insulator (left) and a cleaned wet silicone rubber insulator that was aged for several thousand hours in a salt fog chamber (right).
Chapter Five

5.0 SUMMARY

The work in this thesis was aimed at improving the fundamental understanding of why and where corona discharges appear to localize and the reason they cause damage to the surfaces of composite insulators. The new contributions to knowledge made by this work are summarised below:

From the literature reviews in Chapter One it was shown that water drop discharges tend to localize near to the high voltage and earth end fittings where the electric field strength is the strongest. Table 1.6 in Chapter One shows a collection of the location of discharges observed on real insulators with confirmed loss of hydrophobicity and surface damage. The SiR/PDMS sheath material in this region suffers the most damage. The earth end of the insulator can also have high electric field gradients due to little or no consideration of tower geometry and support structures, and so these end regions, especially at the high voltage end of the insulator, become the most critical locations for damage by corona discharges.

In Chapter Two some of the basic phenomena associated with point-plane type discharges were revisited. A systematic study of negative point-plane Trichel pulses (TP) associated with corona discharges using AC applied voltage has reinforced and extended work previously done by Lama and Galio in 1974 with DC applied voltages.

New observations were made concerning the relationship between the TP height and the time between pulses that show a larger pulse occurs after a long duration and a smaller pulse occurs after a short time. Varying conditions at the tip of the point electrode and corresponding changes in space charge is suggested as the reason for these time-magnitude fluctuations.

For 50 Hz voltage application, unique sets of observations of high resolution current pulses with various gaps up to the positive point onset voltage have been produced. Constant differences were observed in corona discharge onset voltage between positive point and negative point discharges (defined by start of regular TPs) for gaps
with spacings greater than 6 mm. In addition, the locus of the positive point corona discharge onset voltage, and the TP repetition rates up to that point, has also been established for various gap spacings up to 16 mm.

Furthermore, the first complete set of recordings of double-peaked pulses for the positive point streamers ever recorded has been presented which shows a consistent-sized first pulse and a variable second pulse. The effect of the SiR on the double peaked pulses has been established. The SiR over the plane electrode increased the TP onset voltage, but also lowered the positive point discharge onset voltage.

A mechanism for production of double-peaked corona current pulses is hypothesised. It is suggested that the first pulse is produced by an initial ionization wave, based on streamer propagation times. The second pulse is provided by a flow of electrons in the opposite direction. The second pulse starts after the streamer head reaches the plane electrode, in the established streamer channel. The above hypothesis also explains the reason why the second peaks were similar in size for the SiR covered plane electrode by the limited amount of surface charge available for the second pulse.

Measurements of envelopes of many recordings of TPs provided new information about the locus of the peak values of TPs. It is shown that there are clearly defined maximum and minimum levels. The envelopes show TPs are voltage dependant and the peak magnitudes appear at onset and extinction of the discharging for AC voltages.

The effects of smoke on TPs were investigated and it was found that smoke induces discharges at lower than normal voltages. When smoke entered a gap with established corona discharges, the discharge current pulses became very erratic. Double peaked pulses were observed occasionally for smoke in a negative point discharge gap. It was suggested that the first pulse triggers a subsequent discharge with the lower density smoke in the gap.

In Chapter Three a series of innovative experiments were made to assist in the understanding of corona discharges from water drops. In the water drop experiments, the four types of discharges that were observed were; water-drop to water-drop
discharges, water-drop to metal discharges, discharges at the water-air-SiR triple junction, and dry band arcing type discharges.

The dynamics of water drops between metal electrodes of point plane gaps with 50 Hz applied voltage have been observed visually with a camera with simultaneously recorded current pulses. These unique measurements have shown that:

- The onset voltage electric field gradient has been measured as a function of gap length and applied voltage for distorted water drops. For these water drop experiments the electric field gradient for the onset of discharges was found to be approximately 700 V/mm (7 kV/cm).
- Water drops are attracted to conductors of opposite polarity by Coulomb forces from localized charge on the surface of the drop.
- Water drops can fall through the gap without a spark, jump the gap to the opposite electrode without flashover, jump the gap and cause a flashover, disintegrate in the gap with and without causing a flashover, depending on the size of the drop and the gap spacing.
- Current pulses appear in groups starting with a large initial pulse followed by a group of pulses with increasing magnitude and increasing time between the pulses. This increasing height and time between pulses in a group after the initial large pulse is suggested to be caused by the breakup of the Taylor cone jet into various sized droplets each carrying some charge in the gap.

Discharges were also observed, photographed, and measured from water drops on SiR surfaces in a radial electric field. For water drops in a radial electric field, it was found that:

- The less hydrophobic the surface, the less skating of water drops occurred. This is due to an increase of the adhesive force between the drop and the SiR.
- Besides vibration, elongation, and distortion, conical shapes similar to a Taylor cone on its side, were observed to form and stiffen into shape in the radial electric field. Discharges were observed at the distorted drop-air-SiR triple junction interface at the apex and at the base of the cone were the
distorted drop meets the SiR at acute angles. Both positive and negative polarity type discharges were observed and photographed at the triple junction interface. These types of discharges are considered to be more damaging to the insulator because they occur directly across the surface of the SiR, whereas water-drop to water-drop discharges occurs slightly above the surface of the SiR.

- Discharges current pulses involving water drops have very long tails, when compared to dry discharge current pulses that is contributed to a slowly decaying space charge made of charged droplets and cluster ions.

In *Chapter Four*, the spectra of point-plane discharges were measured and compared with *SPECAIR*. An examination of the spectra showed the discharges produced electromagnetic radiation with wavelengths between 200 nm and 440 nm and this was all from the *second positive system* of nitrogen except for a small amount (5%) of N$_2^+$ which was the only ion seen in the emission spectra.

Photons emitted 353 nm to 355 nm align closely with the laser radiation used for etching of SiO$_2$ and melting of SiR/PDMS. Because wavelengths in this region were shown to not cause chemical changes to the SiR/PDMS, it was deduced that chemical changes to the surface of SiR/PDMS occur when both atomic oxygen and UV light are present. Because UV light needs to have a wavelength of about 240 nm to dissociate oxygen, and the fact that no UV was seen below 290 nm means no atomic oxygen was created due to UV by the discharges. Atomic oxygen is therefore created by other means such as electron impact dissociation.

For 50 Hz applied voltage, the intensity of the radiation emitted from the discharge was shown to be proportional to the square of the voltage above the onset threshold; Current I is proportional to $(V_{app} - V_{onset})^2$. This relationship was shown to be consistent from the onset of established discharges to just prior to sparking. It was suggested that this phenomena might be used to monitor discharges to provide an indication of near breakdown conditions.

The spectrum of the light emitted from the surface of SiR was measured and was found to be broad band scattered light. No degradation products could consistently be seen in the spectra.
For wet discharges involving salt water, it was shown that OH radicals in addition to H, O, and Na atoms are produced in a discharge. NH was also shown to be formed with the first positive system of nitrogen. The OH radical is suggested to cause hydrolysis of the SiR/PDMS enabling further crosslinking causing material shrinkage. This explains the results, observed by others during salt fog ageing tests, of cracking and splitting of the protective thin sheath in a region near the high voltage end of insulators. NO formation was seen only in spark discharges. No NO formation was seen in the dry point-plane emission spectra, and no NO formation was seen in discharges that involved water. The weak nitric acid found to be caused by discharges in high humidity and wet environments by previous researchers may possibly come from the combination of NH and O3. In addition, the first ever recorded progressive spectra of a water-drop to water-drop corona discharge was measured and presented. The spectra shows late radiative decay of the Na atoms from the salt dissolved in the water. It was suggested that monitoring discharges on wet surfaces should provide an indication of the elements in any pollution present as well and that these elements should be able to be identified in the spectra.

Furthermore, a spectrum of the solar radiation was taken at noon in summer which shows typical radiation endured by outdoor insulators during the sunny days. In addition, the spectra of a discharge involving water drops was overlaid for comparison which may be advantageous for further work on insulator materials involving surface discharges.

Finally, at the end of Chapter Four, a discussion on damage to silicone rubber from both dry and wet discharges is presented along with an example of a discharging wet insulator showing surface damage indicators that lead to the location of the discharge site (Figure 4.6.3).
5.1 Future work

Fluctuations were found in the Trichel pulse trains. It may be possible that these fluctuations can be related to humidity, dust and particles in atmospheric air. Understanding the cause of these fluctuations may provide a means to monitor changes in the air that relate to changes in discharge activity and answer the question: Are these fluctuations only due to air flow movement, and/or water clusters, and/or particles in the air? A test cell with an air mixer that can be turned on and off, and ports for mixing, changing, and adding gases and/or suspended particles could be utilized for this experiment.

It was shown in the literature that water drops can hold a significant amount of charge. For water, a charge limit exists where the drop becomes unstable and disintegrates, and the amount of charge a drop can hold before it disintegrated is based on surface tension which relates to surface free energy. Therefore, it may be possible that a water drop on the surface of SiR/PDMS could have sufficient charge to cause partial discharge that could damage the SiR/PDMS surface. See Figure 3.3.5 (c). An experiment that puts known quantities of charge onto an isolated water drop sitting on the surface of SIR/PDMS may provide further insights into the way damage is caused by water drop corona. Controlled amounts of charge may be applied to a water drop by discharging a small capacitor onto the drop surface and monitoring any discharge activity around the periphery of the drop to SiR interface.

It was shown that Na from the salt can be seen in the spectra. Therefore it is reasonable to expect that unique lines will be emitted from water drops on the surfaces of insulators that contain dissolved pollutants. Information from the spectra should show the type of pollution that settles on the surface of the insulator from which further studies maybe undertaken of the surrounding environmental conditions and insulator suitability.

Current trends in partial discharge diagnostics use pulse pattern recognition techniques [135]. Using the latest digital oscilloscopes it has been shown from the research work done here that individual discharge pulses can now be measured and these results may be used to diagnose dry air type discharge current pulses (Figure 2.2.15) against discharge current pulses between water and metal (Figure 3.2.13), and
with those that involve only water drops (Figure 3.3.21), provided that high resolution field measurements of discharge pulses can be made. Although these measurements were made in air, this research work may be extended to other types of high voltage power plant such as oil and gas insulated apparatus.

High resolution spectrometers are now portable and with fibre optic interfaces. The optical fibre has similar insulating properties to that of glass and permits continuous very close non-invasive monitoring of known discharge sites and can possibly provide information on water and pollution products involved in the discharges.

Knowing how often discharges occur at a particular location on the critical surfaces of high voltage composite insulators should be able to be used as a measure of surface deterioration until splits and/or erosion to the protective silicone rubber sheath exposes the structural core rod.

The question of ‘how severe is the discharge and do I need to do anything about it?’ is often heard from asset managers. In this research it was found for point-plane type discharges that three stages of discharging have been observed prior to breakdown:

1. Negative-point discharges commence at their onset voltage and increase in intensity with applied voltage.

2. At a higher voltage, positive-point discharges commence and both types of discharges occur alternately during the 50 Hz voltage cycle.

3. At slightly higher voltage, the positive point discharges produce very large double peaked pulses which were discussed in Chapter Two now known as pre-breakdown phenomena.

Therefore, for point-plane discharges in air on AC power systems, it is expected that the onset of double peaked positive-point discharges with established negative point discharges indicate that pre-breakdown conditions are occurring and that the magnitude of the applied voltage is very close to causing a flashover.

In addition, in Figure 4.5.11, it can be seen that the ratio of the 337.1 nm line to the 353 nm and 357 nm lines converge towards sparkover. A change in ratio of the peak
magnitude of the 337.1 nm line to 357 nm lines can also be seen in Figure 4.1.3 between spectrograms of streamer corona (SC) and transient spark (TS) presented by Machala et al. This phenomenon is recognised in this research for short gaps only and an experiment needs to be conducted to verify if this is indeed the case for real insulators at service voltages. Further studies with SPECaira® could assist by attempting to resolve the vibrational and rotational temperatures at different discharge voltages.

For polymer insulators, both wet and dry discharges damage the silicone rubber surface. By design, no discharges should occur in dry weather. However in wet weather water drop to water drop and water drop to metal type discharges can occur for short periods and although the hydrophobicity appears to recover by LMW silicone fluid migrating to the surface, a review of previous research shows that permanent damage does occur and that the protective sheath covering the structural core rod is the most vulnerable of locations and it is this area that should be subject to inspections and surface sampling. For longevity of silicone rubber composite insulators the key factor is a discharge free environment.

For electricity utilities, the percentage of the time water drop discharges occur per annum would be a good indicator to predict the location of the worst affected insulators from the effects of water drop corona; these areas include foggy conditions. The use of a corona camera may assist in identifying the presence of corona discharge activity on the surfaces of insulators while they are in service.

Finally, it is suggested that designers should consider thickening of the sheath material near the high voltage end of the insulator (and at the earth end) to enhance protection of the vulnerable structural fibreglass core rod from the ingress of moisture due to splitting and cracking of the protective sheath from water drop discharges. In addition, thickening of the sheath material in this region would also allow the surface profile to be changed to match the electric field gradient to below levels required for water drop discharges to occur. Small models of insulator ends with different sheath profiles could be tested in a small fog chamber with realistic electric fields to verify various designs. Figure 5.1 has been drawn to show this design concept:
Figure 5.1 A suggested design modification to reduce the electric field surface gradient at the high voltage (and earth) end of composite insulators to below that required for water drop corona discharges to occur.
References


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111. Covinsky M., Suits A., Floyd D., and Lee Y., "The reaction dynamics of sodium with ozone", Department of Chemistry, University of California and Chemical Sciences Division, Lawrence Berkeley Laboratory, California 94720 1992.


Appendix One

Trichel Pulse Repetition Rates
Point – Plane Electrodes with 50Hz applied voltage
Recorded at Positive-point Onset Voltage for Gaps 3.175 mm to 8.89 mm (0.125” to 0.350”)

<table>
<thead>
<tr>
<th>Gap (mm)</th>
<th>Voltage (Volts)</th>
<th>Pulse Rate (Max @ 100 usec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.175</td>
<td>3668</td>
<td>5.88 usec per Space</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td></td>
</tr>
<tr>
<td></td>
<td>68</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>(Max @ 17 Pulses per 100 usec)</td>
</tr>
<tr>
<td>3.810</td>
<td>4058</td>
<td>9.09 usec per Space</td>
</tr>
<tr>
<td></td>
<td>32.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>38</td>
<td></td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>(Max @ 22 Pulses per 200 usec)</td>
</tr>
<tr>
<td>4.445</td>
<td>4391</td>
<td>11.11 usec per Space</td>
</tr>
<tr>
<td></td>
<td>32.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>38</td>
<td></td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>(Max @ 18 Pulses per 200 usec)</td>
</tr>
<tr>
<td>5.08</td>
<td>4705</td>
<td>13.33 usec per Space</td>
</tr>
<tr>
<td></td>
<td>30.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>33.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>35.5</td>
<td>(Max @ 15 Pulses per 200 usec)</td>
</tr>
<tr>
<td>5.715</td>
<td>5058</td>
<td>15.38 usec per Space</td>
</tr>
<tr>
<td></td>
<td>27.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>(Max @ 13 Pulses per 200 usec)</td>
</tr>
</tbody>
</table>
Appendix Two

Refereed conference papers presented by the author during the course of this research

