Lightning Performance Evaluation of Quasi-Hemispherical Air Terminations versus a Franklin Rod

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Declaration

I declare that this dissertation is my own, unaided work, except where otherwise acknowledged. It is being submitted for the degree of Master of Science in Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

Signed this ___ day of _________ 20__

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Igor Djurdjevic

Abstract

This research aims to investigate the effect of adding a quasi-hemispherical object at the top of a Franklin rod. This will significantly reduce corona and hence the space charge under the high electric fields experienced during the descent of the downward moving leader. By obtaining the appropriate size and shape of the object at the top of the air termination the aim is to send a single streamer at precisely the correct moment for it to undergo streamer to leader transition and intercept the downward moving leader. Research as well as preliminary simulation and experimentation point to a critical radius of approximately 300 – 350 mm. A test setup with a 5 m air gap was designed and manufactured with the aim of producing upward leaders from the competing air terminations, thus simulating natural lightning conditions more closely. It is an inverted rod plane gap and includes all the necessary d.c. biasing circuitry and measuring equipment. Eleven air terminations were tested against the Franklin rod in a point to point breakdown configuration and the results captured with a high speed gated camera. A 1.2/50 μs lightning impulse waveform was used during testing and the air gap was 4.5 m long. Results showed that all of the strikes during competition testing were to the Franklin rod. There was no evidence of upward leader formation and electric field enhancement dominated breakdown. The air gap needs to be extended and waveforms with longer rise times, more energy and hence better chance of upward leader formation need to be used. The Franklin rod proved to be the best air termination during testing.

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Chapter 1

Introduction

1.1 General

Traditionally the Franklin rod has been the preferred method of lightning protection since its invention by Benjamin Franklin in the 1750's [1]. This research investigates the possibility of improving the performance of a Franklin rod. There are two main points that one has to take into consideration. These are the electric field conditions necessary for the formation of upward leaders from objects on the ground as well as the concept of space charge and its effect on the surrounding electric field. If streamers are sent too early, the background electric field is insufficiently strong to sustain the streamers and they cannot go through streamer-to-leader transition. This in turn creates left over space charge around the top of the conductor. The effect retards the formation of subsequent upward leaders from the termination point.

The work described in this paper is an attempt of improvement of the performance of the Franklin rod. There has been significant research conducted showing that blunt rods are better lightning strike receptors than sharp rods, an example of which is shown in [2]. The reasons for this are mainly due to less space charge created at the tips of blunt rods during the descent of the downward moving leader in a thunderstorm. The aim of this research is to create a rod which behaves in a way so as not to emit any streamers too early when the background electric field is not strong enough to sustain the streamer to a leader transition. The rod must also be of the correct shape and radius to be able to emit a streamer. This streamer is to be emitted at precisely the right time so that it becomes an upward moving leader. Since the upward leader is launched at the correct moment it intercepts the downward stepped leader and becomes the preferential strike point in its zone of protection.

In order to test this, a setup needs was created such that it replicates natural lightning conditions as closely as possible. It is crucial that the air gap is large enough for upward leaders to be created from competing rods. During preliminary testing smaller test setups have been created and tests performed without upward leader formation. Subsequently a larger test setup was designed and constructed. The tests were performed as competition tests between air terminations in an inverted rod-rod arrangement.

A dissertation plan is laid out in the rest of the introduction. Each of the chapters cover a crucial aspect of the research, starting with explanation of background concepts, leading into the simulation research and preliminary testing and a description of the long air gap testing as well as a discussion of the results. This is followed by a brief layout of possible and recommended future work for this research and a conclusion of the outcomes obtained.

1.2 Dissertation Plan

1.2.1 Chapter 2 Electrical Breakdown in Air

This chapter focuses on the background of electrical breakdown in air. The three relevant breakdown mechanisms are discussed in detail. These are the Townsend, streamer and leader mechanisms. It is very important to distinguish between these mechanisms and to understand the differences between them.

1.2.2 Chapter 3 Lightning

Following the electrical breakdown discussion cloud formation is discussed in detail. This leads onto the discussion of charge formation within the cloud as well as charge separation. This is important as the potential difference between clouds and ground and hence the electric fields created during thundercloud formation are crucial to the rest of the research. The complete process of cloud to ground lightning is discussed in this chapter. This includes the processes of cloud electrification, cloud formation, initiation of a spark, the method of descent of the downward leader to ground, upward leader formation as well as the attachment process. The chapter focuses on negative cloud to ground lightning as this is by far the most common type and one that the testing attempted to replicate.

1.2.3 Chapter 4 Proposed System, Review of Non-Conventional Lightning Protection Methods and Simulations

This chapter explains the proposed methodology of this research. It explains the aim of the project and ties it in with the background concepts already discussed. It also examines the principles of non-conventional lightning protection techniques. Simulations of similar nature performed elsewhere are reviewed. Their relation to this particular research is explained and relevant results highlighted. These results form part of the design criteria.

1.2.4 Chapter 5 Testing

Both preliminary testing and long air gap testing performed are discussed in this chapter. Preliminary testing was performed on a relatively short air gap, 1.5 m, with standard lightning impulse waveforms. The elevated earth plane and the d.c. biasing circuitry were tested at this stage. Most strikes were recorded to the Franklin rod and there was no detection of upward leaders from the competing rods. The corona camera was also used at this stage and provided clear images of the Franklin rod under corona when placed under a certain d.c. bias voltage. This chapter also explains the long air gap testing performed at the National Electrical Test Facility (NETFA). The tests were performed with lightning impulse voltages and with air gaps of over 4.5 m. In this chapter the test setup is explained and the test results shown. There is also a comprehensive discussion of the test results from the tests.

1.2.5. Chapter 6 Explanation of Results

This chapter summarises the main results of the research. It provides the reasons for the results achieved. It offers a brief explanation to the difference between natural lightning and long air gap breakdown in laboratories. It offers explanations for the results achieved and why they differ from the possible results postulated by this research.

1.2.6. Chapter 7 Future Work and Conclusion

This chapter covers the recommended future work subsequent to this research and concludes the research. It deals with extensions of the current tests to include impulse waveforms with a slower rise time and hence more energy to be able to create leader formation. It also outlines possible further testing with rocket triggered lightning. It ties together the main concepts behind the idea and the experiences from the results obtained through testing. It also outlines the recommended future testing for this research.

1.2.7 Conference Publications

Portions of this research have been published in the following conference publications:

International Conference Publications

1) I Djurdjevic, N J West, I R Jandrell. *Lightning Performance Evaluation of a Quasi-Hemispherical Air-Termination vs. a Traditional Franklin Rod.* Ground 2008 & 3rd LPE, Florianopolis, Brazil, November 2008.

2) I Djurdjevic, N J West, T Govender, I R Jandrell. *Lightning Performance Evaluation of a Quasi-Hemispherical Air-Termination versus a Franklin Rod.* International Conference on Lightning Protection, Cagliari, Sardinia, September 2010.

Local Conference Publications (South Africa)

1) I Djurdjevic, N J West and I R Jandrell. *Preliminary Investigation into the Lightning Performance of a Quasi-Hemispherical Air-Termination versus a Traditional Franklin Rod*. South African Universities Power Engineering Conference, Durban, South Africa January 2008.

2) I Djurdjevic, N J West, I R Jandrell. *Critical Evaluation of Testing Procedures During the Lightning Performance Evaluation of a Quasi-Hemispherical Air-Termination vs. a Franklin Rod.* South African Universities Power Engineering Conference, Stellenbosch, South Africa, January 2009.

3) I Djurdjevic, N J West, I R Jandrell. *Lightning Performance Evaluation of a Quasi-Hemispherical Air-Termination vs. a Franklin Rod.* South African Universities Power Engineering Conference, Johannesburg, South Africa, January 2010.

Chapter 2

Electrical Breakdown in Air

2.1 Introduction

Much research has been conducted regarding lightning flashes but there are still a lot of unanswered questions. The main reason for this is that it is impossible to replicate lightning conditions in a laboratory environment. The long spark can be experimented with however and some deductions and similarities can be concluded.

It is very important to understand the principles of electrical breakdown in air. The following section briefly summarises the main principles of breakdown in air and the three main mechanisms of breakdown, namely the Townsend, streamer and leader mechanism. Firstly a few basic definitions are introduced that will be used in the explanations that follow.

Collisions between atoms can be elastic or inelastic. The free path for collisions is the distance a free electron will travel between collisions. Therefore the *mean free path for a given collision* is:

$$\lambda = \frac{1}{n\sigma} \qquad (2.1)$$

Where n is the atomic or molecular number density of gas and σ is the microscopic collision cross-section [3].

Charged particles in a background electric field are influenced in their movement by the electric field. There is a force on the particles caused by the electric field. It is in a direction parallel to the electric field. The particles will drift in the direction of the electric field or opposite, depending on their charge. They will also collide with other atoms and molecules and lose some energy from the electric field. The energy imparted will be higher if the particles have higher speed, drift speed. This speed attained is known as *drift velocity*. Drift velocity depends mainly on the strength of the electric field and the mass and charge of the particle. The ratio of drift velocity to electric field is known as electron mobility [3].

In order for air to become a conductor the requirement is that there is an increase in electron concentration in the air. This is caused by ionisation processes [3].

An electron moving in an electric field can only impart a quantum of its energy to atoms it collides with during inelastic collisions. The atom is left in an excited state after the collision. Ion formation can occur if the electron energy is larger than the ionisation energy of the atom. This ionisation process due to electrons can be quantified in terms of the *coefficient of ionisation*. This is also known as *Townsend's first coefficient*, usually denoted by α. It is defined as the number of ionisation collisions made by an electron in moving a unit distance along the direction of the electric field. The probability of ionisation is the ratio of ionisation collisions per number of all collisions [3]. The mean free path for ionisation collisions is:

$$\lambda_{\text{ion}} = \frac{1}{n\sigma_{(ion)}} \qquad (2.2)$$

The number of ionisation collisions is:

$$\alpha = n\sigma_{(ion)} \qquad (2.3)$$

And probability of ionisation:

$$P = \frac{\sigma_{(ion)}}{\sigma} \qquad (2.4)$$

In equation (2.4) σ is the total collision cross section.

Electrons become free when their energy is higher than the ionisation energy of the atoms [3]. The first collision of the atom with an electron can cause an excitation of the atom and impart energy on it. The next collision may remove the excited electron from the atom. There is a certain probability of ionisation with every collision. In nitrogen and oxygen this probability reaches a maximum at approximately 100 eV and then the probability of ionisation decreases. This decrease is probably due to the short available time for interaction between electrons and atoms. The electron may simply pass near the atom and may not eject an electron from it [3].

The way in which Townsend's first coefficient varies as a function of the electric field is given by:

$$\frac{\alpha}{p} = \mathrm{A}\ e^{-B/(\frac{E}{p})} \qquad (2.5)$$

Where p is atmospheric pressure, E the electric field and A and B constants [3].

Ionisation of atoms can also be caused by photons if the photon energy is larger than the ionisation energy. This process can be shown by equation (2.6).

$$\mathrm{A} + hv = \mathrm{A}^{+} + e \qquad (2.6)$$

In equation (2.6), A is the atom and hv the energy of the photon, where h is Planck's constant [3].

If the gas is heated the heat energy will increase the kinetic energy of the atoms. The atoms may reach energies high enough to cause ionisation through collision [3].

There are also a number of ways in which deionisation (air-recombination) occurs. Some recombination methods are briefly mentioned below:

In air in which a discharge has taken place there is a large number electrons and positive ions. If these particles collide there is a tendency for them to recombine.

During radiative recombination the electron recombines with an ion and the surplus energy is released as a quantum of radiation. During recombination the recombination energy may be released as a photon [3].

In the process of *dissociative recombination* extra energy of the electron is spent on dissociating the ion to which it is attached. Generally this takes place in two steps. Firstly a negative ion is formed. Then this unstable molecule vibrates and dissociates [3].

2.2 Electrical Breakdown Mechanisms

In an environment with a background electric field present, ionisation and deionisation processes occur at the same time. Ionisation increases the number of electrons in the environment and deionisation has the opposite effect. The outcome of this competition is dependent on the background electric field. There is a value at which the background electric field is strong enough for electrical breakdown to take place. This value is approximately 26 kV/cm [3, 4]. There is also a critical length over which the electric field should extend. This length decreases with increasing electric field. It is important to define some of the terms which are explained further in the sections to follow.

Electrical breakdown: A large, usually abrupt rise in electric current in the presence of a small increase in electric voltage. Breakdown may be intentional and controlled or it may be accidental. Lightning is the most familiar example of breakdown. The breakdown in a gas (spark breakdown) is the transition of a non-sustaining discharges into a self-sustaining discharge. The build up of high currents in a breakdown is due to the ionization in which electrons and ions are created from neutral atoms or molecules, and their migration to the anode and cathode respectively leads to high currents [3, 5, 6].

Corona Discharge - It is a localised, cold discharge that forms around objects, sharp conducting points or wires, which produce a sufficient enhancement of the electric-field strength to allow ionization growth. It is an important source of space charge and is also known as partial discharge [5].

Streamer: Streamer - A narrow, highly directed, self-propagating discharge in air. It develops from an electron avalanche when the local space charge is of sufficient density to produce the electric field strength greater than the external, surrounding field. It is a relatively cold discharge and can be the precursor to the formation of a connecting leader [5].

Stepped Leader or simply Leader: Intense spark or plasma channel of finite but variable length in air corresponding to the observed individual steps in a lightning stroke. It is a very high-temperature discharge [5].

Physical processes that occur during breakdown are the following.

An electron starts an avalanche of electrons through ionisation by collision. 'As the avalanche grows the electric field created by the charges at the avalanche head modify the electric field in the vicinity of the avalanche head' [3]. Once this space charge electric field reaches a critical value the avalanche converts into a streamer. If it is a short gap the streamer may bridge the gap and after streamer to spark transition breakdown will occur. In a long gap many streamers may form, the heat generated by these streamer currents increases the temperature of the streamer stem and when a critical value is reached thermal ionisation occurs, the conductivity of the stem increases and the streamer is converted to a leader discharge. The leader channel is a very good conductor and the potential of the electrode is at the head of the leader channel. Very high electric fields are formed at the head of the channel and streamers are created at this channel head. Once the leader reaches the grounded electrode the current in the channel increases and the voltage collapses. This leads to the formation of a spark [3]. As can be noted above the mechanisms of breakdown are different depending on the distance of breakdown or gap length. There are three main mechanisms of breakdown in air. These are the Townsend, streamer and leader breakdown mechanisms. Each of the three breakdown mechanisms is described in the following sections.

2.2.1 The Townsend Mechanism

Avalanche to streamer transition has been observed when the product of pressure and electrode spacing in uniform gaps is approximately 0.5 bar.cm. Below this value space charge is unable to change the background electric field sufficiently. Under these conditions breakdown occurs according to the Townsend mechanism [3].

2.2.1.1 Townsend's Experiments

In Townsend's experiments the parallel plane electrode gap was placed in a cell and the gas kept at low pressures, corresponding to $p \times d$ values of 1000 torr-cm and below [3]. The cathode was illuminated with a beam of ultraviolet radiation leading to a steady stream of electrons. Current across the gap was measured as a function of voltage. Voltage and current vary as shown in *Figure 2.1* [3].

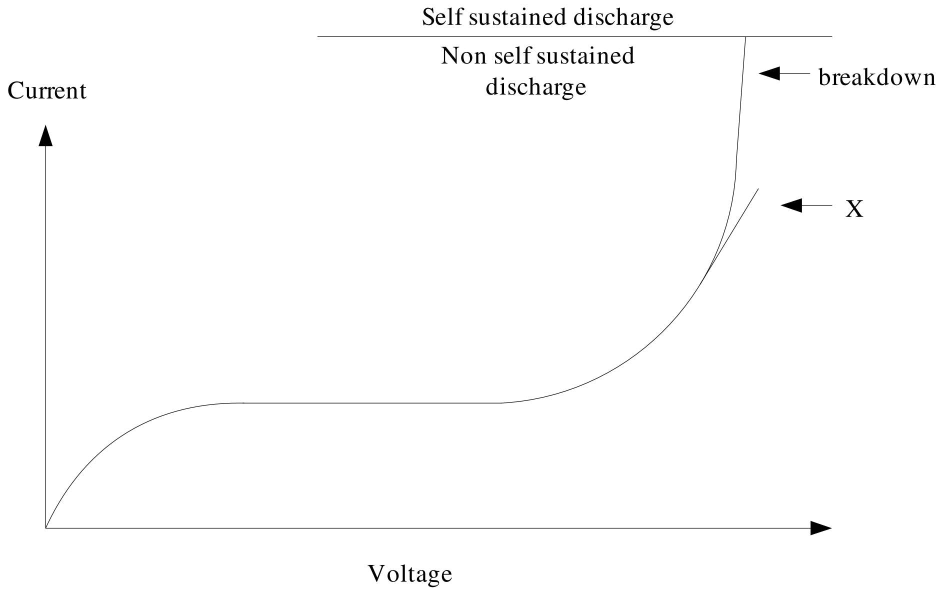

Figure 2.1: Current versus voltage measured during Townsend's experiments [3]

Initially current increases with voltage. This is because some electrons emitted by the cathode disperse back into it and some are lost to the walls. This effect is decreased as the voltage applied increases. When a certain level of voltage is reached almost all the electrons emitted by the cathode are absorbed by the anode and so there is saturation in current. As voltage increases further current starts to exponentially increase with voltage. A further increase in voltage results in breakdown of the gap [3].

2.2.1.2 Townsend's Electrical Breakdown Theory

Townsend assumed that the initial exponential growth of current is due to production of secondary electrons by collisions of primary electrons. The second phase is assumed to be due to ionisation of atoms through collisions. The actual reason for this is the additional production of electrons by collisions of positive ions with the cathode [3].

n_0 is the number of electrons emitted by the cathode per second. Therefore in steady state, and not considering electron attachment, the number of electrons reaching the anode per second n_d is:

$$n_\mathrm{d} = n_0 e^{\alpha d} \qquad (2.7)$$

The current in the tube is then:

$$\mathrm{I_d} = \mathrm{I_0} e^{\alpha d} \qquad (2.8)$$

It is evident that there is exponential growth of current with rising voltage. This discharge is not self sustained [3]. The point where the current is equal to the expression in equation (2.8) is shown by point X in *Figure 2.1*.

Townsend found that in equation (2.7) the graph of log I versus gap length should produce a straight line with slope α, if pressure and electric field remain constant. At higher voltages however the current increases at a higher than expected rate. As voltage increases positive ions gain more energy and this energy is released into the cathode. At a certain stage these ions will have enough energy to free up electrons from the cathode [3]. If n_0 is the number of electrons emitted by the cathode per second due to ultraviolet radiation and n_+ is the number of electrons released from the cathode per second due to the impact of positive ions then the number of electrons reaching the anode at steady state per second is:

$$n = (n_0 + n_+)e^{\alpha d} \qquad (2.9)$$

At steady state the number of positive ions created by the electrons reaching the anode per second is equal to the number of positive ions reaching the cathode per second. Therefore the number of electrons released at the cathode by positive ion bombardment per second is:

$$n_+ = \{\, n - (n_0 - n_+)\}\gamma \qquad (2.10)$$

In (2.10) above γ is the average number of electrons released by each positive ion striking the cathode [3]. It is known as Townsend's secondary ionisation coefficient. Therefore equation (2.9) becomes:

$$n = \frac{e^{\alpha d} n_0}{1 - \gamma(e^{\alpha d} - 1)} \qquad (2.11)$$

The current is thus:

$$I = \frac{e^{\alpha d} I_0}{1 - \gamma(e^{\alpha d} - 1)} \qquad (2.12)$$

This equation shows that there is a faster current growth than in (2.8) with increasing electric field [3].

There are also other secondary ionisation processes to consider. These include ionisation by positive gas ions, photo emission from the electrode, collision of meta-stable ions on the cathode and ionisation of the gas by photons.

2.2.1.3 Requirements for Electrical Breakdown

Discharge current decreases completely if there is no UV illumination on the cathode. As voltage increases the discharge becomes self sustained. At this point there is a great increase of current, in the range of several orders of magnitude. This is known as electrical breakdown in the gap. Townsend described this stage as one where the current in the gap goes to infinity [3]. The equation for Townsend's breakdown criterion then becomes:

$$1 - \gamma[(e^{\alpha d} - 1)] = 0 \qquad (2.13)$$

When Townsend's breakdown criterion is satisfied it means that the number of secondary electrons is equal to the original number of electrons taken, or released, from the cathode. In Townsend's experiments noble gases were used, so electron attachment can be neglected. This is not the case with air [3]. Looking at Townsend's equation with electron attachment, denoted by η, the number of electrons reaching the cathode per second is:

$$n_d = n_0 e^{(\alpha - \eta)d} \qquad (2.14)$$

Where η is the number of attaching collisions.

If d_x is located at a length x from the cathode we can assume that n_x is the number of electrons reaching x per second. Whilst travelling across d_x they will generate d_{n-} negative ions per second. Thus:

$$d_{n-} = \eta n_0 \, e^{(\alpha - \eta)d} \, dx \qquad (2.15)$$

The number of negative ions at the cathode is zero. If one accounts for secondary ionisation due to the bombardment of positive ions on the cathode and through mathematical manipulations shown in [3] the breakdown condition becomes:

$$1 - \left\{\frac{\gamma\alpha}{(\alpha - \eta)}\right\}\left[\left(e^{(\alpha - \eta)d} - 1\right)\right] = 0 \qquad (2.16)$$

Equation (2.16) shows that if α > η electric breakdown is possible. This holds irrespective of the value of α, η and γ if d is large enough. So for a given electric field there is a value d at which the gap breaks down [3]. In a case where α is greater than β and with increasing gap length equation (2.16) reaches asymptotic form. It becomes:

$$\frac{\gamma\alpha}{(\alpha - \eta)} = 1 \qquad (2.17)$$

It can be re-written as:

$$\alpha = \frac{\eta}{(1 + \gamma)} \qquad (2.18)$$

This is the condition for breakdown in an electronegative gas. It is dependent on E/p. γ is much smaller than 1 so the limiting value of E/p for breakdown of electronegative gases to occur can be found by α = η. The graphical representation of this point is shown in *Figure 2.2* [3].

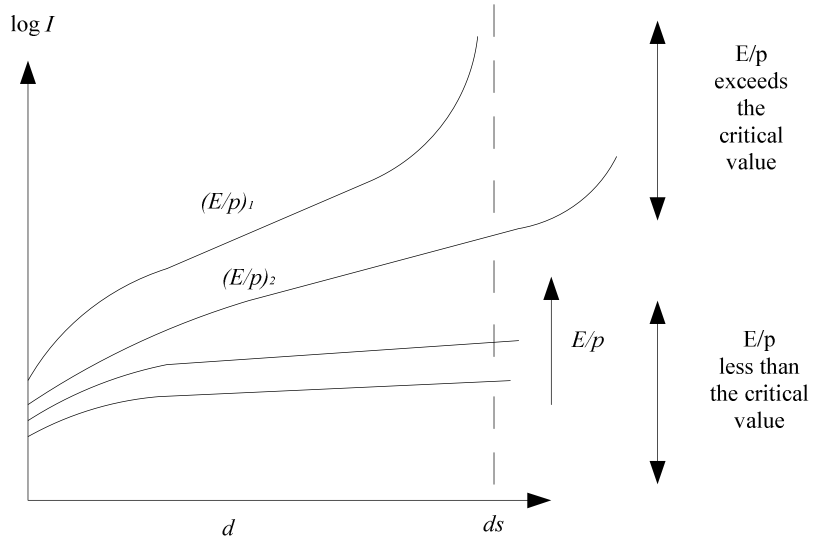

Figure 2.2: Critical value of E/p for breakdown in electronegative gases [3]

2.2.2 The Streamer Mechanism

2.2.2.1 Introduction

When the gap is increased breakdown mechanisms are different to Townsend's mechanism explained earlier. Breakdown mechanisms for longer gaps are described below. Firstly an electron avalanche is created. The number of electrons at the avalanche head is:

$$n = e^{\bar{\alpha}x} \tag{2.19}$$

$\bar{\alpha}$ is the effective ionisation coefficient. If we assume that electrons are located in a spherical region with radius r, the electric field at the head of the avalanche is:

$$E_r = \frac{ee^{\bar{\alpha}x}}{4\pi r^2 \varepsilon_0} \tag{2.20}$$

In the above equation e is the electronic charge. 'As the electron avalanche advances its tip spreads laterally by random diffusion of electrons' [3]. The average radial distance of diffusion is given by $r = \sqrt{4Dt}$, where $t = x/v_d$ and represents the time of advance of the avalanche. D is the coefficient of diffusion and v_d is the drift velocity of electrons [3]. If the above is placed into equation (2.20), equation (2.21) is obtained.

$$E_r = \frac{ee^{\bar{\alpha}x}}{4\pi\varepsilon_0}\left(\frac{vd}{4Dx}\right) \tag{2.21}$$

Therefore with increasing avalanche length the electric field formed due to the space charge increases and at the critical length the electric field created by the space charge becomes equal to the background electric field. At this stage an electron avalanche converts to a streamer [3].

2.2.2.2 Streamer Formation

The explanation to follow considers positive streamer formation. Positive space charge accumulates at the avalanche head during electron avalanche propagation towards the anode [3]. Once the avalanche reaches the anode electrons are absorbed into it. Positive space charge is left behind. The avalanche head is thus a source of high energy photons. These photons create new avalanches close to the positive space charge. 'If the number of positive ions in the avalanche head is greater than the critical value the electric field created by the space charge is comparable to the background electric field and secondary avalanches created by photons are attracted to the positive space charge' [3]. The process repeats itself.

The negative streamer formation process is shown in *Figure 2.3* [3]. In case of a negative streamer, electrons of the avalanche move through the gap and positive charge is left behind, close to the cathode. Once the avalanche reaches the critical size secondary avalanches extend the space charge towards the cathode [3]. When the positive channel reaches the cathode emissions of electrons occur. These electrons neutralise the positive space charge. Negative space charge is propelled further into the gap. Avalanche to streamer transition takes place when the number of charged particles at the avalanche head exceeds a certain critical number [3]. The critical avalanche length for transition to streamer has been calculated experimentally and is:

$$e^{\bar{\alpha} x_c} = 10^8 \qquad (2.22)$$

The critical avalanche length decreases with increasing electric field [3].

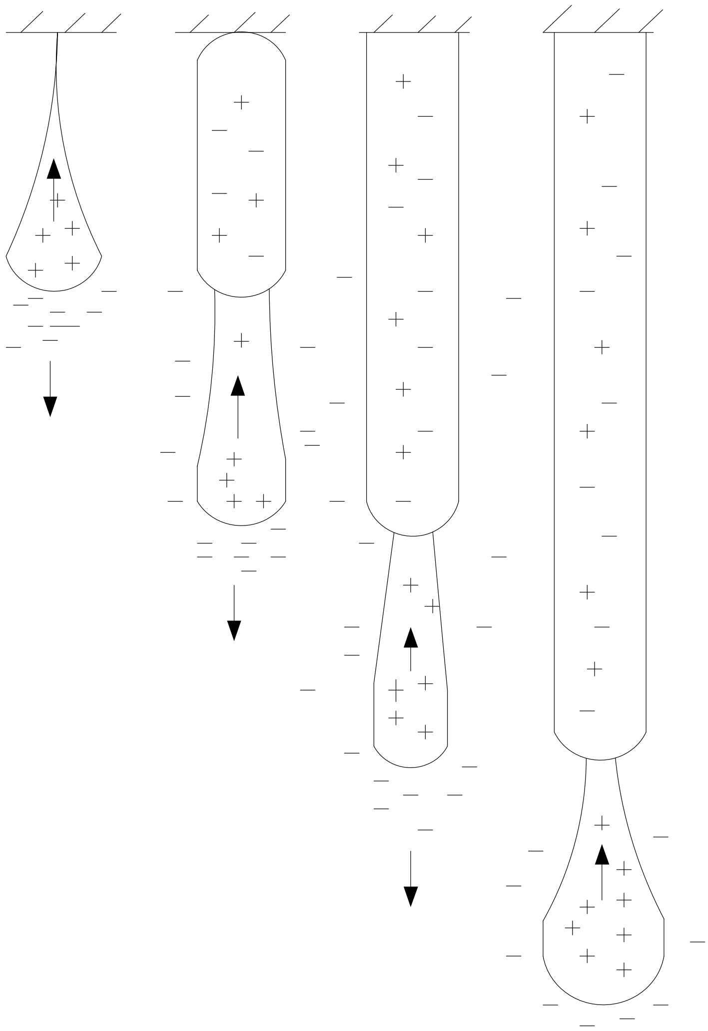

Figure 2.3: Negative streamer formation [3]

2.2.2.3 Streamer Characteristics

Streamer propagation under the influence of a background electric field depends on the distortion of electric field and enhanced production of photons at the head of the streamer [3]. Photons produce secondary electrons at the streamer head which in turn produce secondary avalanches that move towards the streamer head, in case of positive streamers. Streamers can travel in background electric fields that could not support avalanche formation. Therefore secondary streamer formation is confined to a small region just in front of the streamer head, called the active region [3]. In this region the electric field is greater than 2.6 kV/cm, as shown in *Figure 2.4* [4].

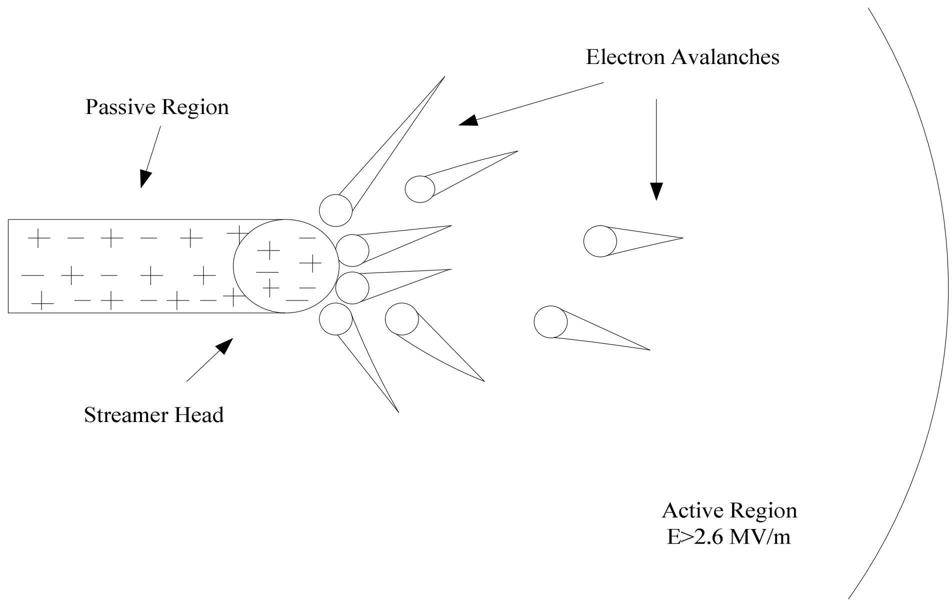

Figure 2.4: The streamer active region [4]

Local strong electric field at the streamer head, in case of a positive streamer, attracts secondary avalanches towards it. Positive space charge is neutralised and an equal amount of positive space charge left behind, slightly ahead of the previous streamer head. Repetition of this process moves the streamer head forward whilst maintaining a weak conducting channel to the anode. Due to electron multiplication in the active region, supported by space charge electric field of the streamer head, the streamer can propagate in electric fields much smaller than required for cumulative electron ionisation [3]. For negative streamers the process is more complex [3]. Firstly the electrode has to supply electrons for neutralisation of the positive space charge left behind by the avalanches. Secondly electrons move into a low electric field region and some are captured by electronegative atoms creating an immobile negative space charge that impedes streamer formation. For these reasons positive streamer propagation is easier [3]. In order for the streamer to keep propagating the number of charged particles at the streamer head has to be greater than a critical number, which is partially dependent on the background electric field [3].

The streamer channel provides a path for electron propagation [3]. It consists of quasi-neutral plasma with an excess of positive charge. The gas in the streamer channel is not warm, approximately at room temperature. The streamer length has no theoretical limits and may be as long as the gap and voltage source permit. Streamers of length up to 10 m have been observed in laboratories, they are probably longer in lightning. The net positive charge in the streamer channel is approximately $0.6 – 3 \times 10^9$ ions/cm [3]. 'Thus streamers are regarded as quasi-neutral plasma filaments' [3].

The electric field necessary for positive streamer propagation is in the range of 4 - 6 kV/cm. For negative streamers it is almost an order of magnitude higher. These values depend on humidity, gas composition, temperature and density [3]. Streamer speed increases with increasing electric field. The current in the streamer channel is an electron conduction current supported by the background electric field. It has a rise time of approximately 10-50 ns and tail time of about 200-500 ns [3].

A streamer discharge does not necessarily mean breakdown. Before breakdown occurs the streamer has to convert to a highly conducting channel. This is done through heating by thermalisation. The streamer creates an ionised track, bridging the gap with the formation of a cathode fall region at the cathode [3]. The streamer has a high local electric field at the head and a filamentary positive column. In this column rate of attachment is higher than ionisation rate due to the small electric field so the discharge current decreases. A small temperature rise of neutral particles occurs raising the pressure in the channel. The dynamics of neutral species reduce this pressure and in turn the neutral density of the discharge channel decreases. Hence the ratio of electric field strength to neutral density increases and when a critical point is reached, where the ionisation coefficient surpasses the attachment coefficient, growth of ionisation occurs. This leads to thermalisation and spark formation [3].

2.2.2.4 Electrical Breakdown by the Streamer Process

If breakdown does not occur when the streamer bridges the gap a voltage increase will cause breakdown [3]. Therefore the voltage required for streamer initiation and propagation can be thought of as the criterion for breakdown. In a plane uniform gap streamer discharge propagation is shown in *Figure 2.5* [3].

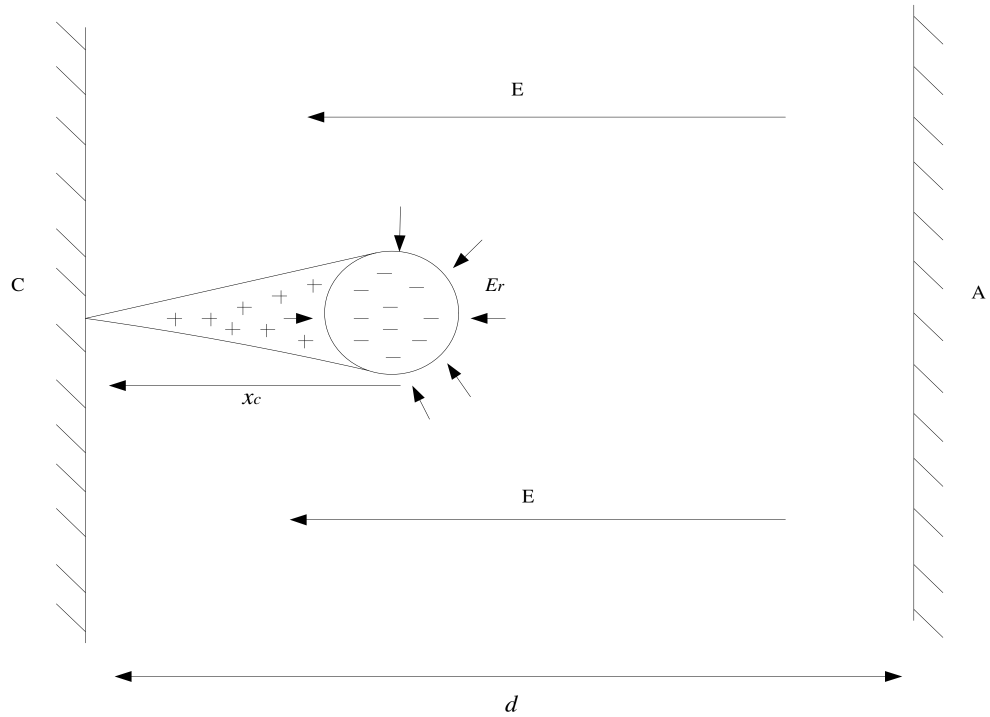

Figure 2.5: A streamer discharge in a plane uniform gap [3]

In order for streamer inception in a uniform gap the electric field needs to be such that the critical avalanche length x_c is less than or equal to gap length. The electrical breakdown criterion then becomes:

$$x_c = d \qquad (2.23)$$

Using the criterion established in (2.15) the breakdown criterion in the gap is:

$$\alpha d \approx 18 \qquad (2.24)$$

In order for streamer initiation to occur the electric field should increase above 26 kV/cm. This field is larger than the critical background field for streamer propagation so once a streamer is initiated conditions necessary for propagation already exist [3].

In a non-uniform gap, in order for the streamer to cross the gap, conditions for streamer inception and propagation need to be fulfilled.

The inception criterion is:

$$\int^{X_c} \alpha(x)dx \geq 18 \qquad (2.25)$$

In (2.25) above x_c is the length of the region where the electric field is greater than 26 kV/cm [3].

The propagation criterion states that once a streamer is created the background electric field must be high enough to sustain this streamer. Once background electric field beyond x_c drops below approximately 5 kV/cm the streamer will be unable to cross the gap. In an electric field of 10-20 kV/cm positive streamers can cross the gap, negative ones may not [3].

Breakdown voltage is not only dependant on gap length, as is stated in Paschen's law. If a voltage is increased slowly across a gap breakdown occurs at a specific, critical voltage level [3]. This breakdown voltage is a function of gas pressure, *p* and gap length, *d*.

$$V_s = f\,(pd) \qquad (2.26)$$

This is visually represented in *Figure 2.6* [3].

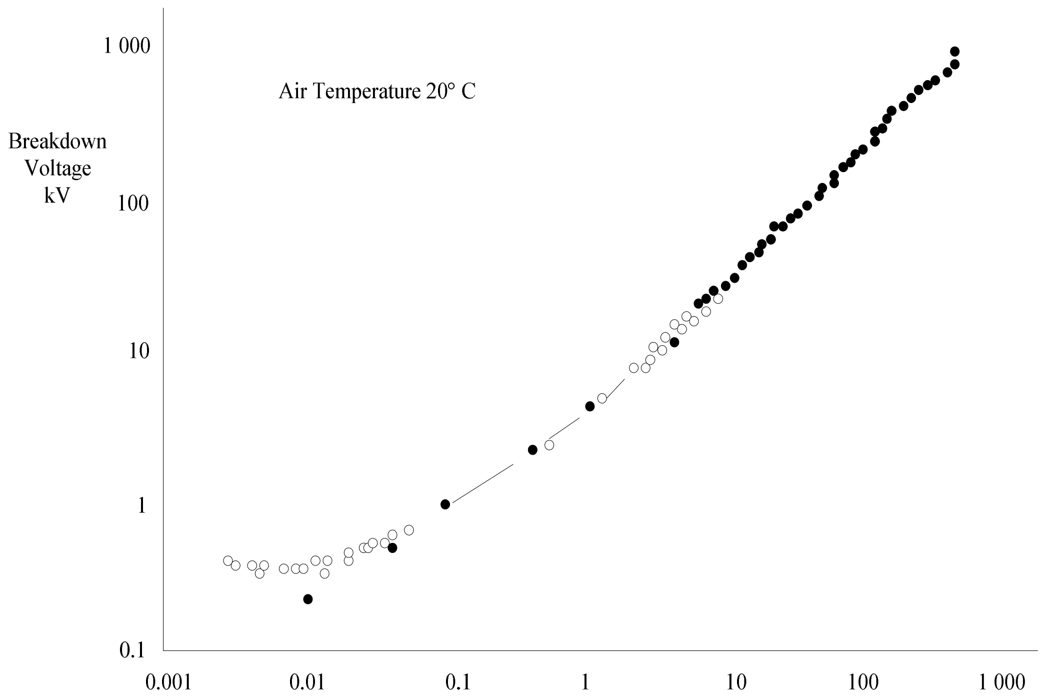

Figure 2.6: Paschen's curve [3]

As can be seen in *Figure 2.6* there is a minimum value on the curve. This is the Paschen minimum. In air $pd = 10^{-2}$ bar.mm.

Townsend's and Meek's criterions conform to Paschen's law. Generally experimental data agrees to Paschen's laws. Exceptions are very high temperatures and very high or low pressures [3].

After streamer to spark transition current in the channel increases rapidly and the resistance drops. Toepler's formula describes the changing channel resistance:

$$R(t) = k_k \left\{ \frac{p_0^3}{A^2 i(t)^6} \right\}^{1/5} \tag{2.27}$$

Where k_k is a constant equal to 24.7, A is the cross sectional area of the discharge in m^2, p_0 is the pressure in Pa and $i(t)$ is the current in the discharge in A. It is, however, not completely correct as in reality the resistance of the channel decreases with increasing current in the discharge channel, but it will recover as the current in the spark channel decreases and goes to zero [3]. There are various types of corona discharges and some of them are discussed in more detail below.

Electric field around objects under high voltage or high electric fields may be higher than the critical electric field for formation of electric avalanches in air. It does not lead to complete breakdown to another object but is confined to a small volume around the object. These are called *corona discharges*. During these discharges ionic space charge of both polarities accumulates near the highly stressed electrode. This space charge modifies electric field distribution. Equilibrium between accumulation and removal of space charge causes several modes of corona. Physical nature of these discharges is affected by the electronegativity of the gas. Generally corona inception follows Townsend's breakdown condition, including corona in non uniform gaps [3]. 'In negative corona electron avalanches are initiated at the cathode and develop towards the anode in a decreasing electric field' [3].

Electrons are highly mobile and quickly move away from the cathode. They leave behind heavier positive space charge closer to the cathode. The electron avalanche will then stop at a point where the background electric field is below the value required for ionisation, since the electron avalanche requires constant ionisation for propagation. At this point electrons are quickly captured by electronegative oxygen atoms, creating a negative space charge [3]. These two opposing space charge regions modify the electric field in the gap so that the electric field increases near the cathode and reduces towards the anode. It can be deduced that avalanches developing later will develop in higher electric fields but will travel for shorter distances [3]. The influence of this space charge in order of appearance is: Trichel streamers (which are negative, regular pulses with a defined repetition frequency), negative pulseless glow, and negative streamers [3].

In a very small gap spacing where the electric field is uniform breakdown is possible without corona inception. This is not valid once the gap is increased [3].

2.2.2.5 Breakdown Dependence on Atmospheric Conditions

As previously mentioned electrical breakdown depends on atmospheric conditions. Ionisation and attachment coefficients are dependant on gas pressure and temperature. Thus they are usually expressed as α/n or γ/n with n representing the density of the gas. The critical electric field for breakdown is:

$$E = E_c\delta \qquad (2.28)$$

With δ the correction factor for conditions deviating from standard temperature and pressure [3]. This correction is only linear for a certain range of pressures as evident from the Paschen curve.

Temperature and pressure also affect the critical electric field for corona inception and not just electrical breakdown electric fields [3]. Corona inception voltage in air between coaxial cylinders is:

$$E_c = 3.15 \times 10^4\delta(1 + 0.305/\sqrt{\delta r}) \qquad (2.29)$$

The equation above is Peek's formula, where δ is the correction factor for conditions deviating from standard temperature and pressure.

In order to achieve electrical breakdown it is not enough to simply increase the voltage until the electric field strength required for breakdown is reached. There are two conditions that need to be satisfied. A free electron should be available in the gap. A free electron may not be available at the time the voltage is applied [3]. The time lag to availability of such an electron is known as statistical time lag. Secondly, once an electron is found it needs to generate a streamer and this streamer needs to go through streamer to spark transition. There is also a time lag associated with this process. This is known as the formative time lag. The total time between the application of voltage to breakdown is called time lag [3].

In the case of impulse voltages once again two conditions need to be satisfied to achieve breakdown in the gap. The applied voltage has to achieve a critical value, and secondly, it must remain at this value until the formation of the discharge is completed. So it must remain above the critical value longer than the time lag [3]. Time lag depends on the voltage applied and breakdown becomes statistical. Breakdown voltage depends on the shape of the applied impulse. 'The narrower the impulse the higher the peak value for breakdown required' [3].

For a given voltage there is a certain probability of breakdown due to the statistical nature of time lags. For long gaps the breakdown mechanism is different to streamer breakdown. The leader mechanism dominates breakdown in this case.

2.2.3 The Leader Mechanism

In small gaps streamer to spark transition takes place immediately after the streamer has crossed the gap. In long gaps the process is different [3]. Firstly a development of a corona discharge occurs. Secondly a highly conducting leader channel is formed from the high voltage electrode. This leader extends, through corona discharges from its head, towards the grounded electrode. Then the final jump occurs. It starts when corona streamers from the leader head reach the grounded electrode [3].

Many of the streamers in the first corona have their origin at the streamer stem. When the electric field decreases below the critical field streamers stop. Streamers are cold discharges and the current associated with them cannot heat the air sufficiently to make it conducting. The combined current of all the streamers however flowing through the stem causes the common region to heat up [3]. This increases the conductivity of the stem. When the temperature of the stem increases to about 1000 – 1500 K the rate of negative ion destruction greatly increases and this retards the drop in conductivity [3]. The current is concentrated into a thin channel and this produces more heating and accelerates ionisation. Through this process the stem is transformed into a hot, conducting channel called the leader [3]. Due to its conductivity most of the applied voltage is transferred to the head of the leader, producing a very high electric field in this region. The production of new streamers now happens from the new stem at the leader head. The new stem is able to transform itself into a new leader section thanks to cumulative streamer currents and the streamer process repeats itself at the new leader head [3]. The streamer head in front of the leader is the source of current that heats up the air and makes the elongation

of the leader possible. As the leader moves forward through air which was originally occupied by streamers the streamer charge forms a space charge sheath around the leader channel [3].
'The ability of the leader to propagate through air is determined by the electric field around the leader head and the streamer zone in front of it' [3]. The electric field at the leader head decreases with increasing leader length. This is due to the voltage drop along the leader channel as well as due to the growth of space charge of opposite polarity induced in the leader head by space charge in the gap. Therefore for leader propagation the voltage applied to the gap must initially be high enough or must be raised during leader development. The temperature in the leader is raised to approximately 5000 K and it supports a current of about 1 A at a relatively low field of about 10^3 V/cm [3].

2.2.3.1 Characteristics of Impulse Breakdown in Rod-Plane gaps

In positive breakdown the breakdown voltage of a rod plane gap depends on the rise time of the applied impulse. Through experiments it has been found that there is a critical rise time at which breakdown voltage is a minimum. It is known as critical time to crest [3].

Firstly there is a primary phase of discharge, corona burst or first corona, occurring at a certain voltage level. The voltage is dependant on the geometry of the gap. Corona streamers develop from the stem. Current measured at the electrode shows an impulse duration of hundreds of milliseconds [3]. 'The space charge injected into the gap during the first corona reduces the electric field' [3].

The electric field recovers, the recovery rate being dependent on the rate of increase of applied voltage and dissipation of space charge [3]. No ionisation activity is detectable during this 'dark' period. If the radius of curvature of the electrode is large enough the dark period can be reduced to zero and leader may start immediately with the first corona. This minimal radius of the electrode is known as the critical radius [3].

'Once initiated the leader channel propagates along a tortuous path with corona developing from its tips' [3]. The leader travels continuously at first, but if the rate of increase of the applied voltage is too low, elongations or brightening of the leader channel occur [3]. These are known as restrikes. Once the streamers of the leader reach the ground plane a phase called the final jump begins. Leader velocity increases exponentially and once the leader head reaches the plane a conducting channel is formed and the return stroke begins [3].

The first corona and the dark period of negative breakdown are similar to positive breakdown. Then a pilot system occurs. It consists of a bright spot called the space stem from which streamers of both polarity develop in opposite directions [3]. The interaction of the positive streamers and streamers of the first corona forms the initiation of a negative leader from the cathode [3]. 'A space stem appears in front of the leader generating positive streamers towards the leader head. Once a connection between the leader head and the positive stem is established a section in front of the leader head is thermalised and this leads to leader extension' [3]. The whole system mentioned above keeps repeating itself as the streamer grows. Sometimes the space stem gives rise to a space leader which propagates towards the cathode at a high velocity. Their connection is followed by simultaneous illumination of the whole channel. The negative leader increases in length by the length of the space leader. Intense corona streamers start propagating towards the ground plane [3].

The inception electric field for corona can be calculated using equation (2.30).

$$\int_{rc}^{ra}(\alpha-\eta)dx = K \qquad (2.30)$$

The equation above is also the streamer inception criterion. x is parallel to the electric field and faces away from the high voltage electrode. The origin of x_c is located at the centre of the sphere with radius r_a. r_c is the value of x at which the electric field is E = 26 kV/cm and K = 10^8 [3].

The inception electric field does not depend on the gap length. It is controlled by the electric field at the electrode surface. It is also strongly influenced by the electric field inhomogoneity close to the electrode [3]. The minimum electric field necessary for corona inception is given by (2.31):

$$E_i = 6.77\log(1.75 \text{ x } 10^3 d_f) \qquad (2.31)$$

And:

$$d_f = \left[-\frac{dE_b}{dxE_b}\right]_{\textit{at the elctrode surface}} \qquad (2.32)$$

Due to the statistical time lag there is a spread in time of corona inception after impulse voltage application. In order to create a streamer the initial electron should appear in the gap in a volume of gas where the electric field is above the critical value [3].

Leader velocity is a function of leader current [3]. The average velocity may increase during the final jump. During the final jump the brightness and velocity of the leader increase [3]. ‘In case of negative leaders when negative streamers reach the anode a positive upward leader is initiated by the anode. These leaders approach each other with exponentially increasing velocity. When they meet a return stroke is initiated at the junction point’ [3].

The *critical radius* is the minimum radius of a spherical electrode in a given gap length which will produce leader inception at the inception of first corona [3]. In a sphere plane geometry the critical radius is given by:

$$R_c = 38(1 - e^{-D/500}) \qquad (2.33)$$

In the equation above D is the gap length in cm. In a conductor plane geometry it is given by:

$$R_c = 37\ln(1 + D/100) \qquad (2.34)$$

This concept of critical radius provides a way to calculate the background electric field necessary for a continuous upward leader from a grounded structure. It is assumed that a connecting leader starts its inception when the electric field at the surface of a hypothetical metal sphere of critical radius at ground potential located at the tip of the structure exceeds the breakdown electric field in air [3].

The critical radius is different for sphere-plane and conductor-plane gaps but the length of corona streamers at the critical radius is about 3 m for both geometries. So the streamer should exceed this length before leader inception. This critical length for leader inception is independent of geometry [3].

The manner of electrical breakdown in air has been discussed. It is evident that different breakdown mechanisms dominate depending primarily on the length of the air gap. It has also been established that there are a number of atmospheric factors that influence breakdown in air. With the breakdown mechanisms established the following chapter discusses lightning in detail.

Chapter 3

Lightning

In order for lightning to occur there needs to be a charge accumulation and separation in the atmosphere. An electric field is created between the ground and a portion of the atmosphere. This charge separation most commonly occurs in clouds and more especially in thunderclouds. This chapter discusses the formation of thunderclouds as well as the process of lightning initiation. Propagation of lightning and lightning attachment are also investigated in more detail.

3.1 The Formation of Clouds

Clouds are largely made up of water droplets and ice crystals. They occur when air becomes locally supersaturated with water vapour. This usually occurs by lifting so the air parcels cool by adiabatic expansion [3]. Lifting of air happens when air near the surface of the earth heats up due to sunlight, and rises as it is warmer. Air can also be lifted by horizontal pressure gradient forces. The altitude at which clouds form through supersaturation is known as the Lifted Condensation Level (LCL). Many times the LCL is reached at approximately 1 000 m above ground, well below the 0º isotherm, which occurs somewhere around 4 000 – 5 000 m above ground, and as such these clouds are only formed with water droplets and don't contain any ice droplets. It has been shown that these clouds do not form thunderclouds [3].

Most lightning occurs from clouds known as cumulonimbus clouds, but there have been observations of lightning activity from other types of clouds such as stratus and nimbostratus [5]. This is not to say that all cumulonimbus clouds are thunderclouds. A thunderstorm is a system of thunderclouds. Sometimes lightning can be generated over volcanoes or in sandstorms but this research focuses on what is know as conventional thundercloud lightning [6].

Thunderclouds are actually large atmospheric heat engines, with sun as the energy input and water vapour as the primary heat agent. Outputs of such a system include winds produced, outflow of precipitation and electrical discharges inside, above and below the cloud [6]. Thunderclouds form from cumulus clouds. As mentioned previously these are formed when warm moist air rises, and is cooled by adiabatic expansion. With the rising and cooling, the relative humidity of the air parcel increases [6]. Once the point of saturation is exceeded moisture condenses on the many particles, dust etc, within the atmosphere and small water particles are formed. The height of the visible cloud base, condensation level, increases with decreasing relative humidity at the ground. These parcels of warm moist air need to continue rising in order to form cumulus and cumulonimbus clouds. In order for this to happen the decrease in temperature with increasing height is larger than the moist-adiabatic lapse rate. This is approximately 0.6 ºC/100 m [6]. Atmosphere is termed as unstable during these conditions as the rising air remains warmer than the surrounding air and hence remains buoyant. As moist air parcels rise they cross the 0 ºC isotherm and freeze to form ice. At this temperature however not all particles freeze. Some remain liquid. At – 40º C all water particles begin to freeze and it is thought that in this region, between 0 ºC and - 40º C, where water and ice particles co-exist, most electrification occurs [6]. Thunderstorms are common in warm coastal regions. Breezes from the water flow inland after sunrise when the land is warmed by solar radiation and is thus warmer than water. In the same manner because mountains are heated before valleys they aid the offset of convection in unstable air. Horizontal winds are forced upwards upon reaching the mountains and aid in vertical convection of air [6].

Small-scale thunderstorms occur due to convection but large–scale storms occur due to frontal activity. Lightning clouds usually range in height of 3 – 20 km and horizontally 3 – 50 km. Sometimes thunderstorms merge and can extend for hundreds of kilometres. Thunderstorms are composed of units of convection known as cells. The usual lifetime of one of these cells is about an hour. A typical multicell storm consists of a succession of cells. Thunderstorms move at approximately 20 – 30 km/h over flat terrain [6].

There are also sprite producing thunderclouds: mesoscale convective systems. These are systems where the ratio of upward elongation compared to lateral is 10 to 20. 'They are a result of aggregation of isolated thunderstorms forming earlier in the diurnal cycle, and hence are most prevalent in the late afternoon and evening' [3]. Laterally extensive layers of space charge in these thunderstorms contribute to more energetic lightning than in ordinary thunderclouds, as much as ten times more Coulomb transfer [3].

There are certain conditions that need to occur for thunderclouds and especially cumulonimbus clouds to form. A cumulonimbus cloud needs to extend at least 2 – 3 km into the subfreezing portion of the atmosphere before lightning occurs [3]. Also a discharge between the lower positive and main negative charge may be crucial for formation of downward negative lightning [3].

Some important factors for location and occurrence of thunderclouds are listed below. It is crucial that there is an availability of water vapour. The most important factor here is the physical law governing the temperature dependence of water vapour concentration at saturation: the Clausius – Clapeyron relation. This relation is a way of characterising discontinuous phase transition between two phases of matter. It is an exponential relationship; generally water vapour concentration tends to double for every 10° C rise in temperature [3]. Strong updrafts produce more violent storms. Nature of surface is important to create atmospheric instability. Land surface heats up quicker than water. Air parcels that extend vertically experience more buoyancy and become more vigorous thunderstorms. Buoyancy stops at the Level of Neutral Buoyancy (LNB) [3]. The height and extent of the 0º C to - 40º C region are usually different in summer and winter. The number of particles in the atmosphere is important, obviously these are greater over land than over oceans [3]. Lightning is more prevalent over land than ocean. There is stronger heating over land, larger updraft and more particles [3].

Thunderstorms also vary according to their geographical location. Below are some of the typical characteristics associated with thunderstorm types.

Tropical thunderstorms

Deep tropical clouds dominate the global thunderstorm category. This is mainly due to the dependence on the Clausius-Clapeyron relation. Almost two of three lightning flashes are found within this tropical belt. Thunderstorms develop nearly every day in these regions [3].

Midlatitude thunderstorms

The tropopause height is lower here; around 12 km in summer, so there are generally fewer tall thunderstorms. In this region there is larger cloud buoyancy and larger vertical velocity. 'Clash of synoptic scale warm and cold air masses prevails' [3]. Supercells are formed. Largest flash rates are recorded here. Clusters of positive ground flashes are also recorded in these storms.

Winter thunderstorms

These are a product of the baroclinic atmosphere, in winter. The 0º C isotherm is very close to the ground. Winter tropopause is very low so the lifting process is widespread. The water vapour available is less than in summer. Lightning storms are difficult to observe as visibility is usually poor but there are a lot more positive flashes than in summer storms [3].

Cloud to ground discharges occur mainly from cumulonimbus thunderclouds but there have been observations of thunderclouds occurring from other types of clouds such as stratus and nimbostratus among others [5].

3.2 Cumulonimbus Clouds

The distribution and motion of thunderstorm electric charges is complex and changes continuously as the cloud evolves. The basic cumulonimbus charge structure is comprised of a net positive charge at the top, a net negative charge below it in the middle and a further net positive charge at the bottom. At the very bottom of the cloud there can also be a fair amount of extra negative charge carried by the falling precipitation [6].

The two top charges are considered as the main charges, equal in magnitude, and the bottom charge is thought to not even exist at times. Due to this the cloud is considered as a dipole. As the positive charge is above the negative, giving it an upward-directed dipole moment, the dipole is considered positive. The electric field E due to the three charges mentioned above is found by replacing ground by three image charges [6]. Fair weather electric field is approximately 100 V/m downward or negative. The cause of this negative electric field is the positive space charge in the atmosphere and the negative charge on the earth's surface. Beneath the thundercloud the field is usually positive and in the region of 1 – 10 kV/m. The electric field created is given by equation (3.1).

$$E(-) = E(+) = \frac{Q}{4\pi\varepsilon_0 (H^2 + r^2)} \tag{3.1}$$

In equation 3.1 E represents the electric field, Q the charge in the cloud, ε_0 is the permittivity of free space, H is the height of the charge (cloud) above ground and r is the radial distance of the observer from the point directly below the cloud charge centre at the ground. If for example the observer was standing on the ground, directly below the cloud charge centre r = 0. If a person is directly below the cloud most of the electric field experienced is due to the negative charge and as one moves further horizontally the positive charge starts having an influence, until the point where positive charge starts dominating [6].

Electric field changes mentioned above are due to the charges in the clouds. Field changes are also caused by lightning discharges. Generally the electric field change is found as the difference between the final field value after charge removal due to lightning and the initial field value due to charge cloud distribution [6]. Measurements of electric fields fall into either the measurement of the slowly varying field, due to cloud charges, or to the rapid field changes due to lightning discharges. A negative polarity of electric field changes due to lightning discharges is expected for the following: cloud to ground discharges, since they remove negative charge from the cloud, and for cloud discharges at close ranges, approximately 5 km, since field changes due to removal of negative charge are larger at close ranges than field changes due to removal of equal amount of positive charge from a higher altitude [6]. Electric fields produced by lightning flashes are almost seen as impulses superimposed onto the electric field produced between the thundercloud and ground and may cause polarity reversal. They are classified as negative polarities of electric field as they effectively remove negative charge from the cloud [6].

The main negative charge causes corona to occur at objects on the ground. Corona first occurs and is most intense at elevated sharp points on the ground. This creates a blanket of positive charge near the earth's surface. Due to this the electric field is usually limited to magnitudes of approximately 1 – 10 kV/m [6]. Much higher electric fields are measured at slightly higher altitudes and over lakes during thundercloud conditions. Negative charge is located in the same, narrow temperature range -10º C to -25º C, regardless of the location, season and stage of storm development. Even the tripolar model is not accurate and a far more complex structure of field distribution exists within the cloud. The tripolar model is one which caters for the main positive and main negative charges inside a cumulonimbus cloud, as well as for the bottom, smaller positive charge. Approximate potential difference of 100 MV between cloud and ground is experienced [6]. For electric field measurements inside thunderclouds most accurate results have been obtained with vertically rising balloons. These types of measurements also have their shortcomings in that a relatively large pocket of charge can be found in a small localised region, yielding possible measurement inaccuracy. According to some findings the tripole charge characterisation of the cloud may extend up to ten layers. Most agree with the negative screening layer at the upper cloud boundary and other charge regions usually in the lower regions of the cloud [6].

For breakdown between two parallel plates an electric field strength of 30 kV/cm is required at sea level. However, at higher altitudes this value decreases with the decrease in atmospheric pressure. At 6 km the value drops to16 kV/cm. Hydrometeors can further reduce this by enhancing the local electric field around their surface. A hydrometeor is any phenomenon which was produced due to condensation or precipitation in the atmosphere. Under conditions experienced in thunderclouds the electric field strength necessary for onset of streamers, which are thought to extend to stepped leaders, can range from 2.5 – 9.5 kV/cm. Very high electric fields are usually located in small portions of thunderclouds. Cloud charge is usually in the region of 0.1 nC/m^3 – 10 nC/m^3 [6].

Cloud electrification includes processes that electrify individual hydrometeors as well as processes that spatially separate these charged hydrometeors by their polarity. The cloud ends up being a relatively good insulator and leakage currents between charged regions are thought to have a small effect on charge separation [6].

There is still debate over the first step in the formation of lightning. The first step being the formation of ionised particles in the clouds. That is where the charged particles that aid in the formation of the electric charge in the atmosphere come from. Some research suggests that these charged particles are radiated from the sun and brought into the atmosphere by solar winds [7]. There are a number of other theories regarding the lower positive charge, from the Graupel particles which charge positively at temperatures higher than the critical temperature to the charge being deposited there during lightning and the charge being carried upwards through convection from the corona on the ground.

The growing consensus, however, is that the Graupel-ice mechanism is the dominant mechanism of cloud electrification [6]. A few of the most important cloud electrification mechanisms are discussed below.

Convection mechanism

With this mechanism the charges are supplied by external sources. These being cosmic rays above the top of the cloud and fair weather space charge and corona near earth's surface. Warm air currents carry positive charge upwards to the top of the growing cumulus. Negative charge is then attracted to the cloud boundary by the positive charge. Downdrafts, from cooling and convective circulation, carry negative charge down the sides of the cloud towards the base. This negative charge at the bottom of the cloud creates even more positive corona and hence forms the positive bottom layer at the base of the cloud [6].

Graupel-ice mechanism

With this mechanism charges are produced by collisions of larger precipitation particles, known as the Graupel particles, and smaller cloud particles, or ice crystals. Precipitation particles are ones that have a relatively high fall speed, > 0.3 m/s. Particles with a lower fall speed are known as cloud particles. Separation of charged particles is due to gravity. This mechanism is able to explain the classical tripolar cloud model described earlier [6]. The electrification of individual particles is due to collisions between Graupel particles and ice crystals in the presence of water droplets. Water droplets are necessary for a significant amount of charge transfer to take place. As heavy Graupel particles fall through the ice crystals and water droplets the droplets freeze upon contact with the ice surface. This process is called rimming. Through experiments it has been shown that when temperature falls below a critical value the Graupel particles acquire a negative charge and when temperature is above the critical value they acquire a positive charge. This sign reversal temperature happens at about 10 – 20 ºC. This is consistent with the main negative charge region temperature within thunderclouds [6].

There are also a number of other cloud electrification mechanisms, some of which include: the inductive mechanism, the convective mechanism, the selective ion capture theory, drop break up theory and melting of ice. There is also the Workman-Reynolds effect which refers to the electric double layer set up across the ice liquid interface during the freezing of dilute aqueous solutions [3].

The thermoelectric effect explains that the mobility of H+ ions is greater than that of OH- ions. They both decrease with temperature. The warmer end acquires a net negative charge [3].

In the quasi-liquid layer theory it is energetically favourable for water molecules in the liquid close to the water vapour interface to orient themselves with the positive H ions pointing towards the vapour side. This results in a drift of negative ions towards the liquid-vapour interface in order to equalise the potential difference [3]. Another theory is the charging due to fragmentation of ice. The effect of chemical impurities is yet another theory of cloud electrification. It states that the presence of trace amounts of NaCl in the rime make the Graupel particles charge negatively during ice-ice collisions while most ammonium salts make it charge positively. Magnitude of charging increases sharply with the decrease of temperature [3].

Non cumulonimbus clouds are also charged. Due to convection currents and presence of fair weather corona all clouds are electrified to some extent. In nimbostratus, stratus and stratocumulus clouds charge densities comparable to those of thunderclouds have been recorded, as well as very high electric fields. In many of the cloud types mentioned above there have also been different layers of positive and negative charges discovered [6]. When the cloud is charged it usually leads to lightning discharges. Most of these discharges happen within the cloud but some discharges occur between the cloud and the ground. The section to follow explains the negative discharge to ground.

3.3 Downward Negative Lightning Discharge to Ground

We define a positive discharge as one where the electrons flow in the opposite direction to the discharge. Therefore a negative return stroke is a positive discharge and a positive return stroke a negative discharge. A positive field is one where negative charge is lowered to the ground or positive charge raised. So according to this definition a lightning flash that transports negative charge to the ground gives rise to a positive field change [3]. There are four main types of discharges between the clouds and the earth.

Firstly and most importantly there is the negative cloud to ground lightning. These discharges account for about 90% of Cloud-to-Ground (CG) lightning throughout the world [8]. A downward moving positive leader initiates less than 10% of lightning. The other two types of lightning are the positive and negative earth to cloud lightning. These are however rare and usually occur from high mountains or very tall structures such as buildings or towers [5]. Lightning is a very frequent phenomenon with approximately 100 flashes occurring each second worldwide [9]. This includes discharges inside clouds as well as Cloud-to-Ground discharges. Although the mechanism of lightning is very similar in other forms of discharges, namely the positive CG and the positive and negative upward lightning discharges, there are certain important differences to note. With regard to positive CG lightning the peak current and the total charge transfer to ground can be much larger than that of negative CG lightning. Positive leaders do not have distinct steps, as do negative downward leaders [5]. They are usually associated with a single return stroke. Positive flashes usually occur in winter thunderstorms and snowstorms. They are also more frequent in cases where the terrain is close to the actual thundercloud such as in mountainous areas or from high-rise man made structures.

In upward lightning it is interesting to note that most of the leaders are positive. Upward lightning forms behave similar to their positive and negative downward counterparts respectively.

Basic charge separation in a vertical cloud structure is shown in *Figure 3.1* [7]. A ground flash is thus a flash occurring between the charge centre inside the cloud and the ground.

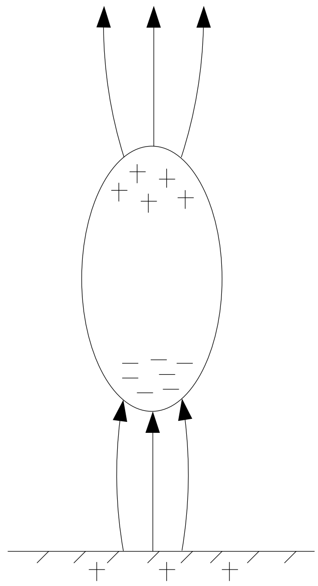

Figure 3.1: Charge separation in vertical cloud structures [7]

The overall cloud to ground lightning discharge is also known as a flash and is usually comprised of a number of different processes. Each flash typically comprises of three to five individual strokes. The largest number of strokes recorded to date in a single flash being 26 [6]. Each stroke is comprised of a downward leader and an upward-moving return stroke. Positive flashes are typically composed of one stroke [6]. The leader effectively creates a conducting path between the cloud, which is a charge source, and the ground. It then passes the negative charge to the ground through this channel and typically neutralises tens of Coulombs of negative charge [10]. The current in the lightning stroke is usually approximately 35 kA but strokes of value as high as 120 kA have been recorded. Each stroke lasts approximately 1 ms and the time between strokes is about 40 to 80 ms [10].

The return stroke travels back up this same path, from ground to cloud, and neutralises the negative leader charge deposited along the current path. The stepped leader differs from dart leaders. The stepped leader appears to be optically intermittent. The tip of the dart leader, however, seems to move continuously [8]. This is due to the fact that the stepped leader develops in non-ionised air and the dart leader follows the pre-conditioned path created by the previous stroke. As shown in *Figure 3.2* below the stepped leader is preceded by a process within the cloud [8].

This is known as initial breakdown. It could be regarded as the discharge that bridges the main negative and lower positive regions of the cloud. These cloud sections are described in more detail in the preceding sections. There is however no consensus on the manner in which initial breakdown occurs. This initial breakdown usually lasts between a few milliseconds to a few tens of milliseconds. It provides the necessary conditions for formation of the stepped leader.

The stepped leader travels from cloud to ground at an approximate speed of 2 x 10^5 m/s. It is a negatively charged plasma channel. As previously mentioned it moves in a succession of discrete steps. Each of these steps takes about 1 μs and is tens of metres in length. The time interval between the steps is in the region of 20 - 50 us [6].

Typical electric field inside the cloud is 10^5 V/m. This field is very difficult to calculate as mentioned previously as there are high concentrations of electric field in relatively small pockets of the clouds. The average electric field at the ground is 10^4 V/m prior to the initiation of the downward leader. Assuming that the height of the lower boundary of the main negative charge inside the thundercloud is 5 km the resultant range of voltage is 50 – 500 MV [6].

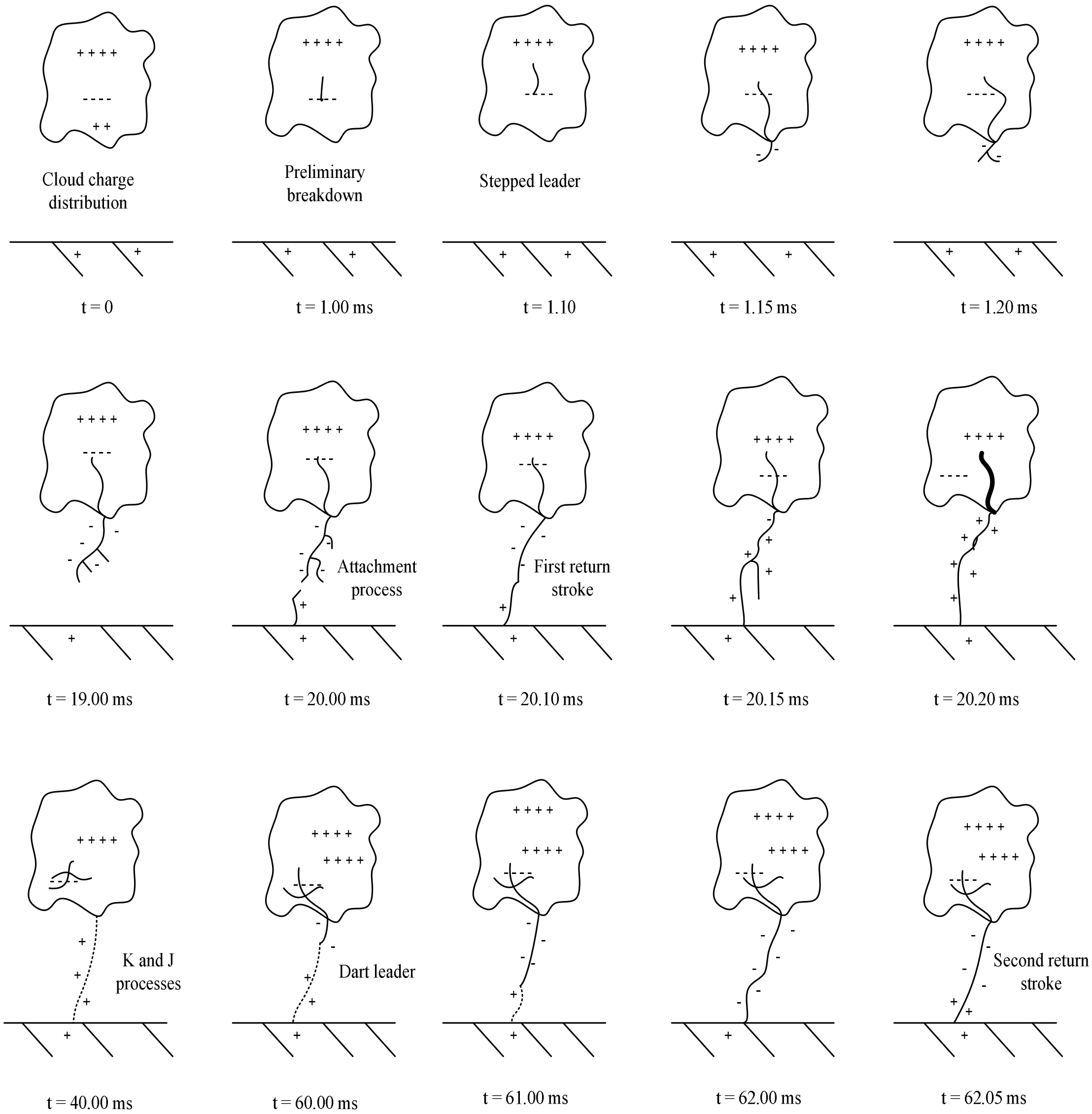

Figure 3.2: The stages of a negative downward lightning strike [8]

The initiation of the upward leader from sharp, elevated points at the ground marks the beginning of the attachment process. The attachment process ends when there is contact between the stepped leader and the upward leader. The return stroke follows. The speed of the return stroke is in the region of a third to a half of the speed of light [6]. The return stroke effectively lowers several Coulombs of charge originally deposited on the stepped leader to ground. This also includes all the charge in the branches. The high current in the return stroke heats up the channel to 30 000 K and creates a channel pressure of 10 atm. [6].

From the time that the first return stroke ends and the next dart leader starts processes occur in the cloud. These are the J and K processes. The K-processes can be seen to be transients occurring during the slower J-processes. The J-processes redistribute the cloud charge in response to the preceding return stroke. It is a relatively slow process that is seen as a positive leader extending from the flash origin to the centre of the negative charge [6]. The K-process is the relatively fast streamer beginning at the tip of the positive leader and propagating towards the flash origin. Both of these processes transport negative charge into and along the existing channel, but not all the way to ground. Processes occurring in single stroke flashes and after the final stroke in multiple-stroke flashes are sometimes called F-processes and are very similar to J-processes [6].

The dart leader moves downward at 10^7 m/s and mostly ignores the branching of the first stroke, depositing approximately 1 C of charge along the channel [6]. The current peak of the dart leader is typically 1 kA. Some leaders have been known to step upon nearing the ground when propagating along the path of the previous return stroke. These are known as dart-stepped leaders. Others deflect from the path all together become stepped leaders and create a new termination point [6].

The attachment process of the dart leader is similar to that of the first stroke. Formation of the upward connecting leader still occurs. This upward leader is however shorter and happens closer to the ground. The upward leader in this case is typically in the order of tens of metres [6]. Once the bottom of the dart leader is connected to the ground the subsequent return stroke is launched upward and serves to neutralise the leader charge. Return stroke currents at ground typically rise to 10 - 15 kA in less than a microsecond and decay to half peak value in tens of microseconds [6]. This impulsive component of the current in the return stroke is often followed by a continuing current with a magnitude of tens to hundreds of amperes and duration of up to hundreds of milliseconds. Approximately 30 – 50% of negative cloud-to-ground discharges contain continuing currents. The source of continuing currents is the cloud charge as opposed to the charge distributed along the leader channel [6].

One can work out the approximate energy of the electrostatic charge in a cloud by multiplying the charge Q by the upper and lower limits of the magnitude of the potential difference between the lower boundary of the cloud charge and ground, V. A typical value for Q is 20 C and a reasonable range for V is between 50 and 500 MV [6]. Each flash, therefore, dissipates energy of 1 to 10 GJ. It is very possible that the majority of the energy is used to create all the filamentary channels in the cloud, which in turn serve to funnel the cloud charge into the narrow channel to ground. One must also consider the amount of energy required for thunder, hot air, light and radio waves [6].

Once a discharge is launched from a cloud towards the ground there are a several steps which it goes through before attachment occurs and several conditions it needs to satisfy in order for successful attachment to occur. These are summarised below.

In hot spots on clouds where streamers are regularly formed they will only turn into lightning if the background field exceeds the critical electric field necessary for streamer propagation. This value decreases with decreasing pressure and increases with increasing humidity. At sea level it is about 450-500 kV/m and at an altitude of 6 km decreases to about 200 kV/m. The clouds are saturated with water so a value of closer to 250-300 kV/m is required [3]. Before a streamer becomes a lightning discharge it needs to undergo streamer to leader transition. It is considered that a system of streamers may give rise to a leader whenever the length of these streamers exceeds three metres [3].

There are also certain conditions that need to be satisfied for leader propagation. In a laboratory discharge the potential gradient of a leader is approximately 100 kV/m. This is similar to the background electric field necessary for leader propagation. Judging from streamer phenomena observed in laboratory sparks one expects this field to decrease with decreasing pressure. Humidity may increase the value but the effect of pressure would dominate in this situation. It is therefore a reasonable assumption that for leader propagation in a cloud environment the background electric field necessary is around or lower than 100 kV/m [3].

In laboratory experiments several corona bursts are noticed prior to the launch of the leader discharge from the high voltage electrode. Some electrical activity, although more complicated, also occurs within the cloud prior to the discharge. This is known as initial breakdown.

It is the in-cloud process that initiates the formation of the downward stepped leader. In early lightning studies initial breakdown was discovered as a unique process from observations of luminosity produced by thunderclouds, observations of long electric field changes of more than 100 ms and the assumption that stepped leader duration lasts few tens of milliseconds. Recent multi station electric field measurements during thunderstorms show that initial breakdown is a sequence of channels extending in random directions from the cloud charge source [6]. One of these evolves into the stepped leader. Initial breakdown is found not to be a separate process but rather the start of the stepped leader. Another interpretation is that the initial breakdown process is a succession of breakdown events which extend horizontally, up to several kilometres, effectively moving charge horizontally from the main negative charge [6].

During descent towards ground the discharge propagates as a stepped leader. The stepped leader is thought of as a hot core, radius between 0.1 and 0.5 m, surrounded by a cold corona sheath. It is believed that this corona sheath is formed partly by charge deposited by streamers propagating ahead and partly by lateral corona discharges from the hot core [3].

The Stepped Leader

Usually, especially in the early studies, leader forms were organised into two categories, namely alpha and beta. Alpha type leaders have a uniform downward speed, approximately 10^5 m/s and steps of similar length and brightness. The steps are also shorter and less luminous than those of beta type leaders [6]. Beta type leaders seem to have two stages of development after leaving the cloud. They come out of the cloud base or the side of the cloud with long, bright steps and high speed, 10^6 m/s. They also exhibit branching near the cloud base. As they approaches the ground however they start exhibiting characteristics of alpha type leaders, i.e. lower propagation speeds and shorter, less luminous steps. Both types of leaders show an increase in the average speed and increased step brightness as they approach the ground [6].

Beta type leaders are then further divided into two subsections. β_1 are the ones having an abrupt discontinuity in their downward speed [6]. The second stage of propagation occurring within the last kilometre of descent. The β_2 leader is similar to the β_1 leader but in the second stage of propagation the channel is traversed by one or more luminosity waves continuously propagating from the cloud to the leader tip. As these waves reach the leader tip outward branching occurs momentarily at the tip. β_2 leaders are very rare [6].

Many leader speeds have been recorded. These do not vary much though. Most of them are found to be between 0.8 x 10^5 and 10 x 10^5 m/s. The accepted value of charge lowered to ground by the negative first return stroke is approximately 4.5 C [6]. This value excludes the charge associated with the continuing current. Charge neutralised by the return stroke is not necessarily the same charge stored on the leader channel. It is within an order of magnitude of the stepped-leader charge. The stepped-leader charge can also be estimated from leader electric field measurements. From various electric field measurements it has been found that charge for the first few strokes ranges from approximately 3 to 20 C. Measurements of leader current as it approached the ground varied from a few hundred Amperes to a few kiloAmperes [6]. According to early research performed by Schonland charge is thought to be distributed uniformly along the channel; however capacitance of the channel increases as it nears the ground so it should be more of an exponential distribution. Leader current should increase with time and it does for more than 50% of the cases [3]. Two forms of current are associated with a stepped leader. These are the time averaged current and the impulse current associated with step formation.

Figure 3.3 shows an example of electric field changes produced by stepped leaders and the subsequent return strokes [6]. The total electric field would be comprised of electrostatic, induction and radiation fields and the magnetic field of magnetostatic and radiation field components [6].

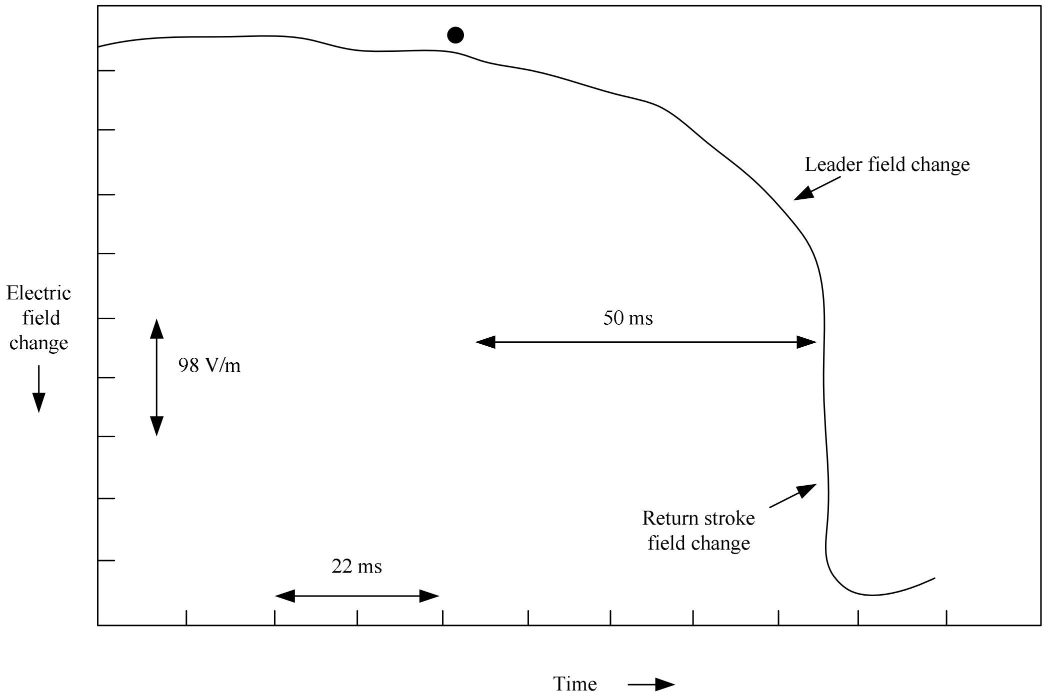

Figure 3.3: Electric field changes associated with stepped leaders after [6]

Return strokes are most responsible for overvoltages on transmission lines and as such have been studied the most. Modern day electronic devices are susceptible to overvoltages from stepped leaders. A leader gives rise to a fast electromagnetic pulse, duration about 1 µs, and to bursts of pulses, lasting 10 – 200 µs. These can create significant disturbances in the digital electronic system [6].

First measured by Schonland leader steps were reported to be between 10 and 200 m, with step intervals taking 40 to 100 µs. It was reported that as leader speed increases both the brightness and step lengths increase. According to Schonland the lowest steps showed increased lengths and reduced interstep intervals as they approached ground [6].

The initial pulse train is attributed to initial breakdown and is generally larger. It lasts a few milliseconds and is followed by a few milliseconds of low, irregular pulse activity by another pulse train. The second pulse train has duration of tens to hundreds of microseconds. In most cases the characteristics of the two pulse trains seem to be different [6].

The frequency spectrum for stepped-leader steps is nearly identical to that of dart leader steps and very similar to the spectrum of initial breakdown pulses. The shapes of the pulses of the leader and return stroke are very similar above 2-3 MHz but leader spectra magnitudes are about five times smaller [6]. The peak step current is at least 2-8 kA close to the ground and the maximum rate of change of step current is 6-24 kA/μs. The minimum charge involved in the formation of a step is 1-4 x 10^{-3} C. The estimated peak temperature of the leader step is estimated to be 30 000 K and it is believed that channel temperature does not fall below 15 000 K [6]. The stepped-leader channel is likely to consist of a thin core, approximately 1 cm in diameter, which carries the current, surrounded by a corona sheath of radius approximately several metres. There is typically an increase in luminosity near the leader tip [6].

"There appears to be a qualitative similarity between a negative stepped leader in lightning and in a long laboratory spark" [6]. The negative leader in the long spark gap exhibits definite steps when the gap is several metres or more. Leader steps are observed in lightning both from negative leaders from the cloud and in negative leaders originated from the ground, i.e. in negative upward leaders. This means that branching is a result of the characteristics of the leader tip and leader channel rather than the leader source. Considering that the potential of the lightning leader is much greater than that of a long spark leader it should have a larger charge per unit channel length, larger leader current and a higher propagation speed [6].

Attachment

The attachment process begins when an upward leader is launched from the ground, usually from elevated sharp points at the ground. It is possible that multiple upward leaders are launched from the ground towards the same downward leader or at times possibly at various branches of the branching downward leader. Multiple terminations on the ground can occur and these involve multiple upward leaders. Upward leaders that do not attach themselves to the downward leader are known as unconnected upward leaders [6].

Conditions necessary for launch of a successful connecting leader from a grounded object are shown below [3].

Condition 1:

Inception of a streamer discharge at the tip of the conductor as described by equation:

$$\exp\left[\int_0^{Xc} (\alpha - \eta)dx\right] = 10^8 \qquad (3.5)$$

Condition 2:

Streamer to leader transition. The requirements for this process have been mentioned previously [3].

Condition 3:

Continuous propagation of the connecting leader and its interception of the stepped leader. When and where the two leaders meet is dependant on their respective speed and orientation [3].

It is very important to remember that the conditions described above may not happen in this order. It is possible for condition 2 occurs before condition 1 and so as soon as there is streamer inception it becomes a leader or that a streamer starts occurring at the tip of a Franklin rod for example because of the high local electric fields generated but the electric field distribution ahead of the rod is not at the optimal value for streamer to leader transition. Therefore streamers continuously occur until conditions are ready for leader inception [3].

The process where downward and upward leaders make contact is known as the final jump [6]. During this process the streamer zones ahead of the two leaders meet and form a common streamer zone. The one return stroke moves down towards the ground and the other upwards towards the cloud [6]. It is obvious that in terms of downward strikes the ground is much closer to this junction point and hence the return stroke directed towards the ground will reach the ground a lot sooner than the return stroke travelling towards the cloud charge source. Once the downward return stroke reaches the ground it results in an upward reflecting wave from the ground moving back up the highly conductive channel created. It probably catches up to the upward moving return stroke generated from the junction point. 'The reflected wave from the ground propagates in the return stroke conditioned channel above the junction point, and hence, is likely to move faster than the upward wave from the junction point that propagates along the leader conditioned channel.' [6]. A high-pressure channel is also produced which then expands creating shock waves. This is what is known as thunder [8].

The attachment process occurs in the first and subsequent return strokes. The upward leader is usually some tens of metres long if initialised from the ground and can be a couple of hundred metres if initiated from a tall object [6]. The length of the upward connecting leader in subsequent strokes is in the order of 10 m. This break through phase has never been observed in natural lightning but has been inferred from observation with long laboratory sparks. The streamer zone is believed to be about 100-200 m in front of the negative stepped leader tip which has an electric potential of 50 – 100 MV [6].

The striking distance is the distance between the object struck and the tip of the stepped leader at interception by the upward leader initiated from the object. Therefore in order to obtain the striking distance it is necessary to obtain the value of the electric field generated by the stepped leader at the ground and the field intensification at the object, termination, on the ground [3]. One can show that the electric field does not depend much on the distribution of the charge on the leader channel when the channel is in the last few hundred metres of descent. The electric field at ground level depends mainly on the charge per unit length at the ground level of the leader channel.

From upward connecting leaders measured it was found that their propagation speed was very similar to the speed of the upward positive leaders in upward positive natural lightning. Average downward leader speed was measured at 2.9 x 10^5 m/s when upward leader average speed for the same event was measured at 0.8 x 10^5 m/s. In case of positive descending leaders upward connecting negative leaders are much longer [6].

In still photographs with downward negative lightning there is evidence of upward connecting leaders in first strokes. One characteristic is a split in the channel image, the other being upward branching in the lower part of the channel and downward branches in the upper part of the channel. Another giveaway is the unconnected upward discharge or a kink in the lower part of the channel [6].

Characteristics of Return Strokes

Pioneering work in this regard was done by Sir Basil Schonland in South Africa. Most parameters have been derived from channel base current measurements. The return stroke current peak for first strokes has been found to be two to three times larger than that of subsequent strokes. It has also been found that negative first strokes transfer about four times the negative charge of subsequent strokes. Subsequent strokes however have a three to four times steeper current rise time. Only a few percent of negative first strokes exceed 100 kA and about 20% of positive ones [6].

Luminosity variation along the channel is thought to reflect the variation in current since current is impossible to measure directly [6]. From streak photography one can also measure propagation speed. When a return stroke reaches a branch there is usually a brightening of the channel below that point. It is thought that this is due to a rapid discharge of a branch, previously charged by the stepped leader. This brightening can also occur after the first return stroke has entered the cloud and in subsequent strokes, which are usually branchless. When no branches are seen this channel brightening is known as the M-component [6].

Typical peak temperatures of the return stroke channel are in the region of 28 000-31 000 K. Electron density is in the region of 8 x 10^{17} cm^{-3} in the first 5 μs and decreasing to 1×10^{17} cm^{-3} at 25 μs. Pressure in the channel is approximately 8 atm during the first 5 us and decays to atmospheric pressure after approximately 20 μs. Channel width from various measurements is approximately 5 cm [6].

Return stroke current is generally measured in two ways. One is from current measurements at tall structures, which are struck more frequently by lightning, and the other from triggered lightning techniques. Knowing the lightning current is important as it helps estimate the voltage developed across resistive devices during lightning strikes [3].

Subsequent Leader

After the first return stroke the others that follow are usually generated by a dart leader. The dart leader moves continuously. 'Many subsequent return strokes are initiated by leaders that exhibit pronounced stepping in the bottom portion of the channel' [6]. These are called dart-stepped leaders. Approximately a third of second stroke leaders deflect from the previously formed channel and continue as stepped leaders. Subsequent strokes which form new termination points on the ground often have both characteristics of dart leaders and of stepped leaders [6].

The average speed of dart leaders tends to be in the region of 1×10^7 m/s and 2×10^7 m/s [6]. Most dart leaders tend to slow down as they approach the ground. The typical duration of the subsequent dart leader is approximately 1 to 2 ms. Subsequent strokes that make a new termination point on the ground however tend to have much longer lasting leaders, in the region of 15 ms [6].

The average measured and estimated peak currents of dart leaders are in the range of 1.6 – 1.8 kA. Charge brought down by the dart leader varies. The minimum charge found to be brought down by a subsequent stroke is 0.21 C while the most frequent value is between 0.5 and 1 C [6]. 'Electric field waveshapes are strongly influenced by leader-channel geometry' [6]. Most waveforms have a hook shape with a net negative field change.

Dart-stepped leader

'Second strokes are initiated by dart-stepped leaders over five times more often than all higher-order strokes together' [6]. The average speeds of dart stepped leaders were found to be 1×10^6 m/s [11]. Downward leader speed tends to decrease. It is estimated that in each step there is a change of a few milliCoulombs and a few killoAmperes [6].

It is found that subsequent return strokes usually follow a calm period, or a period without much measurable current flow to ground. So a stop in channel current is a requirement for formation of dart leaders. Temperature decay in the channel is slow enough to maintain the channel temperature high enough so that no dark currents are required for the dart leader to be initiated [6]. The return stroke current is first cut off near the ground. 'If a grounded, current carrying channel does exist and it becomes energised at the top, the leader-return-stroke sequence is not needed to accomplish the transfer of charge to ground and a different mode of charge transfer, called the M-component takes place instead' [6]. A dart length average of approximately 40 to 50 metres seems to be the most observed [6].

Continuing current

This is a low level current, tens to hundreds of amperes, which immediately follows a return stroke. It is effectively an arc between the cloud and ground along the path of the preceding leader. Short perturbations in the continuing current, lasting a few milliseconds, are known as M-components [6]. Due to their large currents the continuing currents are responsible for most thermal damage associated with lightning. Long-continuing currents are considered to be ones that have currents to ground lasting in excess of 40 ms. The electric field signature of a continuing current is that of large slow electric field change of the same polarity as the preceding return stroke. Continuing currents are usually initiated by subsequent strokes in a multiple stroke flash [6]. ‘A continuing current is usually initiated by a stroke with relatively small charge transfer that follows a stroke with relatively large charge transfer’ [6]. Charge centres associated with continuing currents tend to be in more mature regions of a thunderstorm. The J-process does not initiate continuing current but it is initiated by the return stroke itself. The return stroke removes charge deposited on the channel by a preceding leader while continuing current is associated with the tapping of fresh charge regions in the cloud [6].

M-components are surges in the continuing current phase and in the associated channel luminosity. They are named M components as they were first studied by D.J. Malan. They transport negative electric charge from the cloud to ground. M-components require a presence of current carrying channels to ground in order to occur [6].

M-component light intensity is very different from return stroke intensity. The return strike light pulse has a fast rise to peak at ground level and degrades greatly with height. The first M-component does not vary greatly with height while the second does decrease somewhat with increasing height [6]. The return stroke pulse has maximum amplitude at ground level and the M-component dominates in the upper half of the visible channel section. The M-component light pulses are also very symmetrical [6]. Typically an M-component has a fairly symmetrical light pulse with amplitude 100 – 200 A. This is some two orders of magnitude lower than the return stroke current pulse. They also exhibit a 10 - 90 % rise time of 300 – 500 μs and a charge transfer to ground of 0.1 – 0.2 C [6].

M-component electric fields exhibit characteristic hook shapes [12]. It is suggested that M-components are initiated by fast moving negative streamers, leaders (1×10^6 or 1×10^7 m/s) hitting the upper extremity of the conducting channel to ground and by fast positive streamers developing outward from the upper extremity of the conducting channel to ground [6].

‘The J process also known as the junction process occurs within the cloud during the period between return strokes’ [6]. It is characteristic of a relatively steady electric field change for a period of some tens of milliseconds. The relatively fast electric field changes are known as K changes. These also occur between strokes. There is a lot of controversy and confusion over the definition of K changes. One definition is that K changes in ground flashes are step-like electric field changes that occur during inter stroke intervals and after the last stroke. They have the same polarity of J changes and 10 - 90% rise time of 3 ms or less [6]. Another is that K changes are pulses occurring during inter-stroke intervals and after the last stroke. Yet another is of K changes as in-cloud processes that could not be attributed to any other known lightning process. In this definition the K-processes are indistinguishable from M-processes and dart leaders, except that they don’t propagate all the way to ground [6].

The first sign of a K-process was inferred by Malan and Schonland in 1951. It was thought to be a leader not able to reach the ground and hence only made a small readjustment of charge within the cloud. Subsequently the K-process has been thought of as a recoil streamer occurring when a positive J-type leader propagating within the cloud encounters a region of negative charge. It seems that the K-process charges the lightning channel which has been disconnected from the ground and extends it through breakdown at its extremities. Most K-processes can be seen as unsuccessful subsequent leaders [6]. Usually all pulses within a burst have the same polarity and there are approximately 30 pulses per burst. Both polarities seem equally frequent and the peaks are approximately two orders of magnitude smaller than return stroke initial field peaks in the same flash [6].

The formation of thunderclouds and the mechanism of lightning have been covered in this chapter. Since these concepts have been established the sections to follow deal with the proposed idea for an improvement in traditional lightning protection and the testing performed so far.

Chapter 4

Proposed System, Review of Non-Conventional Lightning Protection Methods and Simulations

4.1 The Proposed System

The importance of adequate lightning protection is obvious. There are a number of deaths and expensive property damage associated with lightning each year [3, 6]. This is more frequent lately due to the number of sensitive equipment in use in homes and big office buildings. This equipment is sensitive to current surges associated with direct lightning strikes. This type of damage usually occurs when the lightning protection system is not struck but instead the structure it protects is struck. If one is able to devise a system that protects its zone of protection more efficiently there will obviously be less loss of lives and damage to equipment.

It is important to understand the behaviour of variously shaped structures under extremely high electric fields experienced during the approach of the downward moving leader. Elevated sharp points on the ground go into corona and streamers start developing from their tips. At this time the background electric field is not sufficient to maintain streamer propagation and these streamers collapse leaving behind space charge. The formation of space charge retards the formation of an upward leader from a grounded structure. Space charge is defined as density of charged particles (ions) in air that modifies the local electric field [13]. The existence of space charge can have significant influence on lightning propagation. It has also been proven that blunt rods perform better than sharp rods in attracting lightning in the conventional protection system. That is that a blunt Franklin rod performs better than the sharp one. This is well documented in [2, 14]. The idea behind any lightning interceptor is to be able to launch a streamer that can propagate and undergo streamer to leader transition becoming the intercepting upward leader. Thus the main attributes that a lightning interceptor needs to have are that it needs to be able to emit a streamer and it also needs to be able to emit the streamer at the right time for the electric field conditions to be such that this streamer is able to undergo streamer to leader transition and thus become the upward connecting leader.

The sharper the tip of the rod the more enhanced the electric field around it is and hence the greater its ability to create discharges will be. It is also important to note that this means that the sharper rod will produce discharges far too early for the background field to be strong enough to sustain the formation of an upward leader from this streamer discharge. This results in formation of space charge and as mentioned this lowers the field around the tip of the rod. There is thus a balance between these two pre-requisites in order to find an ideal Franklin rod. A series of simulations performed in [4] place this critical radius of the conductor at approximately 350 mm.

The aim of the proposed lightning termination is thus to create a rod which behaves in a way so as not to emit any streamers too early when the background field is not strong enough to sustain streamer propagation and streamer to leader transition. It must also be of the correct shape and radius to be able to emit a streamer. This streamer is to be emitted at precisely the right time so that it becomes an upward moving leader. Since it is launched at the correct moment it intercepts the downward stepped leader and becomes the preferential strike point in its zone of protection. This means it is a slight improvement on the existing method but if successful it would show the importance of the effect that space charge plays in the retardation of the formation of the upward connecting leader.

Of course it would be almost impossible to obtain a device which would only ever emit a single streamer during the approach of a downward leader in its zone of protection but the aim is to investigate this effect rather than to obtain a perfect system. If experimentation shows that this indeed is the radius at which the desired effects occur the aim is to try to reduce the radius whilst maintaining acceptable levels of performance. The traditional method of lightning protection mentioned earlier is that of a Franklin rod.

Ever since Benjamin Franklin's kite experiments and the published findings in 1751 there has been a similar method of lightning protection in use [15]. In fact Franklin setup his lightning rods and kites in order to prevent lightning from happening. The idea was to send a sharply pointed kite into the sky, during a thunderstorm, or construct a tall rod and repel or discharge the thundercloud by creating the opposite charge at the tip of his kite/rod [16]. It was soon discovered that rather than prevent lightning the rod actually got struck by lightning, provided it was high enough. The Franklin rod thus, when properly earthed, could protect the structure close to it by being the preferred strike point for lightning in that vicinity and passing the charge safely to ground [16]. Fairly soon it was discovered that at times lightning would bypass the rod and strike the structure lower down causing damage and injury. Even though problems associated with the Franklin rod have been well documented and known for many years superior alternatives have not been proven. There have been varied solutions presented with, at times, startling claims. There has however been no evidence that these devices perform as well as it is claimed under natural lightning conditions [1]. There are two main trains of thought in the non-conventional lightning protection systems. These can be classified as devices that attempt to repel lightning, known as Charge Transfer Systems (CTS) or Lightning Elimination Devices (LED) and ones that work to attract lightning 'earlier' than the Franklin rod. These are known as the Early Streamer Emission (ESE) systems.

The two variations of non-conventional lightning protection are further discussed in the following section.

4.2 Review of Non-Conventional Lightning Protection Methods

4.2.1 Early Streamer Emission Systems (ESE)

This is one of the non-conventional approaches to lightning protection. In essence it is also a lightning attractor, same as a conventional lightning rod. It attempts to create conditions such that a longer upward connecting streamer would be generated from this lightning protection device. According to [16, 17] the attractive effect of an air terminal would be enhanced by a longer upward connecting leader. Therefore, the longer the leader the greater the enhancement. In essence ESE systems are very similar to the conventional Franklin rod but they have air terminals that attempt to create an upward moving streamer earlier than the conventional rod [1]. These streamers would then reach the downward moving stepped leader at an earlier time. This upward moving streamer is said to extend significant distances and as such claims to provide a greater zone of protection than the conventional methods of lightning protection. The manner in which this is claimed is that if one multiplies the time difference by which the ESE device emits the streamer, before the conventional device, with the speed of the upward leader a distance value is reached [1]. It is this distance that is claimed to be the extra zone of protection or height of terminal when calculating the zone of protection by the rolling sphere method or any of the other methods. One of the methods proposed for the new calculation of the zone of protection of these ESE devices is the Collection Volume Method (CVM). The CVM is an attempt at a modified way of calculating the effective protection zone of a lightning termination. It calculates the zone of protection by taking into account the perceived extra length of a lightning termination if that lightning termination enhances the electric field at its tip. It is explained in detail in [18-20]. It then follows that an ESE device would be able to replace a number of Franklin rods and protect the object in question equally well.

There are several types of ESE devices and they are distinguishable by some sort of discharge triggering device at the top of the conductor. Some devices have reasonably complex rod tips. In essence there are two distinct ESE systems. The first kind invented is an active device, known as the radioactive rod. This device is usually fitted with relatively weak alpha particle emitters with long lifetimes. This is most commonly 241 Am with a half-life of 433 years. Other materials used, include 226 Ra, 85 Kr and 60 Co. The manner in which they operate is that the products from the radioactive decay of these materials ionise the air just outside the terminals creating early streamers. This is usually a radius of 10 to 30 mm [1]. It has been argued however that, outside of the small region near the terminal, the ion pair formation rate in the atmosphere from a radioactive source falls significantly below the rate from natural background formation [21]. There have also been many questions raised about their harmful effects to humans and the environment due to their radiation emission.

The other ESE system in use, with many variations, is a passive device that uses a special arrangement of electronics and electrodes to facilitate electrical breakdown of small air gaps in the high electric field generated by the approaching stepped leader. When a very high, rapidly rising voltage is applied to the sphere-sphere or point-sphere gap, depending on the configuration of the device, there needs to be a free electron available to facilitate electron avalanche and the electric field strength needs to exceed the breakdown strength of air. Once breakdown occurs it generates a streamer from the device and it operates identically to the other active ESE devices. Its obvious advantage is that of no radiation being emitted into the atmosphere as well as only acting under the high fields generated by thunderclouds [15]. There has been much debate over the effectiveness of the ESE systems. There are currently two standards, namely the French and Spanish that accept ESE systems as adequate lightning protection mechanisms and have standards for the zone of protection incorporating ESE system mechanics. There are also many other standards and organisations that have rejected the devices completely and have not redesigned the standards based on this technology. These include the American NFPA 780 [22] as well as the IEC 61024-1 [23]. One example of the rejection of these devices is available in [24].

As previously mentioned the proponents of these devices claim that if their device sends a streamer earlier than the conventional Franklin rod by a certain time difference and that time is multiplied by the speed of the leader the extra distance of protection is obtained [25]. In calculations promoting ESE devices the upward moving leader is assumed to be moving at 10^6 m/s. In many measured instances the speed of the upward moving leader is calculated to be in the order of 10^5 m/s or even 10^4 m/s [3, 6]. Another interesting area of contention is that if the ESE device is able to emit a streamer at an earlier time than the conventional rod the upward leader this is supposed to generate is thus generated in a lower electric field. The question then becomes how the streamer is able to propagate in this lower electric field. This is due to the fact that once the streamer propagates further from the rod it relies on the strength of the electric field to supply the energy near the leader tip and the dielectric properties of air undergoing breakdown to carry on propagating. Neither of these factors is influenced by the rod tip. Finally another detrimental factor to the performance of ESE systems is that of corona discharge. The corona formed due to the streamer discharge and the high ionisation of air has an associated space charge with it. This ion space charge can significantly reduce the electric field strength near the top of the air terminal and thus inhibit further streamer initiation. There have been numerous cases where ESE systems have failed to protect structures within their zone of protection. Examples of this are documented [26]. There have also been reports of the installed devices operating without failure. This is documented in [27, 28]. In these cases however it is very possible that a Franklin rod would have operated in exactly the same manner.

4.2.2 Lightning Elimination Devices

In recent years these systems have become known as Charge Transfer Systems (CTS). These devices attempt to create a corona so high so as to repel the downward lightning leader or to neutralise the charge created in the thundercloud. The idea for such a method of lightning protection is not a novel one though. It was thought of as early as 1754 when a Czech scientist Prokop Divisch devised a similar device and called it 'machina meteorologica' [1]. They are often comprised of an array of sharp points similar to barbed wire that are mounted on top of a grounded conductor. They are thus grounded in the same manner as conventional lightning protection systems [29]. These types of devices are mounted on or next to their area of protection.

The manner in which these devices attempt to operate is that from these sharp points a large amount of corona is generated under the presence of the electric field created by the thundercloud imbalance above. This corona is supposed to; either discharge the above thundercloud and hence eliminate the possibility of lightning, or to discourage the downward stepped leader from attaching to the array through the reduction of electric field in the vicinity of the array. It actually suppresses the formation of the upward streamers, hence the upward connecting leader [1].

The actual patent for a multiple point system was only issued in 1930. It was used to protect petroleum storage tanks from lightning. Commercially these types of products have been available from 1971 [30]. Due to this short implementation time against natural lightning it is very difficult to judge their success. These types of systems are usually designed for tall towers but have also been used in the protection of airports and substations. A short description of the proposed method of operation of Charge Transfer Systems follows. Negative lightning is considered in this example. The ground charge collector is said to neutralise the positive charge on the ground which would be caused by the great negative charge gathered in the thundercloud. It also attempts to drive away millions of ionised air molecules towards the thundercloud by creating a high electrostatic filed therefore forming a 'protective space charge'. It in effect attempts to form an ion cloud between the structure and the cloud. Therefore space charge acts almost like a Faraday shield [1].

There have been suggestions that in the same manner needles from pine trees would then be able to protect themselves from lightning and yet these trees are often struck by lightning. There have been varied research results on how much corona a pine tree is able to produce as compared to the CTS. If one takes the cloud regeneration time to be 10 s it is important to attempt to estimate the corona produced charge and the distance this charge can travel over this time. Both the lighter and heavier aerosol space charges move under the influence of the electric field of the charge and space charge as well wind. The ions may reach speeds of 15 m/s above. These charges may therefore reach up to a height of 150 meters [1]. One important aspect not considered by these devices is that of the initiation of the upward connecting leaders in response to the downward approaching leader. If the rapidly varying electric field associated with the approaching stepped leader acts to overcome the shielding effect of corona space charge near the grounded object the upward connecting leader will escape the space charge cloud and intercept the downward leader. This will mean that this system acts identically to the conventional lightning protection systems [1]. It is also highly improbable that one of these devices could generate enough corona to neutralise all the charge in the cloud.

A number of these systems have been installed throughout the world. There have been reports of strikes to the area of protection of these systems and these have been captured. The promoters of these systems claim poor maintenance and installation but even with this in mind there is not enough data to support the claim that these systems prevent the occurrence of lightning in their zone of protection.

4.3 Simulations

Simulations of downward lightning attachment to objects on the ground have been performed previously by numerous studies [2, 4]. Most of these studies point to a critical radius of a lightning conductor at approximately 350 mm. The studies researched are very extensive and include simulations with varying rod heights and varying background electric fields.

An example of one such study is [4]. It performs simulations on conditions required for the launching of a connecting leader from a Franklin rod. These simulations are thus replicating the same scenario discussed in this research. The simulations performed state that for a successful upward leader to be launched, there are certain conditions that need to be satisfied. Firstly the rod requires the inception of a streamer discharge. Secondly this streamer discharge needs to undergo streamer to leader transition. These conditions are examined and the results of the simulations are discussed below.

The simulation setup is shown in *Figure 4.1* [4]. In this scenario the cloud is simulated by an infinitely long conducting plane and given a potential. It is located at a height of 5 km from the earth's surface. With this arrangement there is a uniform electric field created between the cloud and the ground. The downward leader has been given a thickness of radius 20 mm in the simulations. It is modelled as a perfect conductor. It is given the same potential as the cloud. The Franklin rod is modelled as a cylindrical structure. Its tip has the same structure as the cylinder forming its base. It is placed directly beneath the downward approaching leader [4].

Finite element electrostatic simulations were performed using the above mentioned setup. The downward leader is simulated at varying heights, replicating its downward descent towards ground. At each step during the simulations the two conditions mentioned earlier were evaluated. Firstly it was evaluated whether the conditions for streamer inception were satisfied at the Franklin rod. Following this streamer to leader transition conditions were evaluated.

Conditions necessary for streamer inception have been discussed earlier. As stated in previous sections it is assumed that once a streamer has travelled for a distance of 3 m it has undergone streamer to leader transition. Hence, in this simulation streamer to leader transition is assumed if the electric field up to a distance of 3 m from the Franklin rod is at 500 kV/m or more. This assumption implies that if the field at 3 m from the Franklin rod is more than 500 kV/m the streamer emitted from the rod will be able to propagate the required distance after which it becomes a self sustaining leader [4].

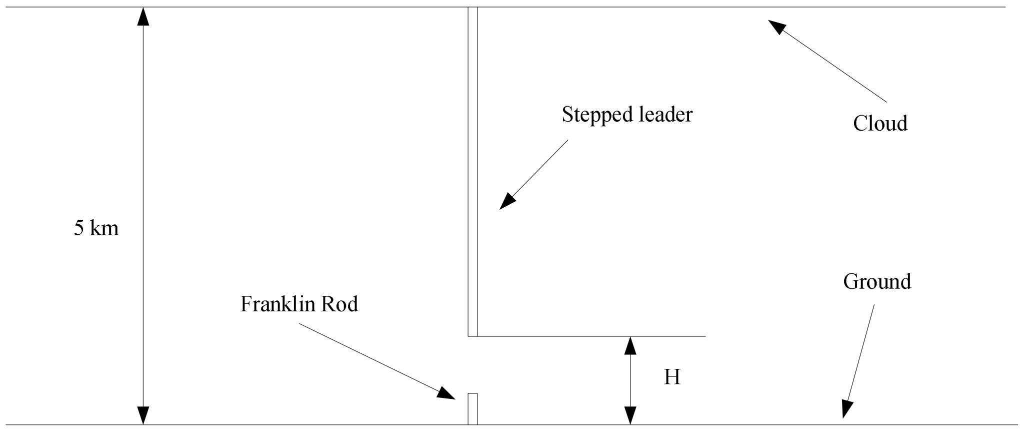

Figure 4.1: Simulation configuration of research conducted after [4]

These simulations give an idea of the effect of height and radius of the Franklin rod on upward leader inception. With the height of the rod set at 10 m and the voltage of the cloud and hence the leader set to -100 MV the results shown in *Figure 4.2* are obtained [4].

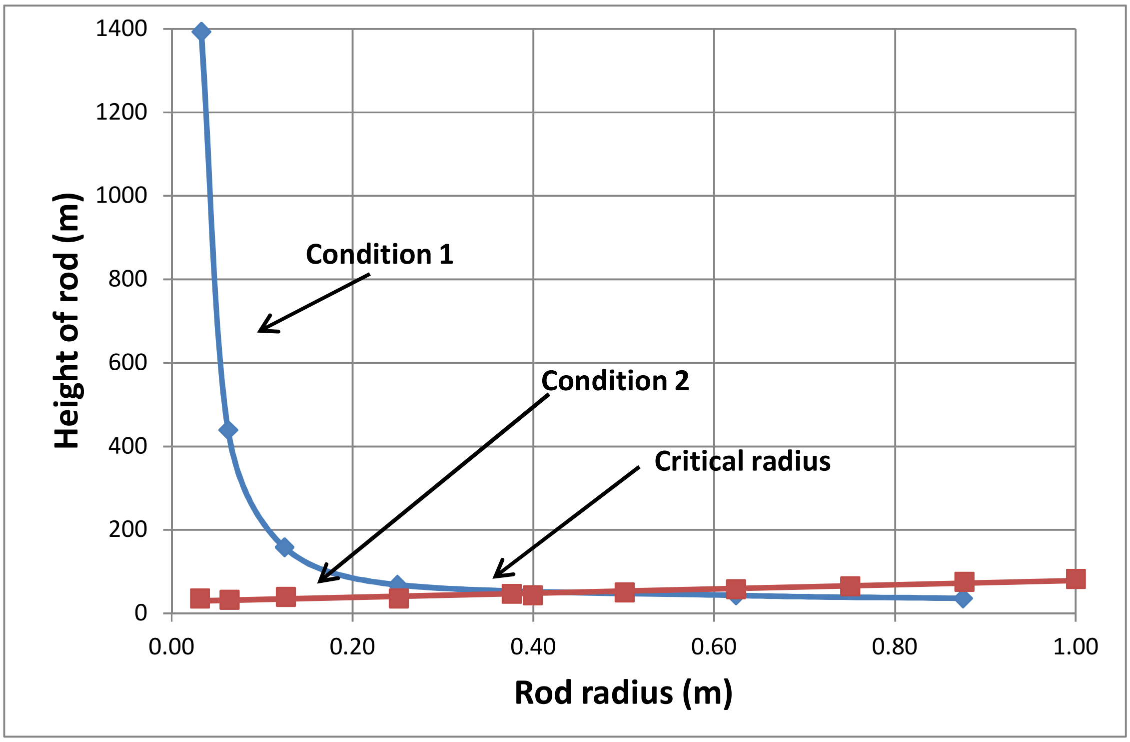

Figure 4.2: Simulation results of research performed after [4]

Figure 4.2 shows the height of the stepped leader tip from the ground against rod radius when both of the previously mentioned conditions are satisfied. The critical radius is placed at approximately 350 mm. Similar studies have been performed in [31] and similar results were obtained.

Research conducted in [32] aimed to model similar effects discussed in this research and in [4]. It modelled the lightning rod's response to ambient field changes due to the charges in the cloud and due to the approach of the downward negative leader. It also investigated the shape of the lightning rod on streamer inception as well as upward leader inception. This research used a slightly different approach of setting a rod diameter and changing other variables such as rod height, downward leader height and atmospheric conditions. These simulations were then followed for a number of rod heights from 1 to 10 m. In one of the simulations where the critical radius was calculated for rods of different heights and at different altitudes it can be seen that the results are very similar to the ones obtained in [4]. This is shown in *Figure 4.3* [32].

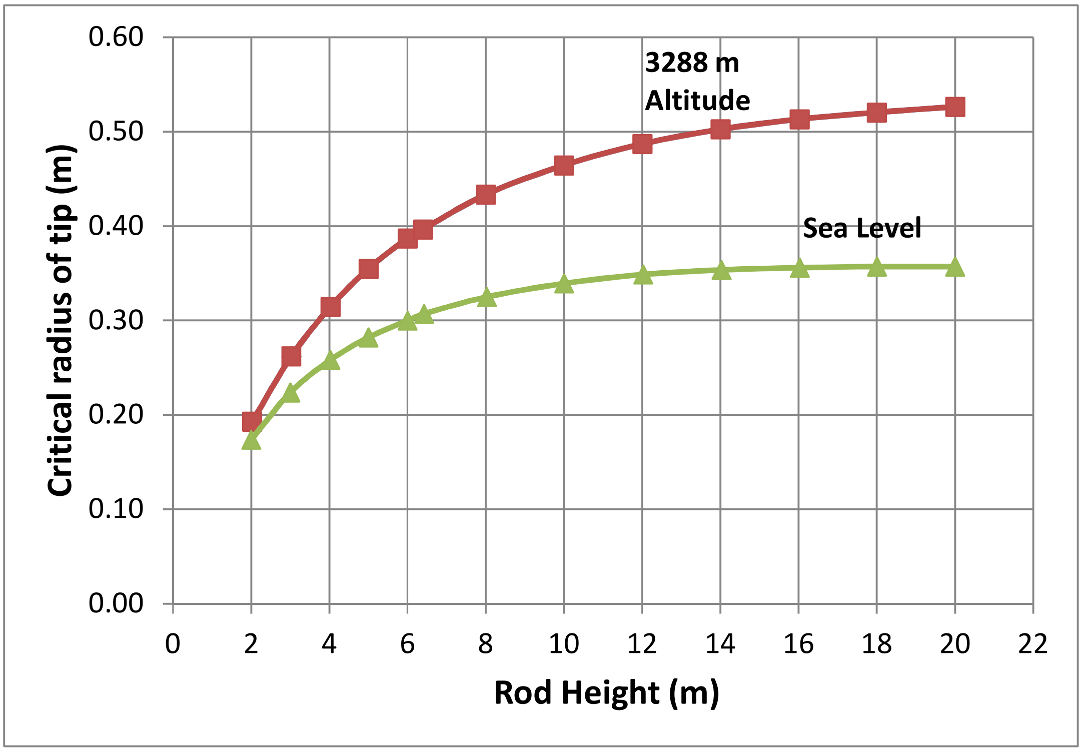

Figure 4.3: Critical radius results of simulation studies performed in [32]

If one concentrates on the results obtained at sea level it is evident that at a height of 10 metres, which is the same rod height used in [4], the critical radius is above 300 mm, at approximately 330 mm. This is very close to the 350 mm critical radius obtained in [4]. Research conducted in [32] used charge simulation and hence a slightly different approach yet yielded very similar results. For this reason the author felt that the critical radius of 350 mm was a valid starting point for testing.

Some simulations were attempted as part of this research. They were performed in Maxwell™. The simulations were performed in 2-D and since Maxwell™ is an electrostatic tool the simulations are merely snapshots in time of the varying condition experienced. A simple simulation setup was constructed based on the setup explained in [4]. A typical simulation setup is shown in *Figure 4.4*. Both comparison tests and tests with a single rod are considered in the simulations. In addition the scale of the simulations extends to both situations, namely under laboratory conditions as well as under natural lightning, outdoor installation conditions.

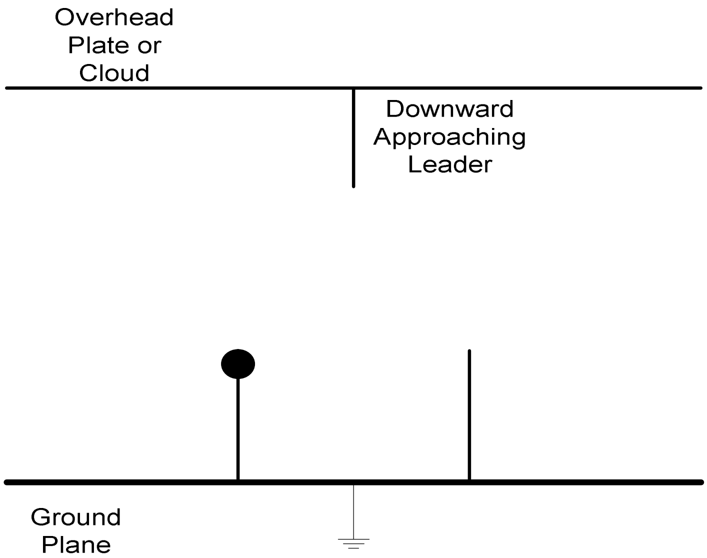

Figure 4.4: Typical simulation setup

During comparison test simulations the Franklin rod and the quasi-hemispherical rods were kept at the same height. The downward leader was also placed directly in the middle of the two competing rods. The downward leader was simulated at varying heights from the ground effectively acting as snapshots in the approach of the leader. The downward leader was simulated as a perfect conductor. There was no consideration of suspended water droplets or humidity effects in the simulations. The ground plane and the cloud were simulated as infinite plains. The ground was simulated as having 0 voltage. The cloud is simulated as having a pre-defined charge value. This charge value was varied in a number of simulations.

The process according to which the simulations are performed is that firstly the setup is drawn as explained above. Consequently electric fields are observed during simulations. The electric field at the tip of the competing rods is considered. One needs to look at two factors. Firstly the point at which the electric field at the tip of the conductor is strong enough for air to break down in that region. This means that there is corona and streamer activity in this region. Secondly it is to look at the electric field strength slightly further from this point and see whether the electric field strength is such that this streamer activity can be sustained. If it is not it means that the streamer will probably extinguish creating space charge. If it is strong enough it could well mean that an upward leader could be formed. This process is very similar to the one described in [4]. Simulations of such magnitude proved to be very complex. As shown in [4, 31, 32] simulations of this type are large research projects. Considering that the simulations performed in [4] are very similar to the simulations attempted by the author and that the results obtained have been confirmed by other research elsewhere it was decided to use the critical radius obtained in these [4] as the design criteria in this research. The critical radius obtained in simulations in [4] was 350 mm and in simulations performed in [32] it was 330 mm.

The aim of the research was to obtain the critical radius of the hemispherical shapes on top of the Franklin rod and to evaluate them through experimentation. The simulations yielding a critical radius of 350 mm thus provided a good starting point. The aim was to also evaluate spheres of varying radii and to evaluate the performance of quasi-hemispherical air terminations through experimentation.

Chapter 5

Testing

5.1 Preliminary Testing

Preliminary testing has been performed at the High Voltage Laboratory at the University of the Witwatersrand, Johannesburg. These preliminary tests are small scale laboratory experiments and do not accurately replicate natural lightning conditions but provide good setup starting point for the investigation.

5.1.1 General Test Setup

The general test setup is closely based on experiments described in [2] and is shown in *Figure 5.1*. This allows for comparison and validation of results. The setup has however been scaled down due to size constraints in the High Voltage Laboratory at the University of the Witwatersrand. The size of the overhead plate is 4.5 x 4.5 m. The reason that this size of plate is chosen is that at air gap distances of up to 2 metres the plate should be sufficiently large to provide uniform electric field lines in the area where the rods are placed. The plate lattice is made of angle iron and the open space is covered with an expanded metal mesh. The idea is to create an equipotential surface parallel to the ground. Due to size and generator voltage constraints, the preliminary tests are limited to gap sizes of approximately 1.5 m. Most of the tests were performed with a negative impulse voltage. This is due to most cloud to ground strikes being negative. The Franklin rod in use has been sharpened so that its tip diameter is less than 1 mm.

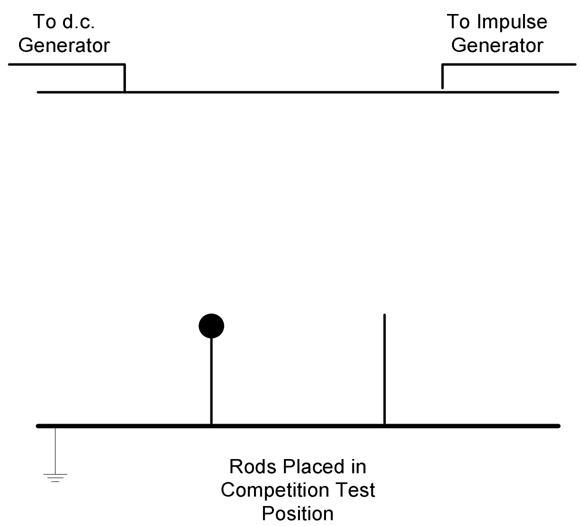

Figure 5.1: General test setup

5.1.2 Testing

A 1.2/50 µs waveform was applied to the overhead rod with the two competing rods placed in between the rod and on a large earth plate. The actual waveform applied was measured to be 1.2/62 µs. An example of a typical waveform used during testing is shown in *Figure 5.2.*

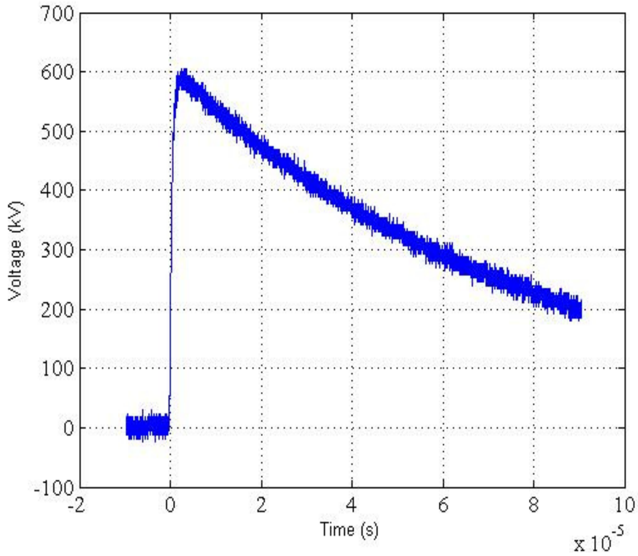

Figure 5.2: Typical positive lightning impulse used during testing

The spark gap was set at 1.5 m and an impulse voltage of approximately - 600 kV was applied. For each of the tests twenty impulses were fired and the number of strikes to each rod was noted. In order to maintain equal conditions for both the competing rods the rods were swapped around half way through the experiment. Tests were performed with the Franklin rod of tip diameter less than 1 mm and a sphere of radius 200 mm. Both the rod and the sphere were placed approximately 1.5 m from the ground. The results of preliminary testing are tabulated and shown in *Table 5.1*.

Table 5.1: Preliminary comparison test results

Voltage	**No. of strikes to Franklin Rod (tip diameter ≈ 1 mm)**	**No. of strikes to sphere (radius = 200 mm)**
- 600 kV	26	14

Tests were repeated with positive impulses and very similar results were obtained. 27 out of 40 strikes were recorded to the Franklin rod. In this first test there was no d.c. bias induced in the test setup. During a thunderstorm a high electric field is set up between the earth and the clouds and this high electric field is experienced by the objects on the ground, such as competing air terminations. This scenario can be replicated by imparting a d.c. bias onto the air terminations of opposite polarity to the polarity of the strike (since the earth will become positively charged due to the large negative charge at the bottom of a thundercloud). With no d.c. bias imparted onto the competing rods the electric field at the tip of the rod will not be enhanced and this is not a true representation of conditions experienced in nature. Under the d.c. bias conditions, and indeed in conditions experienced during natural lightning, the Franklin rod would go into corona at it's tip since the electric field would be most enhanced at this point. The configuration without d.c. bias would favour the Franklin rod as there was no corona, and the associated space charge and its negative effect in the formation of the upward leader, present.

In the second set of tests the aim was to introduce the d.c. bias into the setup and place the plane above the Franklin rods. This would be closer to the setup initially envisaged and would produce more accurate results. The manner in which the d.c. bias was placed into the system is as follows. It is known that the sharply pointed Franklin rod will go into corona before the spherical rods since the electric field around its sharply pointed tip is enhanced. Therefore the Franklin rod was tested by applying a d.c. voltage to it and measuring the voltage at which steady corona occurred at the tip of the rod. A corona camera was used to verify the presence of corona at the tip of the Franklin rod. The voltage at which this condition was satisfied was approximately 22 kV. When both the competing rods were subjected to the above mentioned voltage the spherically shaped rod did not go into corona. In effect this d.c. bias voltage emulates conditions where the background electric field during thunderstorms is high enough to make the Franklin rod go into corona while the spherically pointed rod does not go into corona due to a less enhanced electric field at its tip. Under these conditions space charge would be produced around the Franklin rod and not around the spherical rod. Since the experiment setup is that of a negative CG strike a negative impulse is applied. Under these conditions in nature the ground would become positively charged. Accordingly the d.c. bias applied to the two rods is positive. The setup of the second set of experiments performed is shown in *Figure 5.3*.

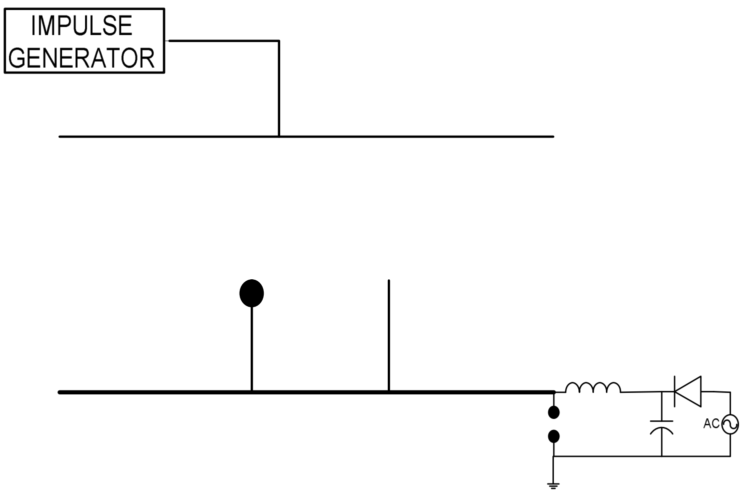

Figure 5.3: Experimental circuit diagram for secondary testing

The d.c. biasing circuit is made up a simple half-wave rectifier being fed from a transformer with the voltage input increased through a variac. The main problem experienced with this type of setup is that of protection of the two voltage sources. Primarily the d.c. biasing voltage source needs to be protected as it will experience a tremendous rise in voltage once the impulse flashes over to either of the competing rods. This will in turn place a strain on both the diodes and the capacitor. In order to solve this problem the two competing rods are earthed through a spark gap. The spark gap is set to flash over at approximately 28 kV. This means that while the rods are only under d.c. voltage the spark gap will not fire but as soon as there is an impulse strike to either of the rods the voltage will rise dramatically and the spark gap will fire and protect the charging circuitry. Since the impulse has very high frequency there is a chance that the diodes in the half-wave rectification circuit will experience this rise in voltage prior to the discharge through the spark gap. This would in turn damage the diodes. In order to safeguard from this an inductor is placed between the rods and the half-wave rectifier.

The results obtained from this particular setup are shown in *Table 5.2*. Once again the position of the competing rods was swapped over half way through the experiment to avoid biasing and the rod and the sphere were kept at the same height. It is clearly evident that there were no strikes to the spherically tipped rod.

Table 5.2: Test results of competition tests with d.c. bias, 1.5 m gap

Applied Voltage	**No. of Strikes to Franklin rod**	**No. of Strikes to Spherically Shaped rod**
- 600 kV	40	0

5.1.3 Discussion of Preliminary Test Results

The reason for all of the strikes being recorded to the Franklin rod is due to the fact that the gap size between the rods and the plate is far too small. This means that there is no formation of an upward leader from either of the rods. Again, this arrangement favours the Franklin rod. Even though there is a formation of space charge around the tip of the Franklin rod the role of this space charge is to retard the formation of the upward leader from the rod. Since there is no upward leader formation the discharge strikes the Franklin rod due to an even further enhancement of the electric field in that region. It is thus crucial for this research that upward leader formation occurs in order for the concepts mentioned to be truly tested.

For reasons mentioned above it is imperative that the test setup be extended to gaps long enough for formation of upward leaders from the competing rods.

5.2 Long Air Gap Testing

5.2.1 Background

Long air gap testing was performed at the South African Bureau of Standards (SABS), National Electrical Test Facility (NETFA) High Voltage Laboratory. The testing took place over five days, from 8 – 12 February 2010. The test setup was designed to be long enough to attempt to create upward leader formation from competing air terminations. It was believed that this would be achieved with gap sizes of over 5 m.

Laboratory time proved very difficult to obtain as it was fully booked for months in advance and since this was not a commercial research the laboratory was available for a slot of 4 days between other tests conducted at NETFA. This meant that everything had to work first time which made the preparation of the tests crucial. Testing was performed in the form of competition tests between the Franklin rod and spheres as well as quasi-hemispherical shapes. Due to time constraints testing was performed with forty impulses per shape. After twenty impulses the competing rods were swapped around.

The test setup was designed in the form of a plane to rod geometry. The elevated earth plane would represent the bottom of the cloud and the rods at the bottom the lightning protection termination points. The competing rods were spaced 3 m apart. The air gap is designed to be 5 m in length. At this gap length the elevated earth plane needs to be appropriately sized so that the electric field lines are kept parallel to the ground. This means that it needs to be large enough so that the edges of the plate do not influence the electric field in the vicinity of the competing rods. For this reason a new, larger elevated earth plate was constructed. This large elevated earth plate is 9 x 9 metres in size.

During small scale tests an earth plane made of angle iron and expanded metal was used. This proved to be heavy and difficult to adjust and align, especially once elevated. For this reason, and considering that the new plate had to be much larger, a more lightweight structure was required. It also had to be dismantled for transport and easily and quickly reconstructed for testing. The problem with a lightweight structure is that it generally isn't able to support its own weight and hence sags. Another design criterion was to ensure a reasonable cost. A number of variations were attempted, including a copper pipe structure as well as a wooden structure overlaid by a wire mesh. Finally the design that was settled on was made of polyvinyl chloride (PVC) electrical conduit.

The electrical conduit was cut into 1 m pieces. As mentioned the elevated plane was 9 x 9 m in size. This meant that the plate required 180 pieces. The conduit pipe selected was 20 mm in diameter. It was joined together by conduit connectors. Testing on the connected pieces showed that two meters of conduit could support itself but three 1 m pieces when connected would sag too much. This meant that every two metres the grid had to be supported or lifted. Hence the grid was constructed in such a way that it had 36 lifting points. The layout and the lifting points are shown in *Figure 5.4*.

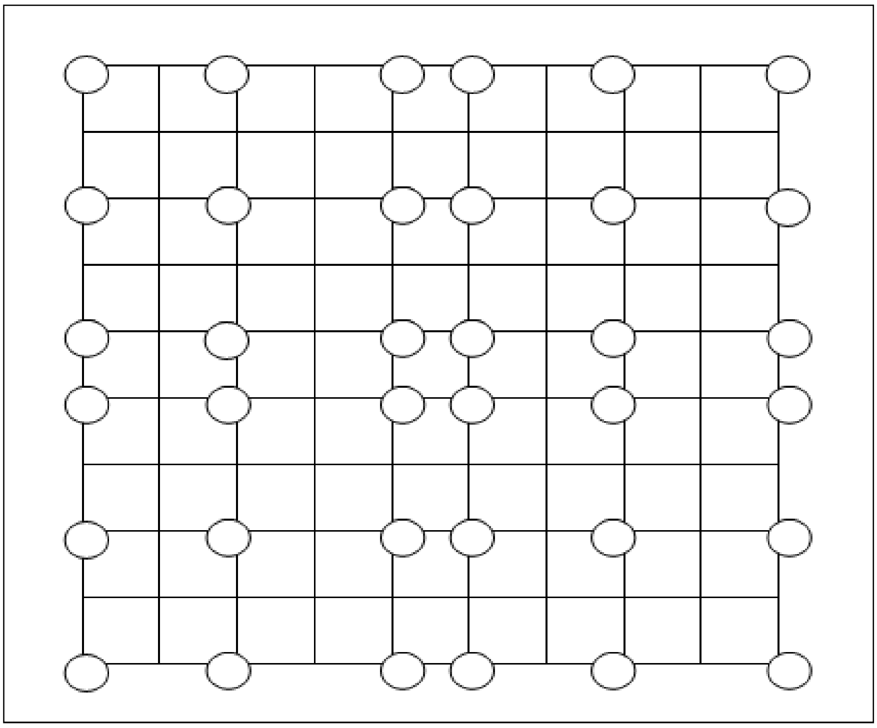

Figure 5.4: The elevated earth plane layout with the lifting points

The 36 lifting points meant that 18 straps were required for lifting. These straps are adjustable so that the levelling of the plane can be aligned once it is lifted, if required. Straps were placed between the elevated earth plane and the crane. Since the crane is grounded it means that the length of the straps needs to be such that the gap between the plane and the crane is greater than 5 m, to prevent flashover to the crane. The straps therefore range in length from 15 m to 18 m, and were specially ordered in these lengths. Hooks are placed on the lifting points of the grid. The grid is then covered with a wire mesh. It was chosen as it is light enough and can be easily rolled, transported and placed into the required position. It is also cost effective. The wire mesh consists of 9 m lengths, is 1 m wide and is fastened to the conduit structure with cable ties. The overlapping wire lengths were connected so that they are electrically continuous, producing a 9 x 9 m equipotential, conductive surface. The elevated earth plane remains flat once adjusted and mimics the bottom of the cloud in thunderstorm conditions.

The entire system proved far less costly than alternatives attempted. The conduit grid structure is shown laid out on the floor in *Figure 5.5.*

A d.c. bias is introduced into the circuit to replicate the electric field conditions experienced during thunderstorms. As stated there are two ways of replicating this effect in a laboratory environment. One is to apply a d.c. voltage to the elevated earth plane and the other is to apply a d.c. voltage directly onto the competing rods. By placing a voltage onto the plane one creates an electric field between the plane and the ground. The air terminals are subjected to this field and this closely represents conditions experienced during actual thunderstorms.

There are complexities introduced by this method however. One needs to create an electric field similar to the one experienced in real lightning conditions. The exact value is difficult to estimate as it differs from storm to storm. With regard to the South African summer storms a good estimate is 50 – 100 kV/m [6]. Considering that the air gap is 5 m in length and that the rods are approximately 2 m from the ground this would mean that a d.c. voltage of approximately 350 – 700 kV would need to be applied to the elevated earth plane. This is a very high voltage and a d.c. generator with this capability was not available.

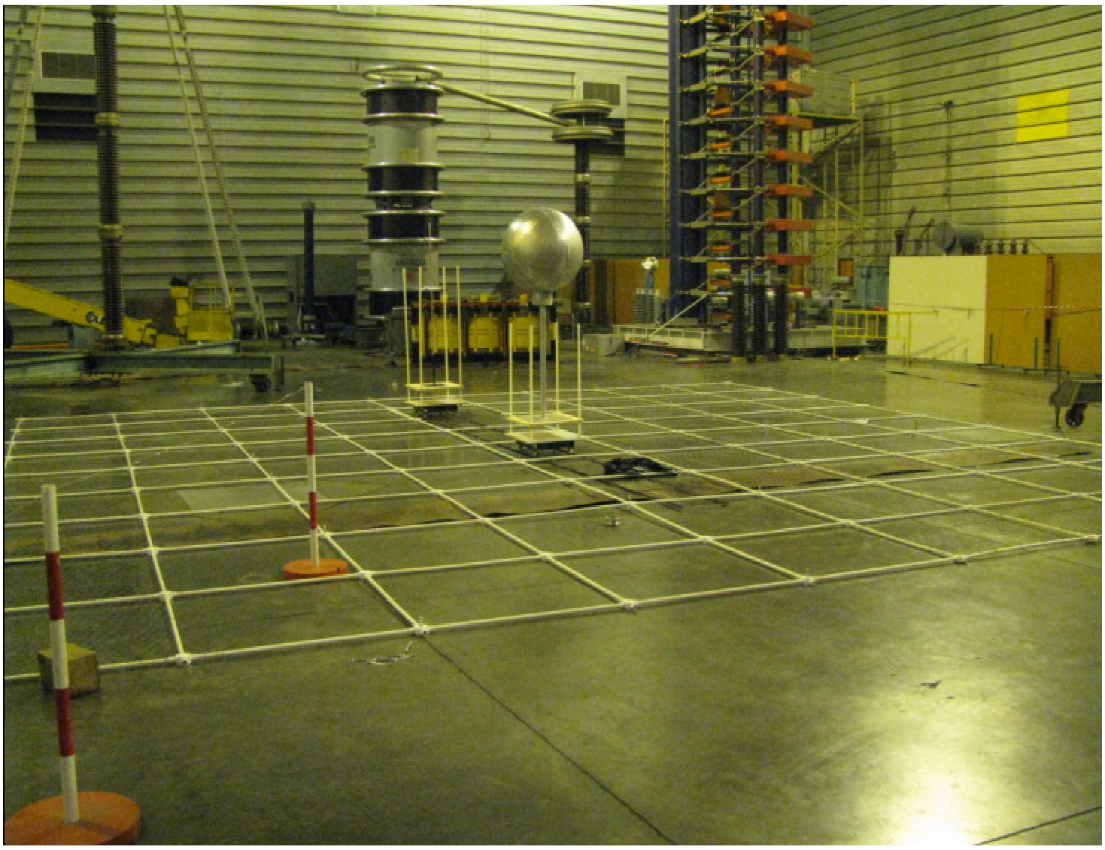

Figure 5.5: The elevated earth plane conduit structure put together and laid out on the floor

The second problem was that of protection. A generator capable of producing the voltages needed for the planned testing is very expensive, up to a few million Rand. As such it is crucial that it is not damaged during testing. If one considers that this generator is connected to the elevated plate and is applying a voltage of + 500 kV d.c. and an impulse of – 3 MV is applied to the same plate it means that the generator also experiences this – 3 MV of voltage. This could cause damage to the d.c. generator.

Another method of reproducing the electric fields experienced during thunderstorms is to apply a d.c. voltage onto the competing rods. If one applies a certain voltage onto the rods the tips of the rods will experience similar electric fields as experienced during thunderstorms. This voltage will however be a lot lower than the voltage required on the elevated earth plane. By applying this voltage to the rods the Franklin rod will go into corona as the electric field at the sharply pointed tip is enhanced. The quasi-hemispherical shapes will not go into corona at this voltage. The voltage that was applied to the competing rods was between 35 – 40 kV. At this voltage the Franklin rod went into corona at the tip and none of the quasi-hemispherical shapes or spheres went into corona. The voltage applied produced an electric field around the rods comparable to that experienced during a thunderstorm. It was measured with an electric field mill. This is shown in *Figure 5.6.*

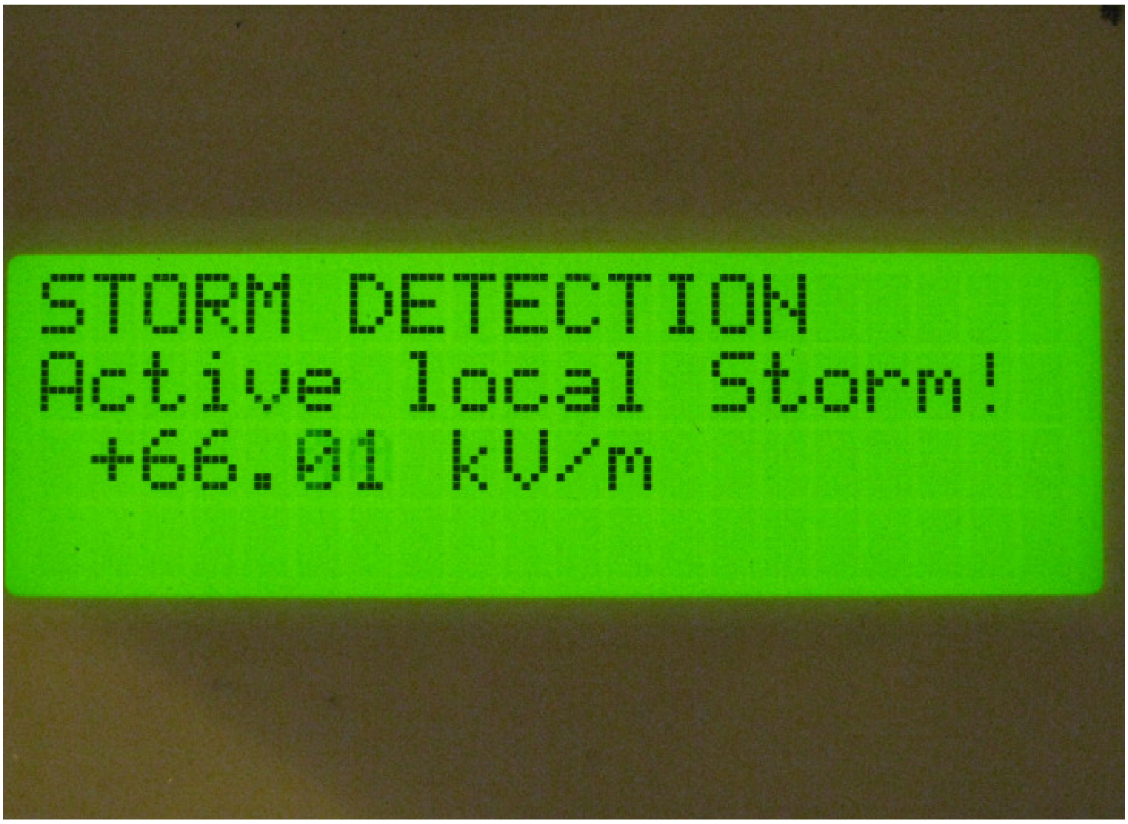

Figure 5.6: Typical electric field experienced at rods during testing with the d.c. bias introduced

The electric field mill was placed between the two competing rods at a height of 1.5 m. Since the competing air terminations are spaced 3 m apart this means that the field mill was 1.5 m from each rod when the measurements were taken.

Stands for the competing rods were manufactured so that they could be adjustable in height. The stands were constructed from aluminium and steel and as such were conductive. Since a voltage of approximately 40 kV was placed on the rods it meant that they had to be isolated from the floor. For this reason the termination holders were placed on wooden square boards which were in turn elevated from the trolleys with 20 mm diameter nylon rods placed at the corners of the board. The nylon rods were threaded and nuts placed on them so that the height of the wooden board and hence the competing rods could be adjusted. Nylon bolts were then drilled through another wooden board lower down which was fastened to the trolleys. The trolleys were manufactured from cast iron and had nylon wheels. They were placed on rails. The rails were over 6 metres in length. The reason for the rails is to maintain the competing rods in line and so that adjusting the distance between the rods could be easier. There is also a steel rod connecting the two trolleys of the respective competing rods which allows for accurate adjustment of the distance between the trolleys. The rod is 4 m in length. This means that the trolley system is easily capable of keeping the two competing rods at a distance of 3 metres.

Since the rod between the trolleys can be fastened or loosened it also means that the competing rods can be moved closer together or further apart but also that both of the rods can be moved to the left or right with the distance between them remaining fixed. This system was devised so that the rods can be moved around in order to monitor the effect of bringing one of the rods closer to the strike point or moving both rods either side so that one of them can be closer to the strike point whilst the distance between them remains 3 m. The trolley system layout is shown in *Figure 5.7*.

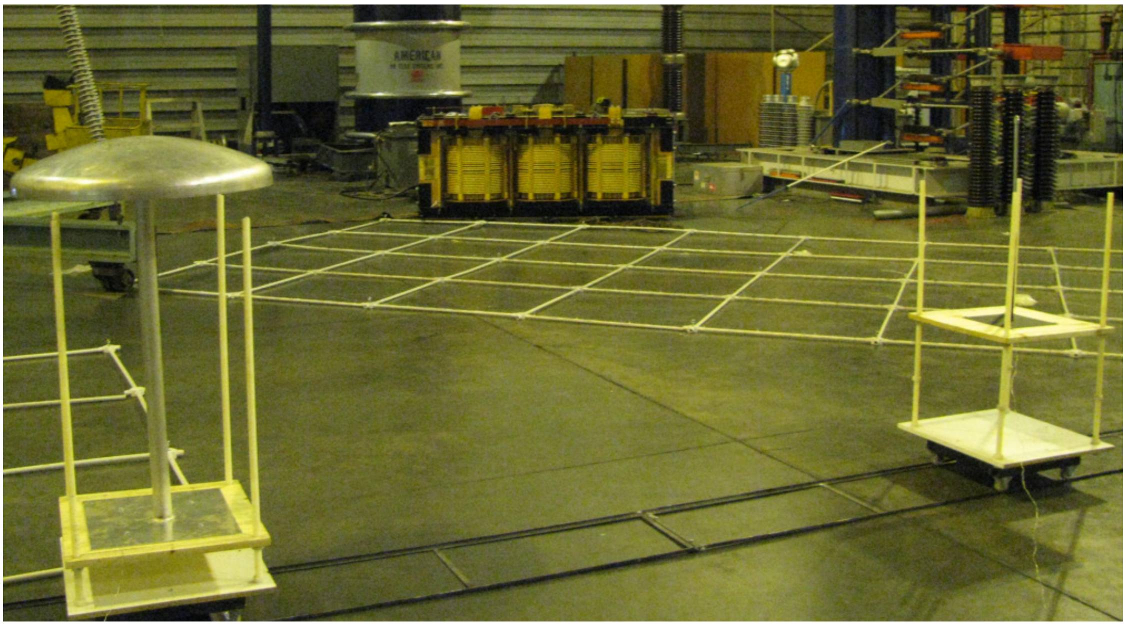

Figure 5.7: Trolley system of air termination adjustment

The distance of 3 m is chosen as it is estimated to be a distance at which space charge created at the Franklin rod will not affect the other rods. At the dimensions of the gap (namely 5 m) it is also a distance which gives a clear distinction in the zone of protection of the competing rods.

5.2.2 Measurements, Manufacture and Setup

A number of measurements were to be taken. The first measurement is the visual evaluation of which of the competing rods was struck. In this regard witnesses were placed at various angles in order to observe the strike to either of the rods. A high speed gated camera was also used to capture the events. It was placed approximately 30 m away so that the largest distance could be covered in the shot. Various lenses were attempted but none could provide a wide angle view as the charge-coupled device (ccd) of the camera was unable to process a wider view. Hence only approximately 0.6 m was visible on the camera view. The camera was therefore focused at the tip of a sphere or rod in order to investigate upward streamer or leader formation or to look at the breakdown process. The camera has settings which make it possible to adjust the delay. This means that one is able to delay the shutter opening from the trigger pulse in the range of 1 μs to 999 μs. The period for which the shutter is open can also be adjusted in the same manner and by the same margin. So for example one is able to make a setting such that the camera opens the shutter and takes an image ten microseconds after the trigger and keeps the shutter open for two microseconds in which time it captures the picture. This is important as one is able to use these adjustments to only capture portions of the event or to delay the capturing and hence get an insight into the time duration of the events taking place, hence gaining a better understanding of these events.

Another camera, a Canon Power Shot A720™ digital camera, was used to capture attachment. It was set to a wide exposure of 1.6 seconds. Although some reflections were visible and some of the events could have been overlapped it provided some fascinating images of upward streamers. An example of this is shown in *Figure 5.8.*

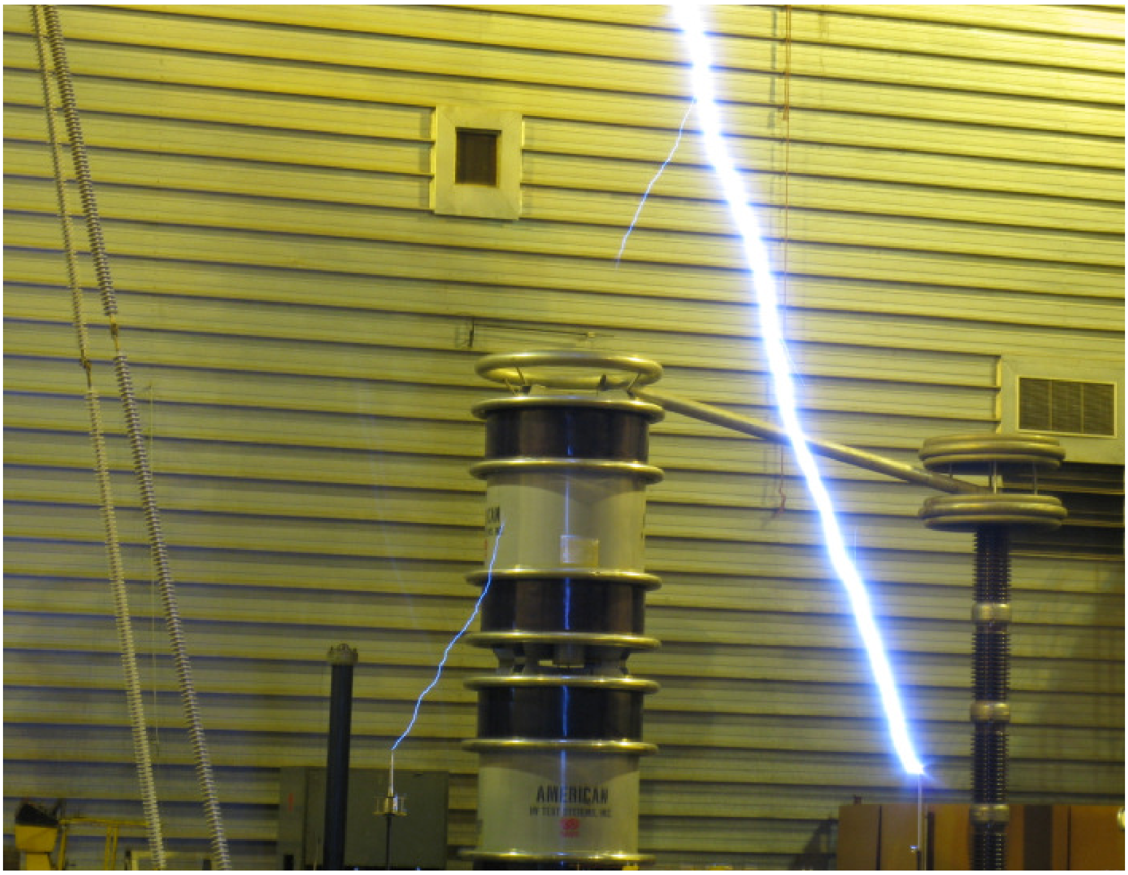

Figure 5.8: Upward streamer formation captured from the digital camera

The digital camera was also placed approximately 30 m from the test setup and was positioned at a different angle to the high speed gated camera. The top view of the test layout is shown in *Figure 5.9*. This digital camera also confirmed which air termination was struck.

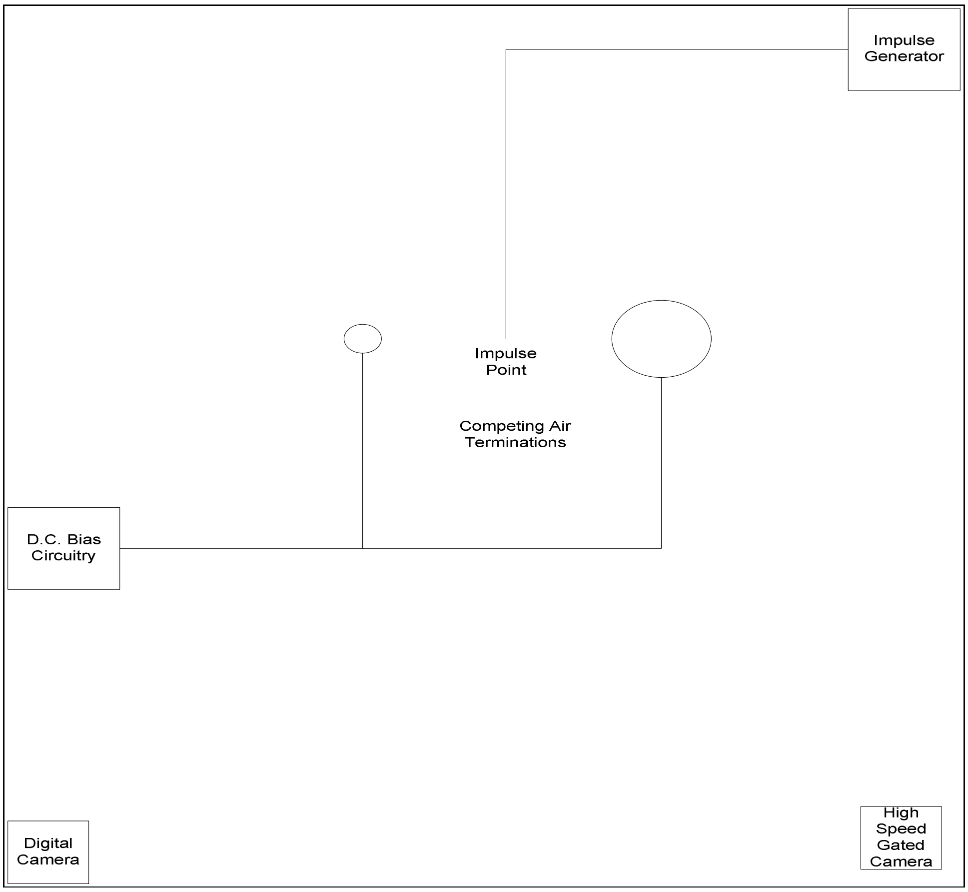

Figure 5.9: Top view of the test setup

An impulse divider was used together with an oscilloscope in order to capture the waveform of the strike. The waveform was adjusted until the required 1.2/50 μs waveform was obtained. The average waveform had the value of 0.96/45 μs which is within acceptable tolerances [33]. A corona camera was used to verify the presence or non-presence of corona from the competing rods while they were subjected to the d.c. bias. An electric field mill was used to measure electric field around the competing rods, while they were subjected to the d.c. bias. Under the d.c. bias conditions the Franklin rod went into corona. This would create space charge around the tip of the Franklin rod. The space charge created around the tip of the Franklin rod would be mobile and would drift away from the tip of the Franklin rod over time. It is possible that some of the space charge created at the Franklin rod would drift towards the spherical and quasi-hemispherical air terminations it was in competition tests with. It was not possible to measure the amount of space charge that would drift across from the Franklin rod to the other competing rods during testing. This could only be done by the use of corona cages or complicated electric field mills which would be intrusive to the experiment. According to previous simulations and tests shown performed by other researchers it was found that in a gap of 6 m the distance of 3 m between the air terminations was adequate for the effect space charge created from one air termination drifting to the other competing air termination to be minimal [2]. Since the air gap used in these experiments was 5 m it was decided to position the competing air terminations 3 m apart. This would ensure that the influence of drifting space charge, from the Franklin rod to the competing air terminations, on the electric field around the tip of the competing air terminations would be minimal.

Two different Franklin rods were used during testing. The one had a very sharply pointed tip with a tip radius of 0.1 mm and the other was less pointed with a tip radius of 1 mm. The spheres were made in two different ways. The 300, 400 and 500 mm spheres were made from spun half spheres which were welded together. The 600 and 700 mm spheres were too large to be made by the metal spinning companies. Whilst their manufacture in this way was possible the tool required for their spinning had to be individually manufactured. This proved very costly. Another method of manufacture was to construct the spheres from sections. Each hemisphere consists of four sections which were cut to the required shape so that once bent correctly they would come together to form a half sphere. Once all of the shapes were bent and cut they were welded together to form the respective spheres. The manufactured spheres are shown in *Figure 5.10.*

Figure 5.10. Spheres manufactured for testing

A stand was also created capable of holding all of the spheres and quasi-hemispherical shapes whilst providing electrical conductivity. The spheres and the stand were all manufactured from aluminium due to its lightweight nature. An ESE device was also obtained for testing purposes.

5.2.3 Testing Plan

The plan of testing was as follows:

1. Calibration shots
2. Sphere testing
3. Quasi-hemispherical shape testing
4. ESE comparison testing (not completed)

Firstly there would be calibration shots with the rod-rod gap to evaluate the maximum gap which could be broken down with the available generator. Following this, tests with a sphere and a rod were to be attempted to ensure that all of the related circuitry and testing equipment was working. The elevated earth plane would then be mounted, lifted and aligned. Once all of the equipment was operational testing plan to follow the outline shown in *Table 5.3.*

Table 5.3. Long gap testing plan

Waveform	Air gap size	Air termination vs.	Air termination	No. of shots
1.2/50 μs	5 m	300 mm diameter sphere	Franklin rod	40
1.2/50 μs	5 m	400 mm diameter sphere	Franklin rod	40
1.2/50 μs	5 m	500 mm diameter sphere	Franklin rod	40
1.2/50 μs	5 m	600 mm diameter sphere	Franklin rod	40
1.2/50 μs	5 m	700 mm diameter sphere	Franklin rod	40
1.2/50 μs	5 m	400 mm diameter shape	Franklin rod	40
1.2/50 μs	5 m	500 mm diameter shape	Franklin rod	40
1.2/50 μs	5 m	600 mm diameter shape	Franklin rod	40
1.2/50 μs	5 m	700 mm diameter shape	Franklin rod	40
1.2/50 μs	5 m	ESE device	Franklin rod	40

5.2.4 Testing

After the setup of the rails, stands and the measuring of the distances and heights of the competing rods, the calibration shots were attempted. On the first day of testing the decision was made that the elevated earth plane was too large for the confines of the laboratory. If it was elevated it would cause flashovers to the equipment and laboratory walls during testing. It was thus decided not to use the elevated plane during testing but rather to test with a point to point gap. The new testing configuration is shown in *Figure 5.11.*

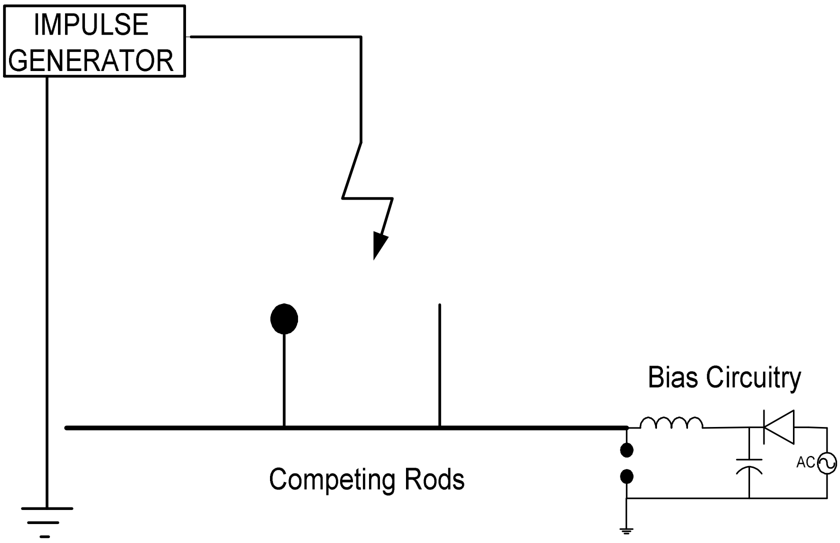

Figure 5.11. Revised test configuration with point to point breakdown

During calibration shots it was discovered that the maximum distance that could consistently be broken down by the generator was approximately 4.7 m. In order to break down this gap the generator had to produce 2.5 MV with a 1.2/50 μs waveform. With the switching waveform the generator could not exceed 1 MV and could not break down a gap required for testing. Another problem was that there was testing taking place with switching surges using the outside generator so there were not enough resistors to set up the inside generator for switching waveforms. Calibration testing commenced with a 700 mm sphere and a 1 mm radius Franklin rod. The first set of calibration shots did not include a d.c. bias. Everything operated as expected and all the measurements were recorded and yielded reasonable results. Subsequently d.c. bias was introduced into the circuit. An unexpected development followed.

The d.c. bias is protected with the use of a spark gap, as mentioned previously. After the strike to the competing rod there was no damage to the d.c. bias and it remained operational. The impulse generator measuring circuitry had tripped as had the main switch of the laboratory. The experiment was repeated and the same effect experienced. It was discovered that the impulse generator, which had been set to charge to a negative voltage had its protection set in, as it saw a positive charging voltage. Since the d.c. bias was positive the only explanation was that the d.c. bias was actually trying to charge the impulse generator through the arc during the few milliseconds that the flashover was occurring for. This effect also affected the rest of the circuitry related to the test as it reset all the measurement equipment and destroyed two laptop chargers. A resistor was placed in series with the inductor at the d.c. bias circuit, with partial success. Isolation transformers were then placed at all the plug points. There were still sporadic surges which reset the generator measuring oscilloscope but it did not affect the rest of the experiments greatly.

During calibration shots the rail system and hence the rods were placed so that they were in line with the wire from the output of the impulse generator, as shown in *Figure 5.11.* As the calibration shots were all striking the Franklin rod it was decided to replace the sphere with another Franklin rod. After repeating the experiments and swapping the rods around it was evident that the test was unfairly biased. The electric field enhancement created by the overhanging wire was the reason that breakdown occurred more frequently in that region. The arrangement was subsequently rotated by 90º so that the rails and the rods are perpendicular to the wire carrying the output of the generator and that this wire is in the middle of the setup. This new configuration is shown in *Figure 5.12.*

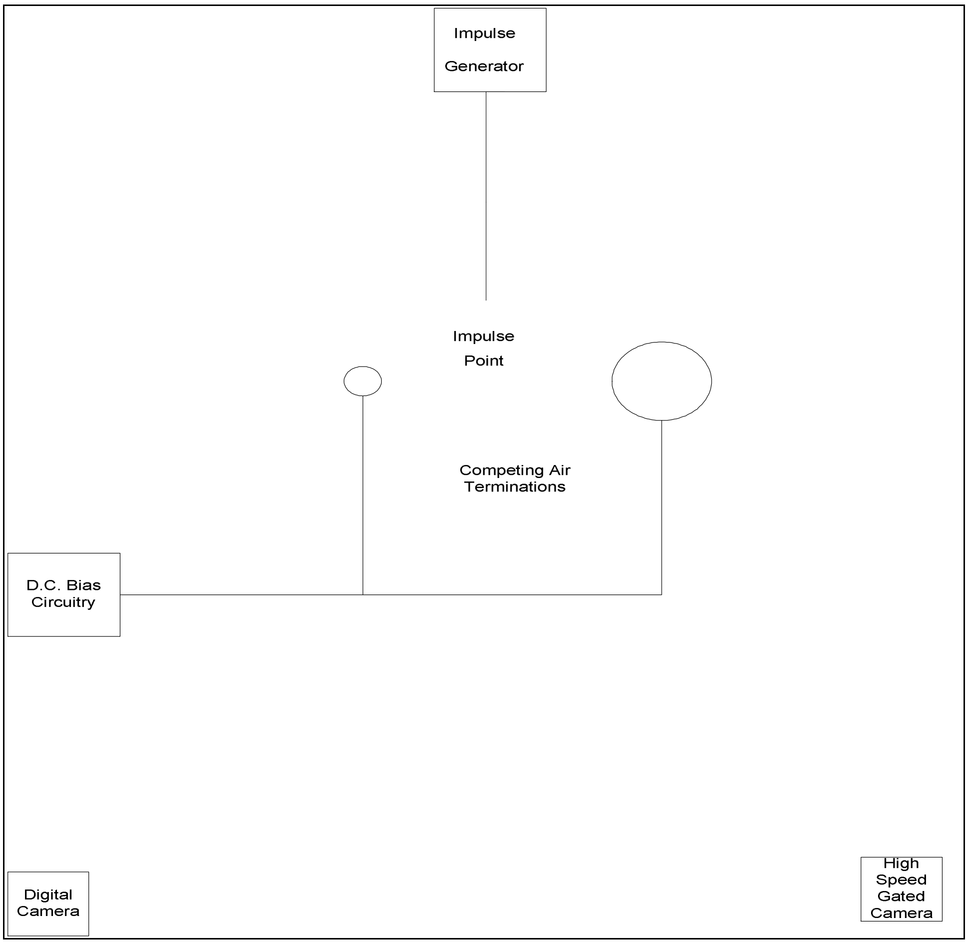

Figure 5.12: New testing layout, top view, rotated by 90º

Since all of the calibration shots were completed and all of the problems eradicated testing proper started. The first test was a competition test between a Franklin rod and a 700 mm diameter sphere. Due to time constraints it was decided to perform the tests with 40 shots in each configuration. After twenty shots the competing rods were swapped around and the experiment repeated another twenty times. In this way neither rod is favoured due to its physical condition. The gap distance was set at 4.51 m and the distance between the competing rods 3.1 m. The d.c. bias was set at 37 kV. The test results are shown in Table 5.4.

Table 5.4: Competition test results Franklin rod vs. 700 mm sphere

Air Termination	700 mm sphere	Franklin rod
No. of Strikes	0	40

As can be seen no strikes were recorded to the 700 mm diameter sphere. This gave an indication that there was no upward leader formation. The high speed gated camera did not show any indication of upward streamer formation from the sphere. This image is shown at the beginning of Appendix B. It is evident that there is no image in the picture taken by the high speed gated camera. At the end of the 40 planned shots the 700 mm diameter sphere was moved closer to the centre of the strike point so that it was 10 cm closer to the overhead strike point than the Franklin rod. The strike was still recorded to the Franklin rod. The sphere was then moved directly below the strike point and the strike was once again to the Franklin rod.

Following the completion of these tests, competition tests with a Franklin rod and 600 mm sphere were conducted. The same setup was used and the distances re-measured. The rods were at a height of 1.9 m. The distance between the rods was set at 3.1 m and the strike distance was set at 4.6 m. Once again the same testing procedure was followed. Twenty shots were fired in each position of the rods, totalling 40 shots. Test results are shown in *Table 5.5*.

Table 5.5: Competition test results Franklin rod vs. 600 mm sphere

Air Termination	600 mm sphere	Franklin rod
No. of Strikes	0	40

Once again there was no evidence of upward leader formation from the high speed gated camera or the digital camera. When the sphere was moved closer to the strike point the strike was still to the Franklin rod, once again pointing to no upward leader formation.

The next set of experiments was conducted between the Franklin rod and the ESE device. The ESE device is shown in *Figure 5.13*.

Figure 5.13: ESE device tested

The manner in which this device is supposed to operate is as follows. The three little spikes on the side of the device are insulated from the rest of the structure. The main long terminal point is connected and electronically continuous with the body of the device. When there is a very strong electric field during thunderstorm conditions the intensification of the electric field around the tips of the smaller insulated spikes causes breakdown between the spikes and the structure of the device from which it is insulated. These constant breakdowns are supposed to intensify the field around the whole ESE device and aid in the early formation of streamers from its tip. This was very difficult to simulate in a laboratory. The reason being that the only way one could simulate this is to place the d.c. bias of 40 kV onto the little spikes and ground the structure. This was attempted but each time there was a flashover to ground from the little spikes it creates a short circuit for the d.c. biasing circuitry. This was damaging the diodes, variac, transformer and the resistor. For this reason it was impossible to continue with the setup as described. Instead the d.c. bias was connected to the structure of the ESE device and the small spikes on the side remained floating. When connected in this manner the ESE device acts as a Franklin rod. It would be interesting to note the difference, if any, to the results when compared to those of the spheres.

The rods were placed and measured in the same way as previously with the spheres. The ESE device had a very sharply pointed tip, radius of approximately 0.1 mm and the Franklin rod had a tip radius of approximately 1 mm. The tests were again performed with 40 shots. Twenty shots would be fired in each direction. The air gap was set at 4.52 m and the distance between the rods was 2.9 m. The d.c. bias was set at 38 kV. Test results are shown in *Table 5.6* and *Table 5.7*.

Table 5.6: Competition test results Franklin rod vs. Sharp Franklin rod (ESE)

Air Termination	Sharp Franklin rod (ESE)	Franklin rod
No. of Strikes	9	11

Table 5.7: Competition test results Franklin rod vs. Sharp Franklin rod (ESE), position swapped

Air Termination	Sharp Franklin rod (ESE)	Franklin rod
No. of Strikes	10	10

As can be seen from the results there is a much more even distribution between the strikes to the two rods. A very similar percentage of strikes to the rods is maintained even when the rods are swapped around showing that there is no bias in either direction. There are very long upward streamers captured from the tips of the rods not being struck. This is evident both from the high speed gated camera as well as from the digital camera photographs. The images are shown in *Figure 5.14* and *Figure 5.15*.

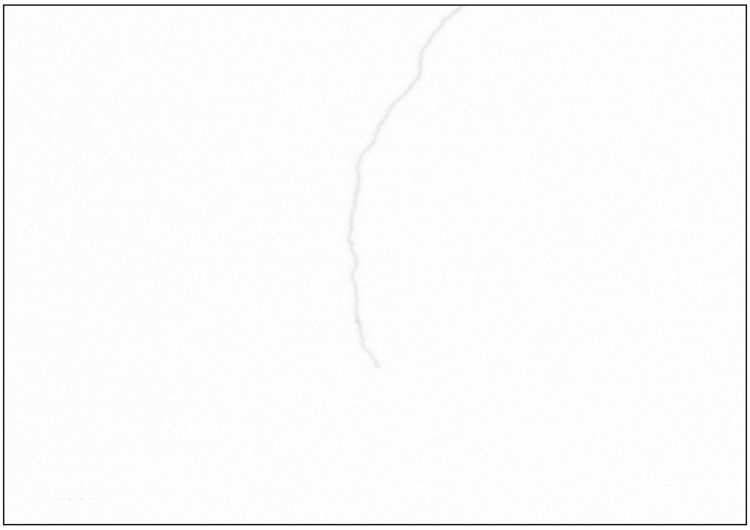

Figure 5.14: Upward streamer from the top of the sharply pointed Franklin rod captured by the high speed gated camera

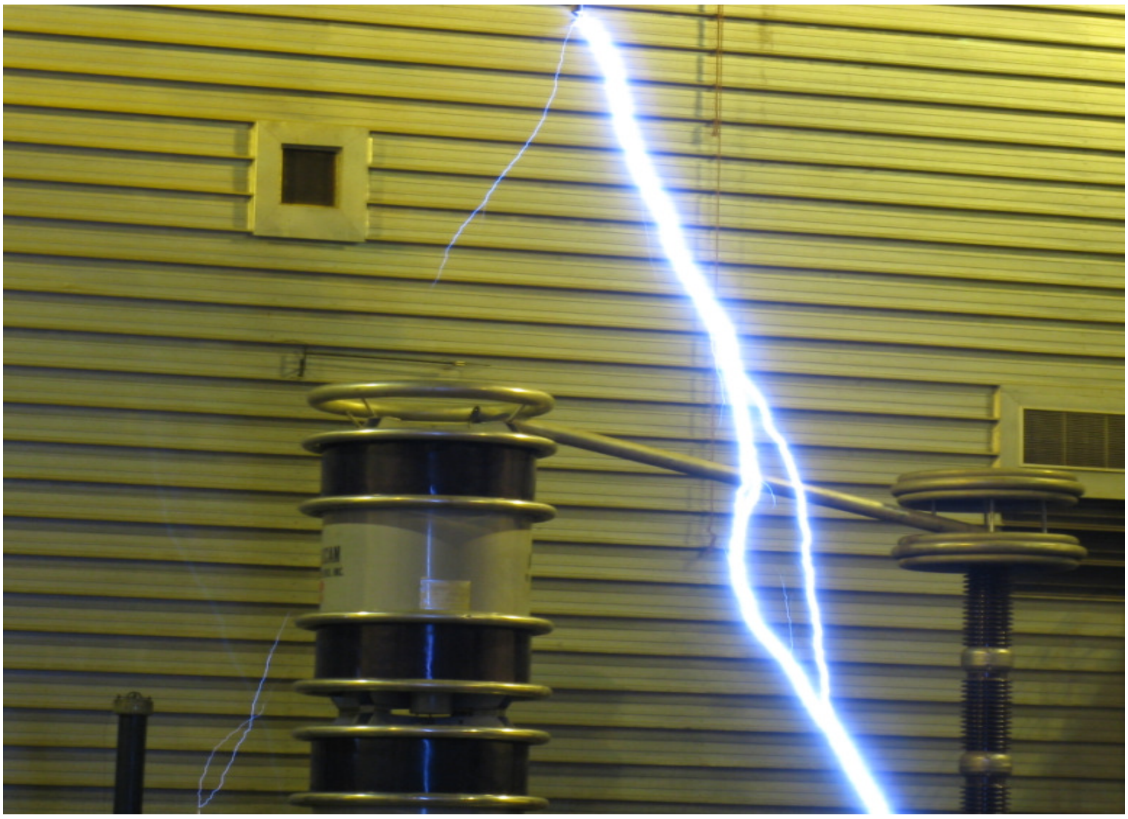

Figure 5.15: Upward streamers from the Franklin rod

The results are discussed in more detail in section 5.2.5 but it is interesting to note that the upward streamers tend to be longer from the ESE rod. The high speed gated camera was also adjusted, both in delay and the time the shutter was left open. The delay is from the time of the triggering of the camera and not from the time that the generator fires. Due to the difficulty in the triggering of the camera from the output of the oscilloscope this delay between breakdown and camera trigger was a few milliseconds. These delays gave a portrayal of how long after the start of the downward leader the upward streamers start and for how long they last.

The following day it was decided to continue the tests with the remaining 500, 400 and 300 mm diameter spheres.

The 300 mm sphere was set up in the same manner as previous testing. The distance between the terminals was set to 3.07 m and the strike distance was set to 4.54 m. The results are shown in *Table 5.8.*

Table 5.8: Competition test results Franklin rod vs. 300 mm sphere

Air Termination	300 mm sphere	Franklin rod
No. of Strikes	0	40

As can be seen all of the strikes were recorded to the Franklin rod again. The photographs taken from the high speed gated camera show no sign of upward leader formation. This is supported by digital camera images.

The digital camera image is shown in *Figures 5.16*. The high speed gated camera is identical to the first image in Appendix B and shows simply a blank image.

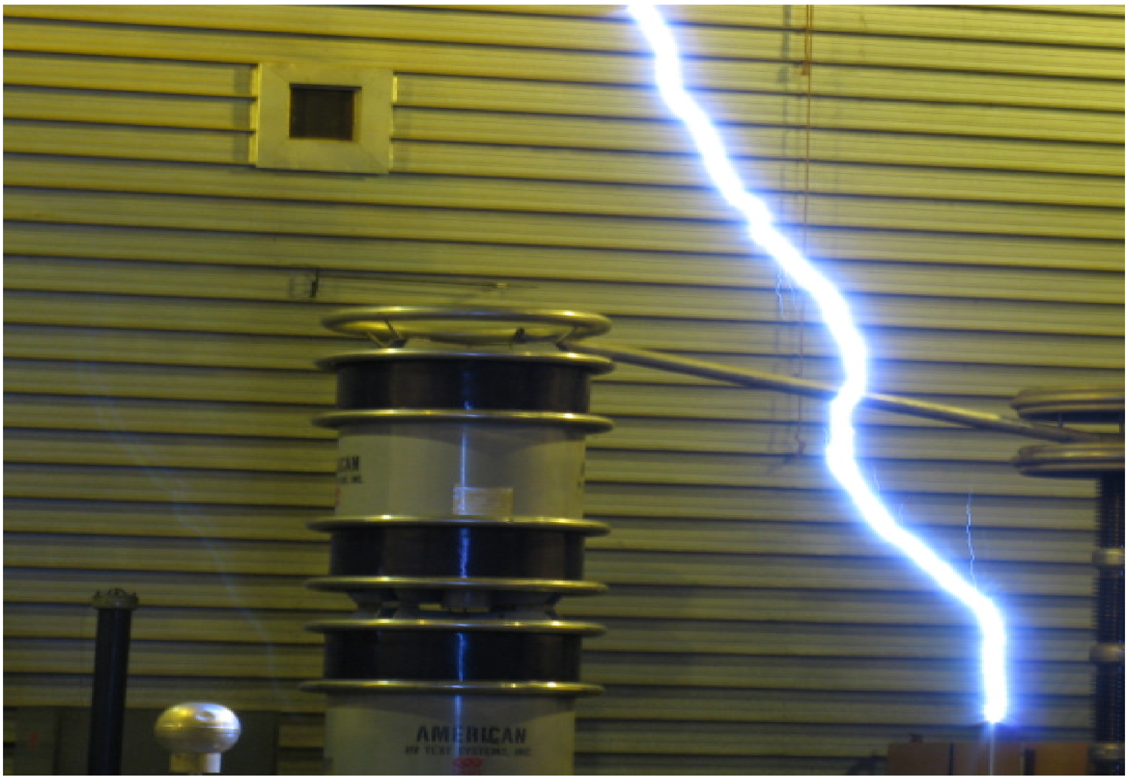

Figure 5.16: No upward streamer formation from the 300 mm diameter sphere, digital camera image

The 400 mm sphere was tested next, followed by the 500 mm diameter sphere. The results of these tests are shown in *Tables 5.9* and *5.10*.

Table 5.9: Competition test results Franklin rod vs. 400 mm sphere

Air Termination	400 mm sphere	Franklin rod
No. of Strikes	0	40

Table 5.10: Competition test results Franklin rod vs. 500 mm sphere

Air Termination	500 mm sphere	Franklin rod
No. of Strikes	0	40

In both of these experiments there were no strikes recorded to the spheres and there was no evidence of upward leader formation from either of the cameras in use.

The following day the tests on the quasi-hemispherical shapes commenced. There were four quasi-hemispherical shapes in use. They had diameters of 400, 500, 600 and 700 mm respectively. The quasi-hemispherical shapes are shown in *Figure 5.17*.

Figure 5.17: Quasi-hemispherical shapes manufactured for testing

Due to time constraints and due to the fact that all of the strikes continued to be to the Franklin rod and that there was no formation of upward leaders it was decided to shorten the testing to 20 shots per shape. This meant that after ten shots in one direction the shape and the Franklin rod would be swapped around so that no biasing occurs. Testing was started with a 400 mm quasi-hemispherical shape and a Franklin rod. The competing rods were positioned in an identical fashion as the previous testing conducted. Results of the tests are shown in *Table 5.11*.

Table 5.11: Competition test results Franklin rod vs. 400 mm quasi-hemisphere

Air Termination	400 mm quasi-hemisphere	Franklin rod
No. of Strikes	0	20

The high speed gated camera was pointed at the top of the quasi-hemispherical shape. It showed no upward leader formation. No upward leader formation was evident from pictures of the digital camera either.

The tests with a 500 mm quasi-hemispherical shape followed. The results are shown in *Table 5.12*.

Table 5.12: Competition test results Franklin rod vs. 500 mm quasi-hemisphere

Air Termination	500 mm quasi-hemisphere	Franklin rod
No. of Strikes	0	20

There was no evidence of upward leader formation from the 500 mm diameter quasi-hemisphere. There were also no strikes to the quasi-hemispherical shape and once again all the strikes were to the Franklin rod. There was a rather interesting photograph on one of the shots taken with a camera. It is shown in *Figure 5.18*. This phenomenon is discussed further in the following section but it is clearly evident that there is an upward streamer formation from the side edge of the quasi-hemispherical termination.

Testing with quasi-hemispherical spheres of 600 and 700 mm radius followed. All of the strikes recorded were to the Franklin rod as is shown in *Table 5.13* and *Table 5.14*.

Table 5.13: Competition test results Franklin rod vs. 600 mm quasi-hemisphere

Air Termination	600 mm quasi-hemisphere	Franklin rod
No. of Strikes	0	20

Table 5.14: Competition test results Franklin rod vs. 700 mm quasi-hemisphere

Air Termination	700 mm quasi-hemisphere	Franklin rod
No. of Strikes	0	20

There was no upward streamer formation evident from the high speed gated camera and there was no upward streamer formation visible with the digital camera.

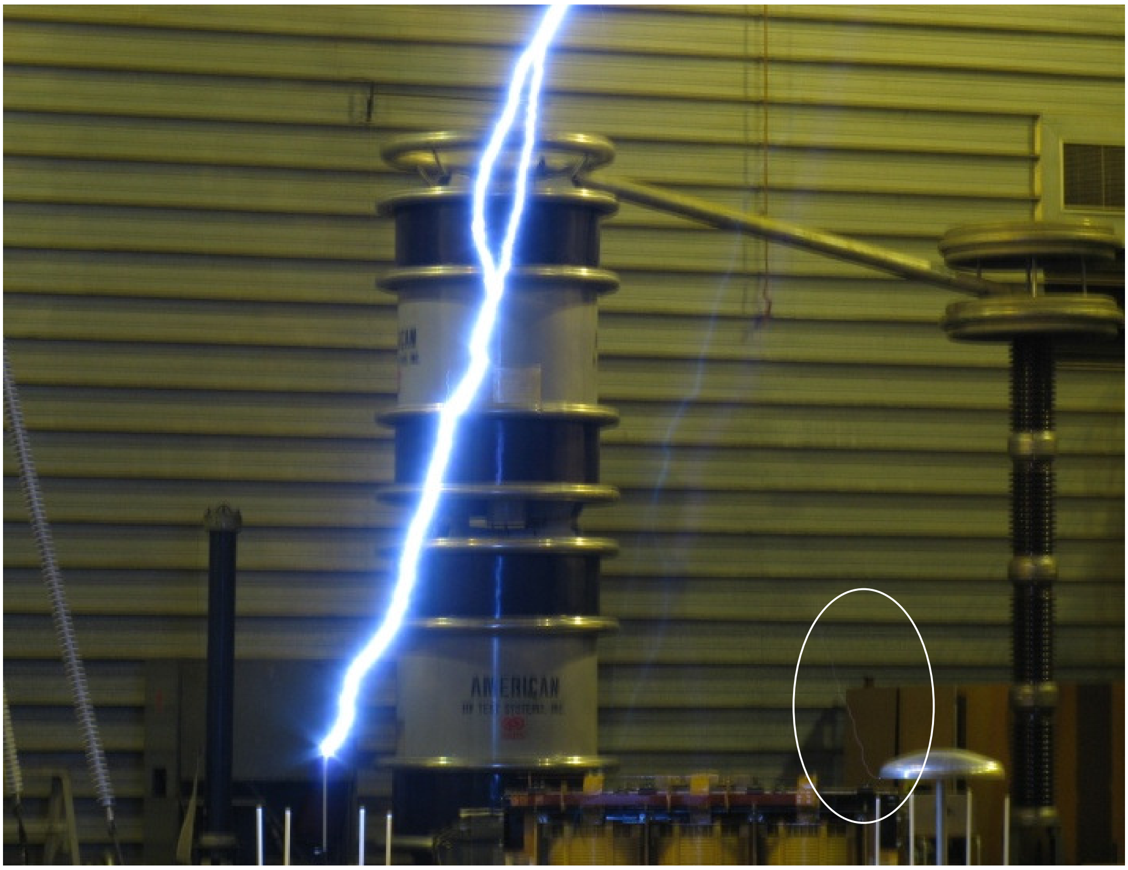

Figure 5.18: Upward streamer formation from the side of the quasi-hemispherical shape

This concluded the scheduled testing. Since there was still some time available it was decided to perform competition tests with two spheres. The spheres chosen were the 300 mm and 500 mm diameter spheres. This would show whether the electric field enhancement is dominating breakdown. The air gap was set to 4.3 m and the distance between the spheres 3.08 m. The results are shown in *Table 5.15*.

Table 5.15: Competition test results 300 mm sphere vs. 500 mm sphere

Air Termination	500 mm sphere	300 mm sphere
No. of Strikes	0	20

During testing the following air conditions were recorded. The air pressure was 853 mg, the temperature 20º C and the humidity 40 %. This meant a correction factor of 0.83. Since average breakdown voltage was 2.5 MV with the correction factor the actual breakdown or firing voltage was 3.01 MV. The results of all the competition tests between the Franklin rod and quasi-hemispherical and spherical air terminations as well as the sharply pointed Franklin (ESE) rod are shown in *Table 5.16*.

Table 5.16 Combined results: Franklin rod vs. competing air terminations

	Waveform	**Air termination**	**vs. Air termination**
		Franklin rod	300 mm diameter sphere
No. of shots	1.2/50 μs	40	0
		Franklin rod	400 mm diameter sphere
No. of shots	1.2/50 μs	40	0
		Franklin rod	500 mm diameter sphere
No. of shots	1.2/50 μs	40	0
		Franklin rod	600 mm diameter sphere
No. of shots	1.2/50 μs	40	0
		Franklin rod	700 mm diameter sphere
No. of shots	1.2/50 μs	40	0
		Franklin rod	400 mm diameter sphere
No. of shots	1.2/50 μs	20	0
		Franklin rod	500 mm diameter sphere
No. of shots	1.2/50 μs	20	0
		Franklin rod	600 mm diameter sphere
No. of shots	1.2/50 μs	20	0
		Franklin rod	700 mm diameter sphere
No. of shots	1.2/50 μs	20	0
		Franklin rod	Sharply pointed Franklin rod (ESE)
No. of shots	1.2/50 μs	21	19

5.2.5 Discussion of Test Results

During competition testing between the Franklin rod and the spheres as well as the quasi-hemispherical shapes all of the strikes were to the Franklin rod. During testing between the two Franklin rods there was a much more even distribution of strikes between the two rods. These results point very strongly to no upward leader formation from competing air terminations being present.

It was evident that breakdown favoured the Franklin rod in all of the experiments with all of the spheres. It is also obvious that in order for natural lightning effects to be even remotely simulated upward leader formation from the competing rods is crucial. Previously it was mentioned that a streamer needs to travel three metres before it goes through streamer to leader transition. Since the gap is only 4.5 m it would be impossible for the upward leader to travel this distance. There have been instances in laboratory experiments of upward leader formation from rods whose streamers/leaders travelled less than 3 m however [2]. During testing mentioned in [2] waveforms with long front times were used. During the testing covered in this research a standard lightning impulse waveform was used. This waveform has a very steep rise time and a lot less energy in the discharge. For this reason it is more difficult to create leaders in laboratory sparks with this waveform.

The spheres were moved directly below the strike point at times, effectively making them 0.5 m closer to the strike point than the Franklin rod, yet the strike was still to the Franklin rod.

With the high speed gated camera there was no evidence of upward leader formation from any of the spheres or the quasi-hemispherical shapes. The camera was focused on the top of the spheres and the shapes which would be the most likely area of upward leader formation.

It is clear that there is no upward streamer formation and at the same time that all of the strikes are to the Franklin rod.

When the tests were performed with a second Franklin rod it is very clear that there is upward streamer formation from the Franklin rod not struck. It is a much lighter streamer than the breakdown seen on the rod being struck. *Figure 5.19* represents streamer formation from the competing rod not struck by the discharge and *Figure 5.20* represents the image at the top of the rod struck by the discharge. The difference between images is clearly evident and one can be certain that the image captured in *Figure 5.19* is that of an upward competing streamer.

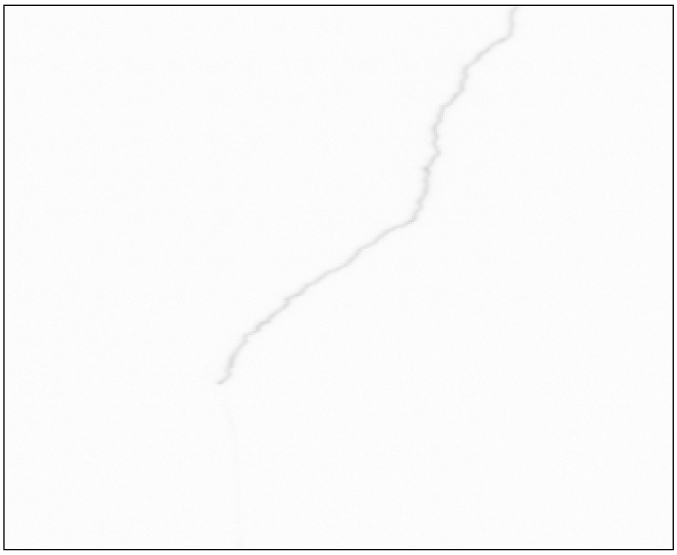

Figure 5.19: Upward streamer from the competing Franklin rod

Figure 5.20: Typical breakdown to the Franklin rod captured by the high speed gated camera

This upward streamer from the rod not struck was also confirmed by the images from the digital camera as shown in *Figure 5.21*.

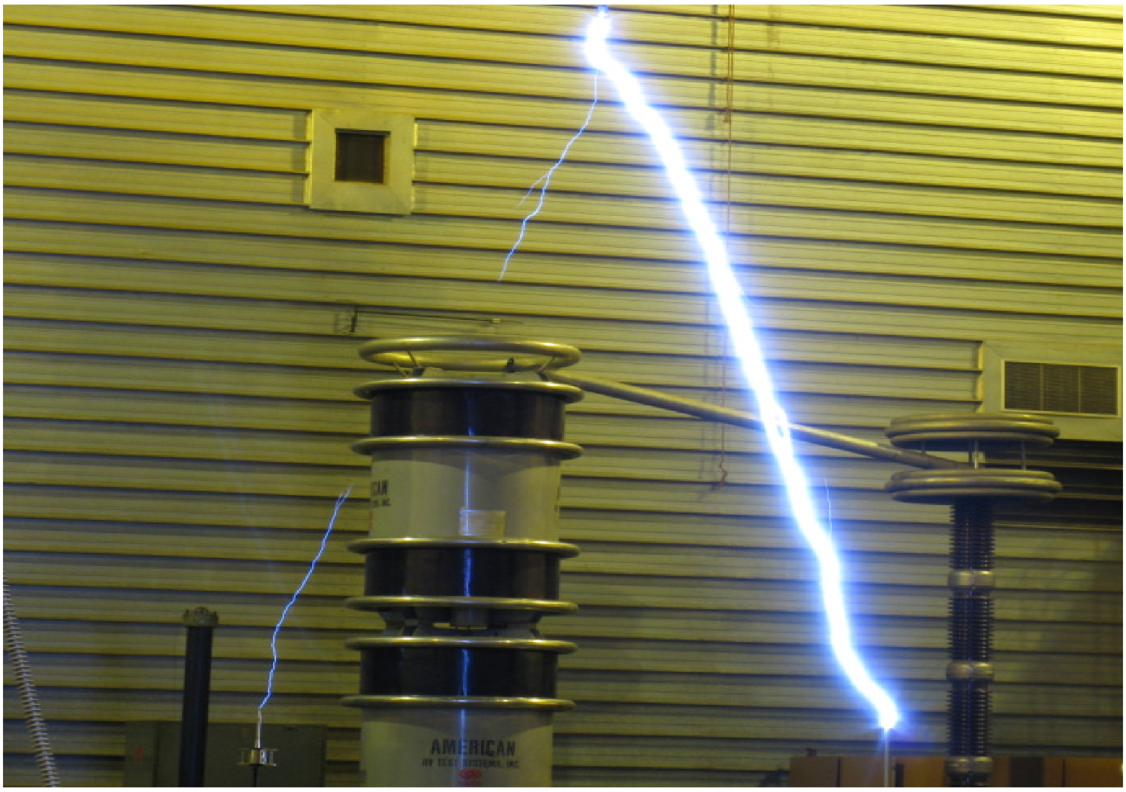

Figure 5.21: Long upward streamers from the sharply pointed Franklin rod (ESE)

It is also evident that upward streamers from the sharper Franklin rod extended upwards longer than streamers created from the blunter Franklin rod. This is shown, in two typical photographs of a phenomenon often repeated during testing, in *Figure 5.22* and *Figure 5.23*. The reason is that at the tip of the sharper Franklin rod the electric field is more enhanced. This is a clear indication that the local electric field dominates breakdown. It shows that in this environment the process of lightning attachment is not accurately replicated.

Figure 5.22 Typical breakdown to the sharp Franklin rod and a small streamer from the blunt Franklin rod

One way in which it could be possible to create conditions where upward leaders are more likely is to use different waveforms. Waveforms with a longer rise time, in particular are required. Switching waveforms may produce upward leaders as they carry more energy. Testing with switching surges was considered. The generator inside the High Voltage laboratory was not capable of generating a voltage high enough to break down gaps substantial enough. The outdoor generator was not available for testing as it was being used for testing taking a few months. The outdoor test generator is capable of breaking down gaps of over 6 metres with a waveforms of 350/3000 µs. This would be suitable for future testing. The disadvantage with outdoor testing is that images from the high speed gated camera would not be visible and hence there could be no image capturing of events taking place during breakdown. One could however establish which air termination got struck more times and whether the principle works.

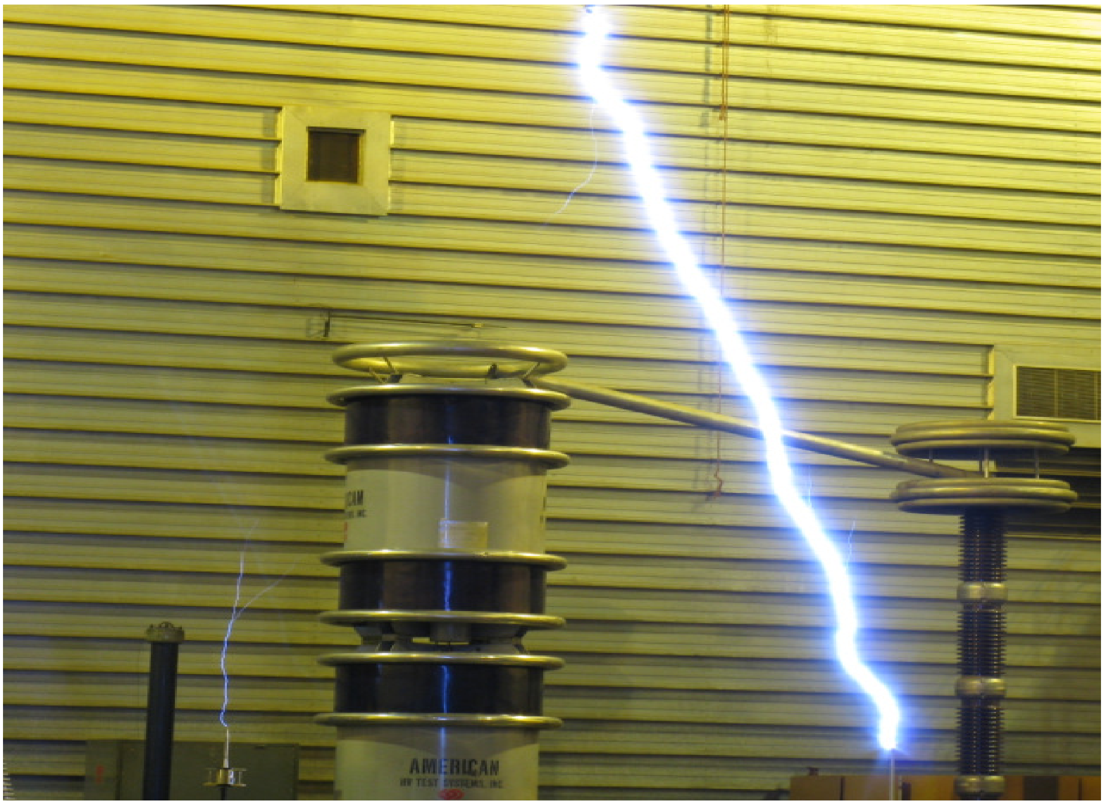

Figure 5.23: Typical breakdown to the blunt Franklin rod and a long upward streamer from the sharp Franklin rod

An interesting development was the formation of upward streamers from the side of the quasi-hemispherical shape. These shapes are made as halves. This means that the bottom of the shape has a sharp edge. Under the high electric field conditions the sharp edge intensifies this field further, the air starts to breakdown and streamers are created. This is further proof that electric field enhancement is the sole dominating factor of breakdown. This is shown in *Figure 5.18.*

It is clearly evident that in order for air termination competition testing to have any relevance to natural lightning conditions and ultimately to provide results of air termination capability for lightning protection one needs to test with upward leader formation from the competing rods.

Chapter 6

Explanation of Results

During testing at the NETFA laboratories the Franklin rod was the air termination type which was struck by every impulse. The testing was performed with a standard lightning impulse waveform (1.2/50 µs). The air gap was set at 4.5 m. All of the competing air terminations were the same height.

It is important to explain the reasons for the Franklin rod being struck each time. The main reason that all of the impulses struck the Franklin rod was that it was the sharpest point when compared to other competing air terminations.

During this research the aim was to show that the Franklin rod was not the best air termination under natural lightning conditions. The simulations that were researched pointed to a critical radius of approximately 350 mm for a sphere to be able to emit an upward leader at the optimal moment during the descent of the downward stepped leader. This would an air termination with a spherical radius tip of 350 mm the preferred strike point during a lightning strike in its zone of protection. These simulations were performed with natural lightning conditions. Since testing with natural lightning would be impractical as it could take many years the testing was carried out in a high voltage laboratory. In natural lightning conditions, where the air gap stretches over a few kilometres, the attachment process is different to the breakdown process in small air gaps, such as ones that can be replicated in a laboratory. In order to prove or disprove the theory it was thus important to replicate natural lightning attachment conditions and processes as closely as possible.

The main difference between natural lightning and breakdown in a small air gap is the breakdown mechanism. In natural lightning a high electric field is created between the cloud and the ground. Due to this high electric field, and high charge in the cloud, objects on the ground become charged. At elevated, sharp points on the ground, which enhance the electric field the most, air starts to break down and partial discharges occur. In the cloud discharges start occurring and at times these discharges travel to the ground as stepped downward leaders. During the descent of the downward leader the electric field is enhanced even further at the objects on the ground.

The objects on the ground emit upward leaders towards the downward moving leader. One of these upward leaders intercepts the downward leader and a conductive channel for the lightning strike to occur is created. Therefore if two air terminations of the same height and spaced equidistantly from the downward approaching leader both emit upward leaders the downward leader will be intercepted by the longer upward leader. This means that the air termination which sends an upward leader at the optimal moment will be the air termination struck by the lightning strike.

One would think that an air termination which enhances the electric field at its tip most so that air will break down at its tip at the smallest possible value of background electric field will be the best lightning interceptor. This is not the case because merely breaking down the air at the tip of the air termination is not enough to send an upward leader. In order for the discharge from an air termination to propagate high and intercept the downward leader it needs to become a leader. This means that the background electric field needs to be strong enough, not just at the tip of the air termination, but also at a distance away from the tip in order to sustain the streamer discharge until it becomes a leader. If the air termination is shaped so that the electric field is enhanced too highly at its tip then the streamer created will propagate upwards and into an area of low electric field (since the background electric field is not yet high enough as the downward leader is too far away or has not started propagating yet). The upward streamer will not be able to propagate long enough for it to become a leader. If it did propagate for long enough to become a leader it would then be able to self propagate, even in areas of lower electric field, and intercept the downward leader. The key is thus to create an air termination which is able to enhance the electric field at the tip of the air termination so that it emits a streamer at the earliest possible moment when the background electric field is strong enough to maintain streamer propagation until the time that the streamer becomes a self sustained upward leader. If the streamer is sent too early it is not able to propagate far in the weak background electric field and it collapses. This collapsing of the streamer leaves behind ionised particles known as space charge. Space charge has the effect of lowering the electric field in the area (around the air termination). This process of streamers being sent upwards and collapsing leaving behind space charge keeps repeating if streamers are sent too early from an air termination. At a later stage the background electric field further from the air termination becomes strong enough to sustain the streamer for long enough for it to become a self sustaining upward leader. However the space charge created at the tip of the air termination in the mean time has lowered the electric field in this region so far that the streamer is not emitted at the tip of the air termination at this optimal moment.

The main idea behind this research is that the Franklin rod, with its sharply pointed tip, goes into corona too early and creates streamers when the background electric field is too weak to sustain them. In order to test the effectiveness of air terminations in a laboratory therefore it is crucial that the setup be such that there is a downward leader moving towards the air terminations, that the high background electric fields are replicated, and that the air gap is sufficiently large for there to be definite upward leader formation from the air termination.

During the testing at NETFA the background electric field was replicated by setting up a voltage on the competing air terminations. This would cause the sharper Franklin rod to go into corona and it would create space charge at its tip.

The downward strike was created by the use of the impulse generator.

There was however no creation of upward leaders from the competing air terminations.

The upward leaders were not created from the competing air terminations as the electric field in the gap was not enhanced enough during the descent of the downward impulse and due to the relatively small size of the air gap. As mentioned previously a 1.2/50 μs waveform was used. Using a waveform with a longer rise time, such as a switching waveform 250/2 500 μs, would provide more possibility of upward leader formation as it would enhance the field in the gap more. This is because the switching waveform is a higher energy waveform and with the longer rise time it provides the air more time to ionise, staying at a high voltage for a longer period of time than the 1.2/50 μs standard lightning waveform. If the gap was increased the upward streamers would have more space in which to propagate upwards and therefore would be able to undergo streamer to leader transition and become self sustaining leaders. In this way the attachment process of natural lightning would be replicated more closely.

A test setup as described above would thus be able to test whether the premature enhancement of the electric field at its tip by the Franklin rod makes it a worse lightning air termination than a spherical or quasi-hemispherical air termination with an approximate radius of 350 mm.

In the setup described in this research the Franklin rod becomes the dominant air termination. The downward strike followed the path of the most enhanced electric field, as this is the manner of streamer mechanism propagation. In this case it is the Franklin rod. Even though space charge was created at the tip of the Franklin rod and this lowered the local electric field around the tip it had a much smaller effect since it did not retard the formation of upward leaders as there was no upward leader formation. The effect of the enhancement of the electric field was most influential, as it provided a path for the downward streamer to propagate and attach itself to the Franklin rod.

For the reasons mentioned above the method of attachment in natural lightning was not fully replicated in laboratory testing. In order to create conditions where one would replicate natural lightning more closely and create upward moving leaders from competing air terminations the air gap would have to be increased to more than 8 m, or perhaps more than 10 m, and more powerful impulse generators would need to be used capable of breaking down gaps of this size with long rise time waveforms.

For the reasons explained above the Franklin rod proved to be the best air termination of all air terminations tested in this research.

Chapter 7

Future Work and Conclusion

The most important step regarding future testing would be to create a test setup capable of producing upward leaders from the competing rods. This can be done with bigger impulse generators and switching impulses. The obvious first step would be to test at the NETFA High Voltage Laboratory with the outdoor generator utilising slow rise time waveforms at gaps of between 6 and 8 metres. The generator is capable of consistently breaking down these gaps.

At these gaps, i.e. over 5 m the effect of the elevated earth plate becomes tedious. The plate becomes very large, difficult to manufacture, transport, stabilise, maintain flat and utilise properly. At gaps this large the plate goes well beyond 10 x 10 m in order to effectively maintain electric field lines parallel to the ground, as the cloud does during natural lightning. The plate needs to be large enough so that its edges do not distort the electric field. With gaps over 5 m the generators required to break down these gaps with the waveforms required are very large and mostly situated outside. This means that the tests are most likely to be conducted outdoors. As such the effect of wind should not be neglected as it can easily shift the elevated plate and render it useless. For these reasons it is more practical to perform the tests without the elevated earth plane but rather with a point to point gap. In order to replicate the electric field conditions experienced on the ground during thunderstorms due to the charge build up at the bottom of the cloud one needs to produce a voltage with respect to ground at the plate. Once the gap is this big, over 5 m, this voltage becomes very large. A generator required for this once again becomes very large and the protection on it challenging and costly.

It would be impossible to take pictures with a high speed gated camera during outdoor testing but one could make some electric field measurements as well as current measurements with the use of a resistive shunt. This could provide verification of upward leader formation.

Another possibility for testing would be with rocket triggered lightning. A project is currently under way at the University of the Witwatersrand investigating the possibility of rocket triggered lightning research. There are, however, some quite obvious problems with using rocket triggered lightning for competition tests. The most obvious one is the positioning of a lightning strike in the middle of the two competing rods. One method of doing this is to use a setup such as the one designed in *Figure 6.1*.

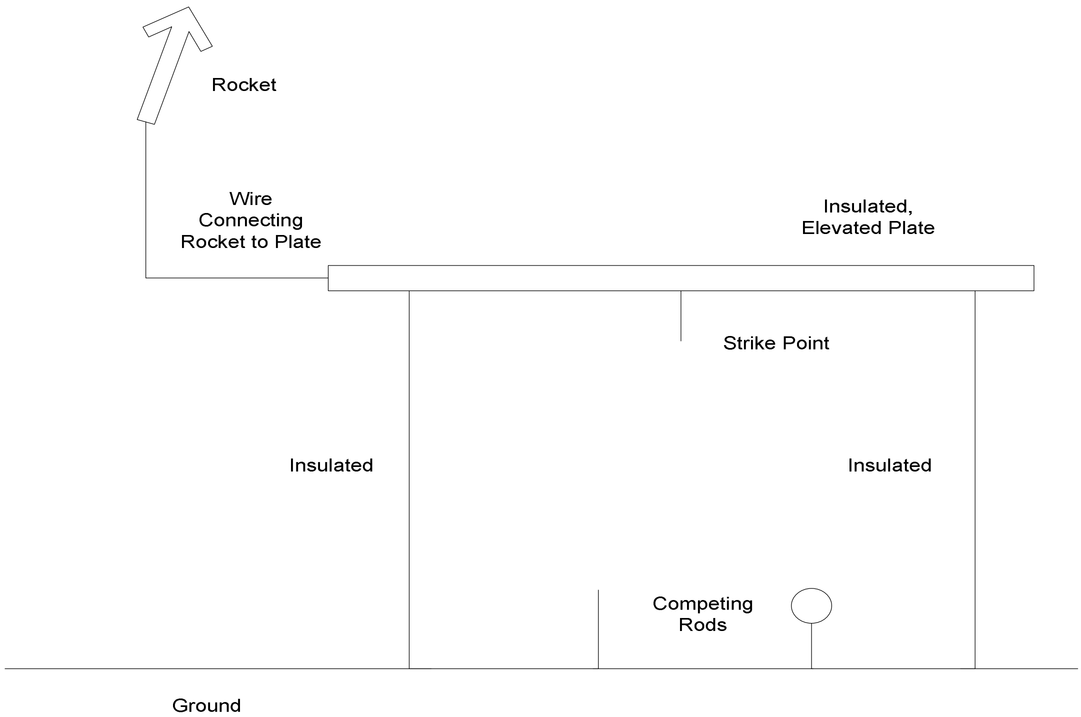

Figure 7.1: Rocket triggered lightning test setup

In this setup the wire from the rocket would be attached to the overhead grid supported by an insulated structure. In effect the rocket triggered lightning would act as a generator. The gap could then be set to the desired distance. A manageable gap would probably be somewhere in the region of 20 metres. The entire overhead grid would be exposed to the voltage of the rocket triggered strike. In order to place the strike directly between the competing rods at the ground one would need to hang an overhead rod from the grid. This would be a much closer representation of the conditions experienced during natural lightning.

If this testing proves successful the research could then be extended to long term testing with natural lightning. Currently there are long term air termination tests underway at the University corner building at the University of the Witwatersrand. This research ends in 2011. Following this it would be probable that permission for similar testing but with quasi-hemispherical shapes chosen could be obtained. It would be conducted over a period of a few years. This would be the true test of the research and would provide concrete results if conducted over a long period of time. Other sites both on the University premises and elsewhere could be looked into as possibilities for extending the research.

Another possible extension to the research, if large scale testing proves successful, would be to combine this research with the laser triggering of spark gaps research conducted at the University of the Witwatersrand. Once a preferable shape has been designed to create favourable conditions for upward leader formation at the correct time from the top of the air termination the air above it could be further enhanced to aid leader development. A high powered laser would be used to create plasma above the air termination at the correct moment when the upward leader is being created. This would enhance upward leader formation. It would extend the upward connecting leader making it the preferential strike point in its zone of protection.

The most important research would be to perform tests with upward leader formation from competing air terminations. This needs to be done with gaps of over 5 m and with waveforms with longer front times. If this research proves successful other research such as the one with rocket triggered lightning and perhaps with natural lightning can be considered.

The aim of this research was to design and test quasi-hemispherical air terminations in competition tests with a Franklin rod under long spark gaps in air. Natural lightning conditions need to be replicated closely and as such need to be understood first. The process of breakdown in air is thus explained in detail. Breakdown mechanisms in air differ depending on gap length. The Townsend mechanism is dominant in very short gaps. In longer gaps streamer and leader mechanisms prevail. A streamer is a relatively cold discharge which is not self sustained and relies on the electric field set up between the anode and cathode for ionisation and propagation through the gap. Once a streamer discharge has travelled a certain distance it goes through the streamer to leader transition. It becomes a self sustaining, hot, conducting plasma. The leader is able to self propagate as it enhances the electric field in front of it and creates ionisation. From research it has been shown that once a streamer discharge propagates for more than 3 m it becomes a leader [3]. Lightning strikes thus propagate to the ground as leaders. The mechanism of lightning is also discussed in this research.

The process of lightning is covered in detail in this dissertation. This includes the formation of clouds and ionisation of particles within the clouds. Charged layers of clouds and the assumption of the cloud as a dipole are explained. Most cloud to ground lightning is negative and this is the type of lightning that the research focuses on. The initiation of lightning is explained as is the propagation of the downward leader to ground. During electric field formation and the descent of the downward leader very high electric fields are set up on the ground. During negative downward lightning the ground and objects on the ground become positively charged. At elevated, sharply pointed locations on the ground the electric field is even further enhanced and breakdown starts to occur. First it is in the form of corona and streamer discharges and eventually upward leaders are formed from these points and they extend upwards towards the downward leader. One or more of these upward leaders intercept the downward leader and attachment occurs. This is followed by return strokes and a large amount of charge is transferred from the cloud to the ground in this process. In this way lightning strikes cause a lot of property damage and more importantly injury and death. This is why lightning protection is very important and a methodology for the improvement of conventional lightning protection methods is introduced.

The proposed system is essentially still a Franklin rod but with a quasi-hemispherical tip. As mentioned the Franklin rod goes into corona under the high electric fields experienced during thunderstorms. Streamer discharges are set up at the tip but the background electric field is not high enough for streamer propagation slightly further from the rod tip. The streamer distinguishes and space charge is left behind. This space charge lowers the surrounding electric field retarding formation of upward leaders from the Franklin rod. The aim of this project is to design quasi-hemispherical shapes at the top of the Franklin rod which would not go into corona prematurely during downward leader descent. This would minimise the space charge created. The termination would also need to be shaped so that it is able to enhance the electric field sufficiently for upward streamers to be created at the point where the background electric field at the rod tip and further from it is high enough for streamer propagation of over 3 m and for streamer to leader transition to occur. This would create an upward connecting leader at the optimal instance and make this air termination the preferential strike point in its zone of protection.

There have been some attempts at an improvement on the Franklin rod with varying methodologies and often startling claims of improved performance. These non-conventional lightning protection methods can be placed into two categories. Those that attempt to repel lightning (Lightning Elimination Devices or Charge Transfer Systems, (CTS) or devices which aim to attract lightning from a further distance, thus increasing their zone of protection by enhancing the electric field at their tip and sending streamers earlier. Hence they are known as Early Streamer Emission (ESE) systems. Both of these systems have failed to produce the claimed improved performance in natural lightning installations. They have been widely rejected as adequate lightning protection mechanisms [1, 21, 24]. It important to emphasise that the system presented in this research is a conventional lightning protection mechanism and does not fall into the category mentioned above. It is in essence a very blunt Franklin rod. It works on the same principle as the traditional Franklin rod but aims to influence the electric field at its tip in order to emit a streamer at the moment when the background electric field conditions are such to support streamer propagation and streamer to leader transition.

Once the idea was conceptualised a research into simulations performed on the subject rendered a starting point for the design of the quasi-hemispherical air terminations. Simulations researched were performed on the conditions experienced at variously shaped objects on the ground. The electric fields at the tip of Franklin rods of varying radii were examined during downward leader descent [4]. The downward leader was increased incrementally and electric fields measured at varied snapshots in time. The electric fields were measured at the tip of the air termination to determine whether the electric fields were high enough for streamer inception. Electric fields were also measured further from the air terminations to verify whether the electric fields at these points were high enough to sustain streamer propagation until the streamer reaches 3 m in length and hence becomes a self sustained leader. These simulations concluded that the optimal radius for leader inception was approximately 350 mm. These results were confirmed by more separate simulation research performed by some of the leading experts in lightning research [32]. Some simulation studies were attempted but due to inadequate software available and the complexity of the simulations the results obtained were inaccurate when compared to the simulations of the experts in the area of lightning simulation research. When comparing the electric field values at various distances from the air terminations to the values obtained in [4, 32] with similar setups the results obtained varied greatly from the results obtained by the experts in the area. Some of the reasons for the inaccuracies were that the simulations attempted in this research simulated the downward leader as an ideal conductor and no leader capacitance and resistance was added. The effects of space charge, humidity and water droplets were omitted. The software package available would not allow for such complicated simulations. The author's inexperience in the field of such simulations also contributed to the inaccurate results. Simulations from other studies provided accurate and reliable results and were thus used as a starting point for the design of quasi-hemispherical and hemispherical shapes used in testing.

Primary testing was conducted at the High Voltage Laboratory of the University of the Witwatersrand, Johannesburg. The tests were conducted with a standard lightning impulse waveform (1.2/50 μs) and an air gap of 1.5 m. The tests were designed in preparation for long air gap testing. An overhead plate was constructed to mimic the bottom region of the cloud and create equipotential electric field lines between the point of impulse and the air terminations. A Franklin rod was tested against a spherically tipped rod. Tests with d.c. bias placed on the rods and without d.c. bias were conducted. A corona camera was used to ensure that the tip of the Franklin rod went into corona at the d.c. bias voltage. Most of the strikes were recorded to the Franklin rod. The air gap was too small for upward leader formation and lightning attachment was not correctly replicated. This showed the need to extend the air gap in future testing and lead to the tests performed at the National Electrical Test Facility (NETFA).

Testing with long spark gaps in air and a lightning impulse waveform of quasi-hemispherical air terminations as well as spherical air terminations versus a Franklin rod has also been completed. The results showed that all of the strikes during competition tests between the Franklin rod and the spheres as well as the quasi-hemispherical shapes were to the Franklin rod. In this environment the Franklin rod proved to be the best air termination. Tests with an ESE device were attempted but there was difficulty in operating the device in the manner it was intended to work so instead it was operated as a Franklin rod. It however had a sharper tip than the conventional Franklin rod used for testing so it was used for competition tests between a sharper and blunter Franklin rod. There has been no evidence of upward leader formation from the competing rods. This means that the enhancement of the electric field is the dominating factor of attachment which would obviously favour the sharper rods. During testing with the two Franklin rods, namely the sharp and slightly blunter one, the strike distribution was very even. The sharp Franklin rod had longer upward streamers when not struck but this did not seem to influence the strike frequency to the rods. During testing a 1.2/50 μs waveform was used.

It was clearly shown during testing at NETFA that for meaningful testing of lightning protection air terminations upward leaders need to be created from the competing air terminations. Only in this way could the process of natural lightning attachment be replicated. It must also be noted that even in this case of upward leader formation there are other factors in natural lightning that cannot be replicated easily in a laboratory. These are wind and distance of leader propagation. For upward leader formation to be replicated in a laboratory the air gaps from the impulse to the competing rods need to be extended to over 6 m and possibly to over 10 m. Waveforms with long rise times need to be used as they allow more time for increased electric field conditions in the gap and this aids upward leader formation from the competing air terminations.

A switching waveform would obviously have a longer rise time and more energy and could perhaps produce upward leaders from the competing rods. Tests with longer gaps and waveforms with longer wavefronts should be attempted before a definite conclusion can be made. These tests could also include air gaps of 6 – 8 m. As such they would have to be performed outdoors. The high speed gated camera used to capture upward streamer formation from the competing rods could therefore not be used and other atmospheric conditions such as wind would have an effect. The tests would represent natural lightning attachment more closely and one would be able to determine the better performing air termination under these conditions. Other possible future testing includes installations of quasi-hemispherical air terminations at buildings at the University of the Witwatersrand. These would be long term tests on various buildings.

Currently rocket triggered lightning research is under way at the University of the Witwatersrand. It could be used for testing of various air terminations effectively acting as a very large generator if the right support structure is constructed. This could extend air gap size to over 20 m and would replicate natural lightning attachment closely. All of the above mentioned research hinges around one crucial point. That is to replicate natural lightning attachment to competing air terminations as closely as possible. This is the only way to truly test the proposed idea of correctly sized and shaped quasi-hemispherical air terminations of this research.

From the tests conducted so far however, it is clearly evident that the best lightning protection termination is the Franklin rod. Even if the postulated theory of the sphere of critical radius proves successful in the future the effect is believed to be such that simply extending the Franklin rod by a few centimetres in height would make the Franklin rod a better air termination once again. Economically and from a simplicity point of view the Franklin rod thus seems to be the obvious choice for lightning protection.

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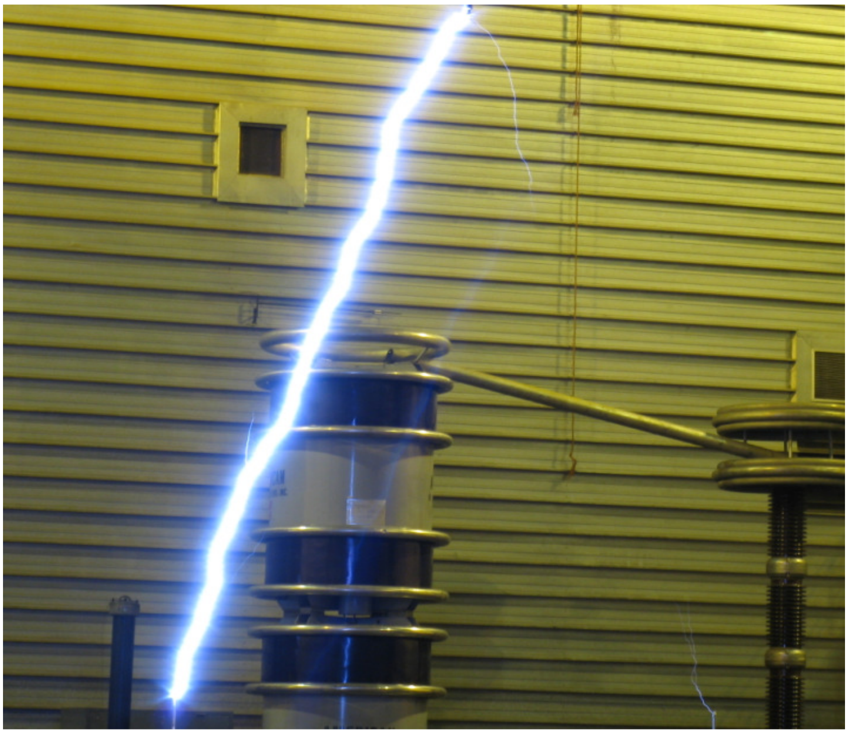
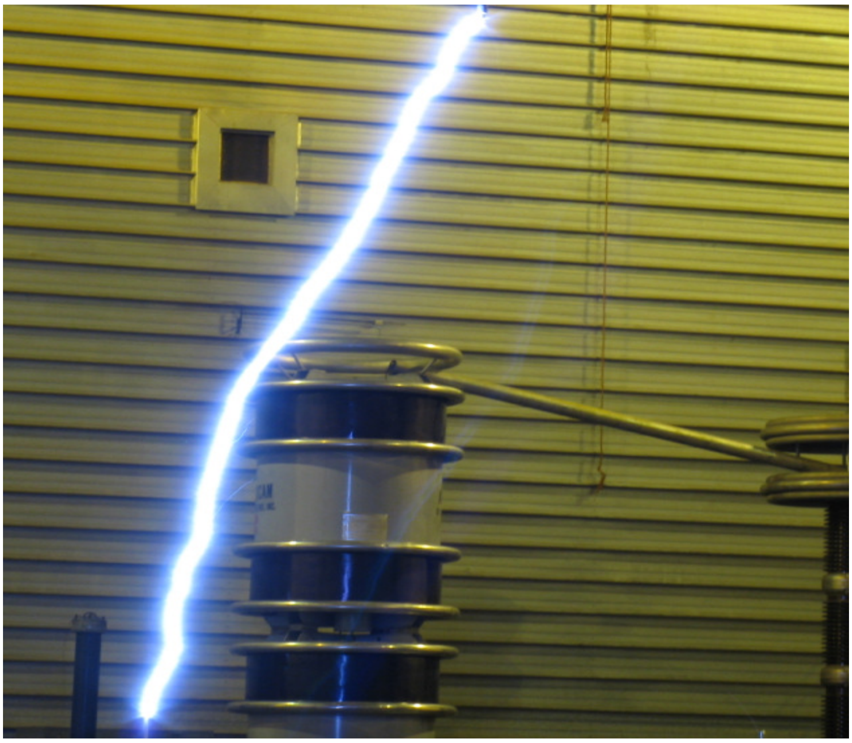
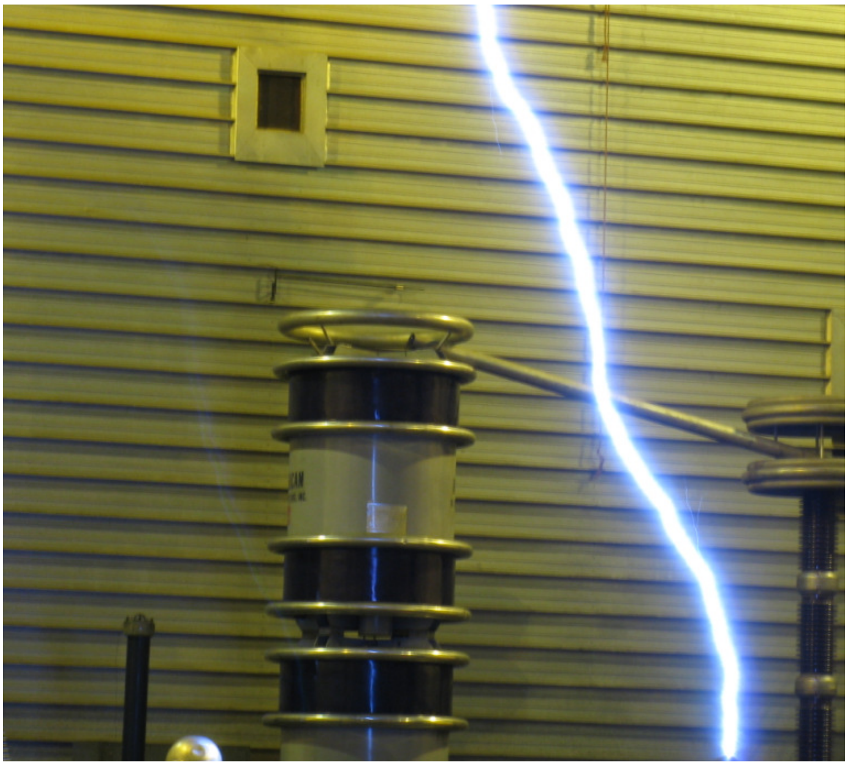
Appendix

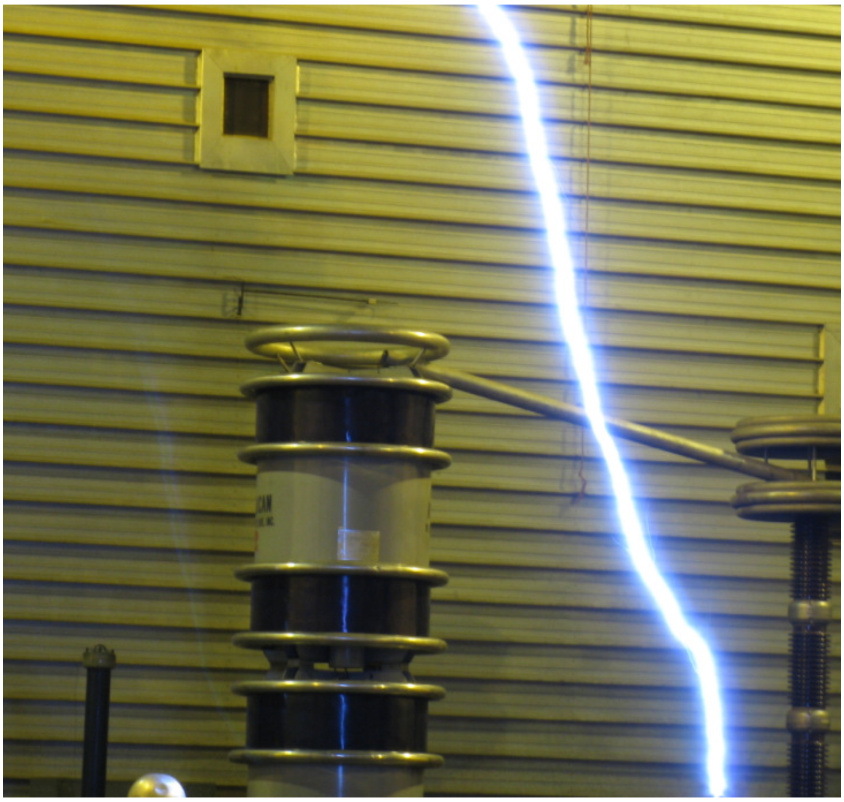
Appendix A

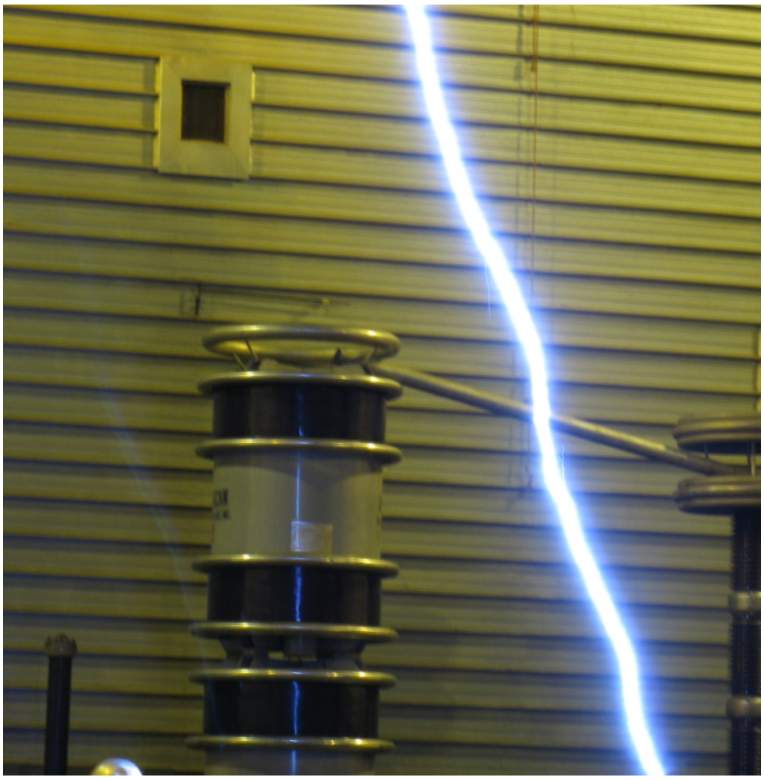
Appendix A contains photographs of breakdowns taken during long air gap testing at the NETFA High Voltage Laboratory.

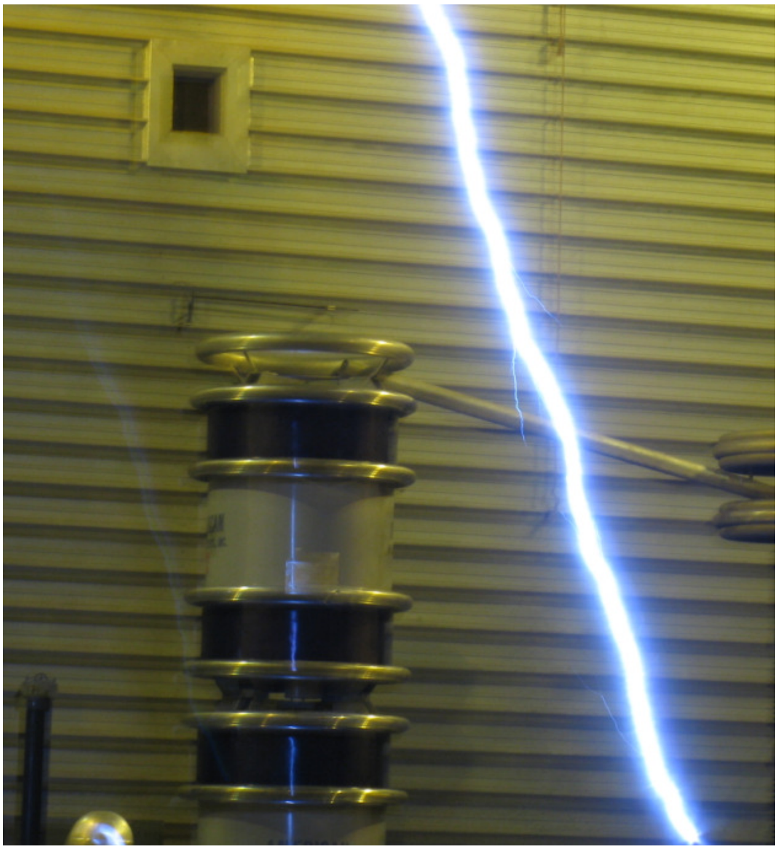


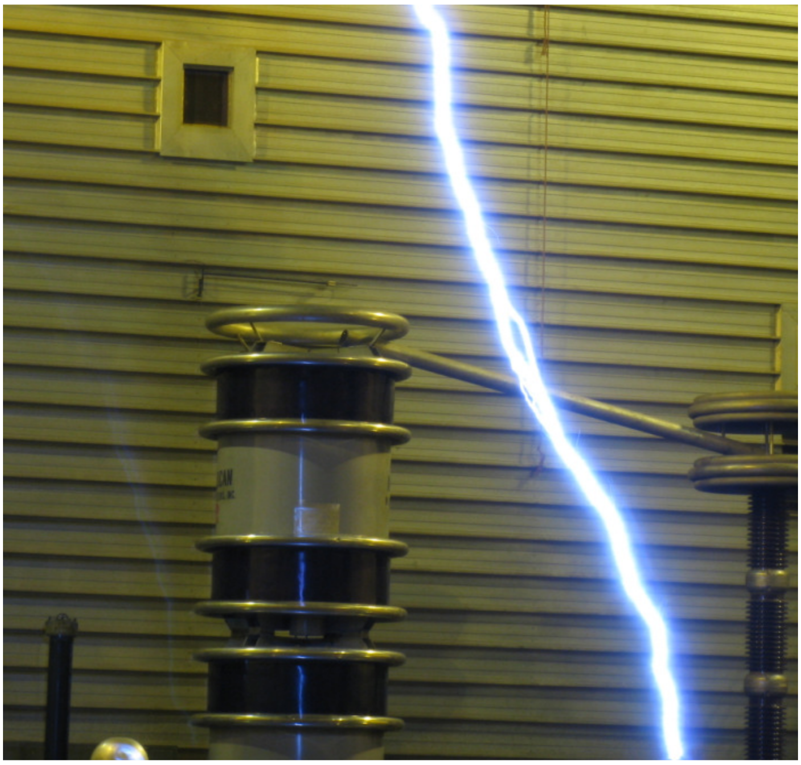


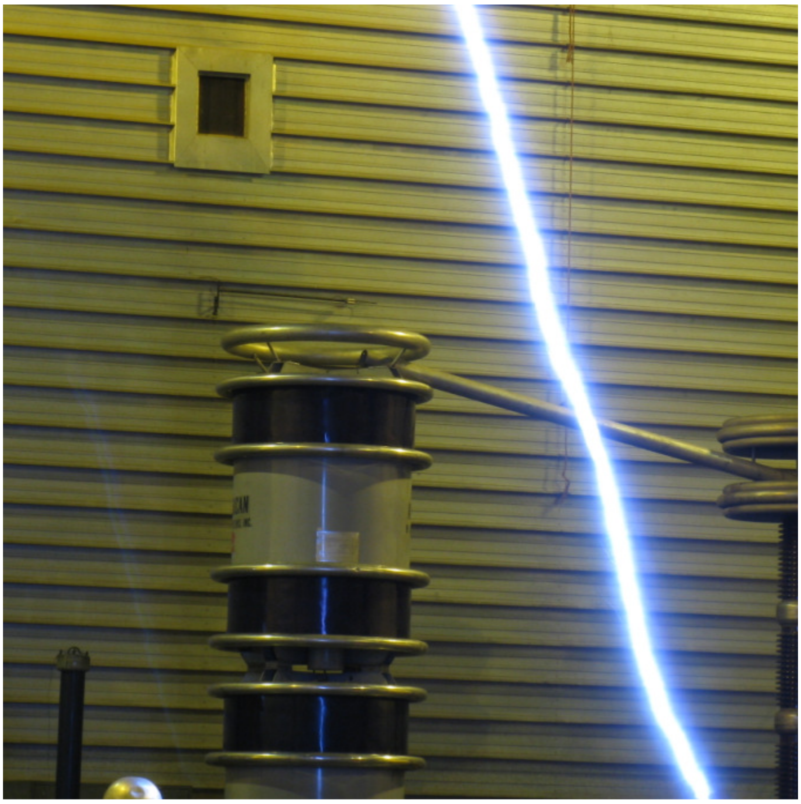


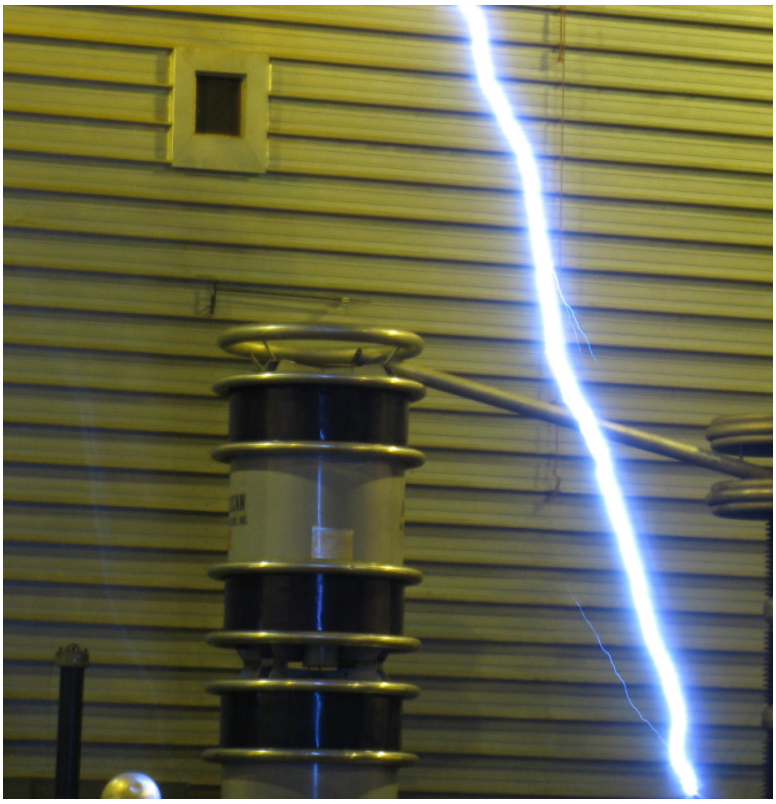


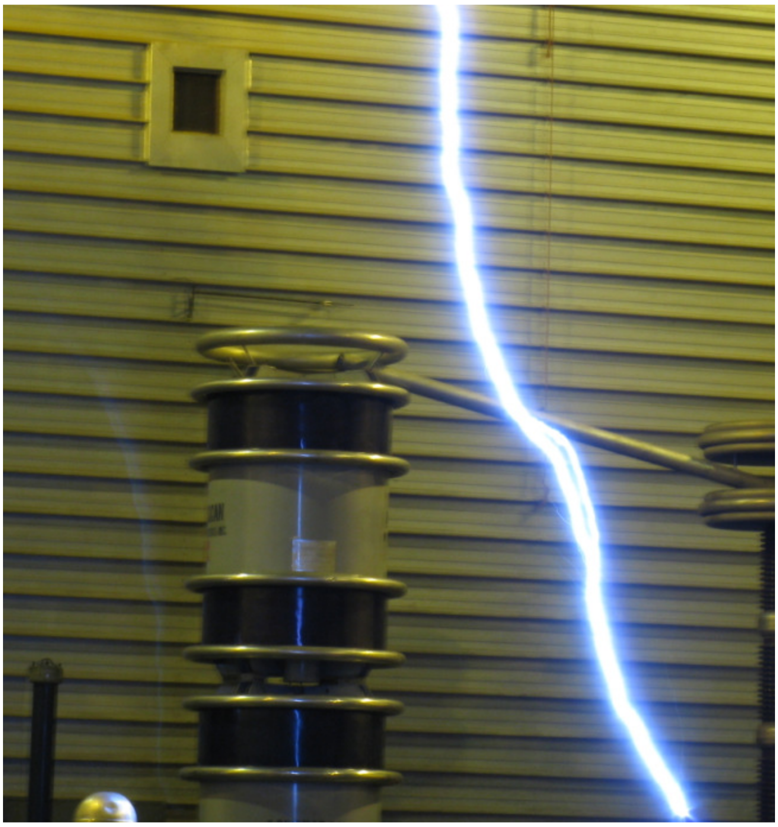










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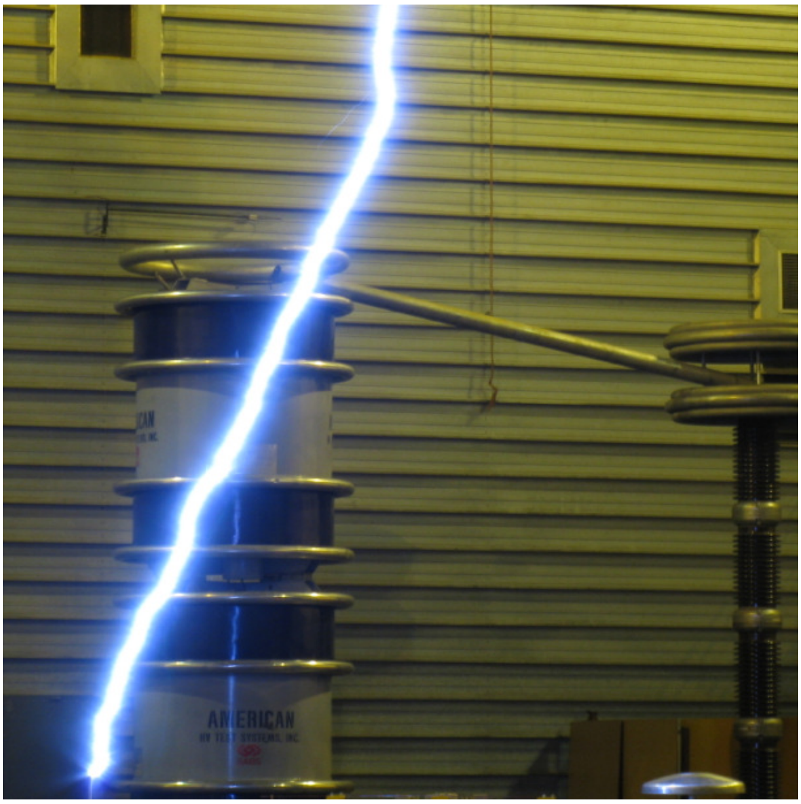
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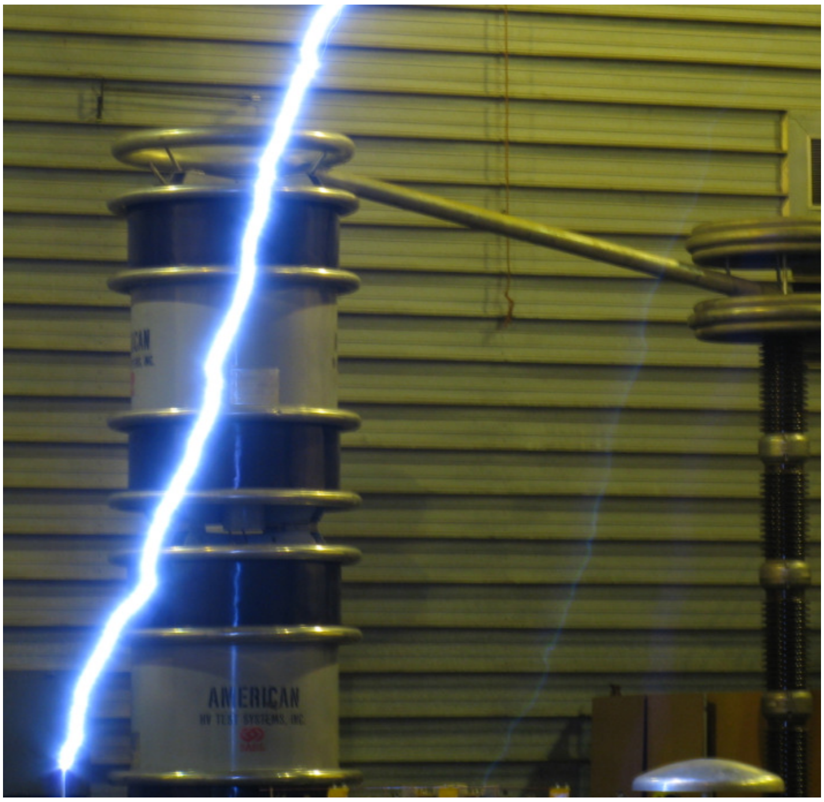
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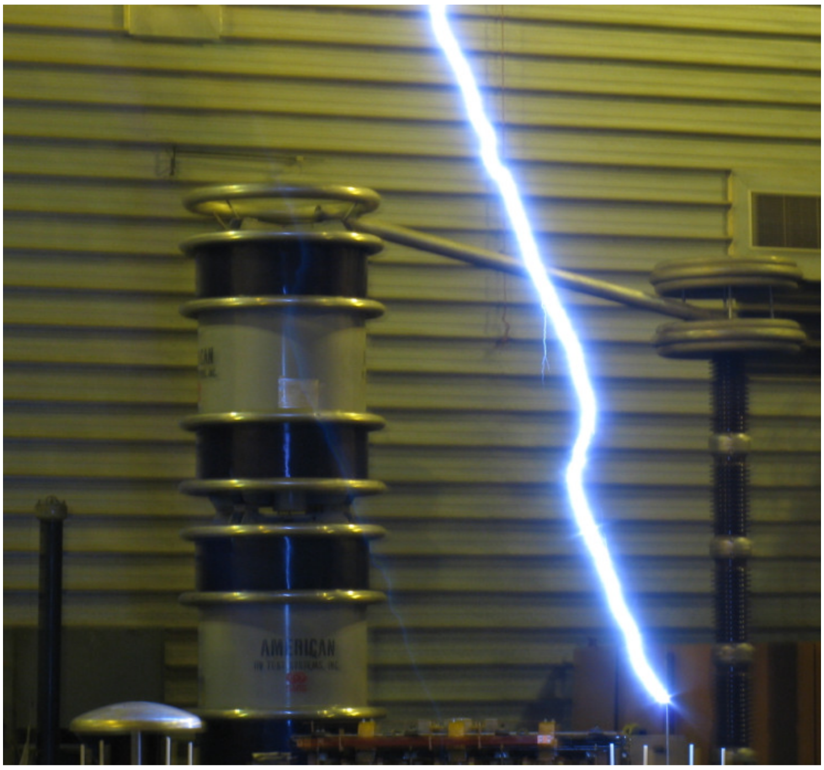
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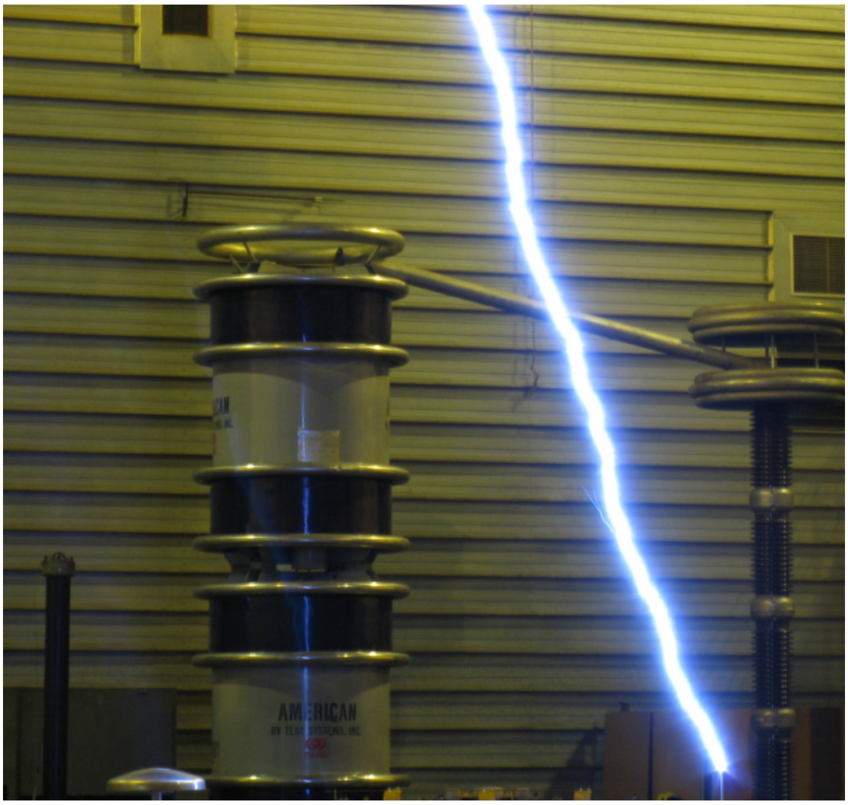
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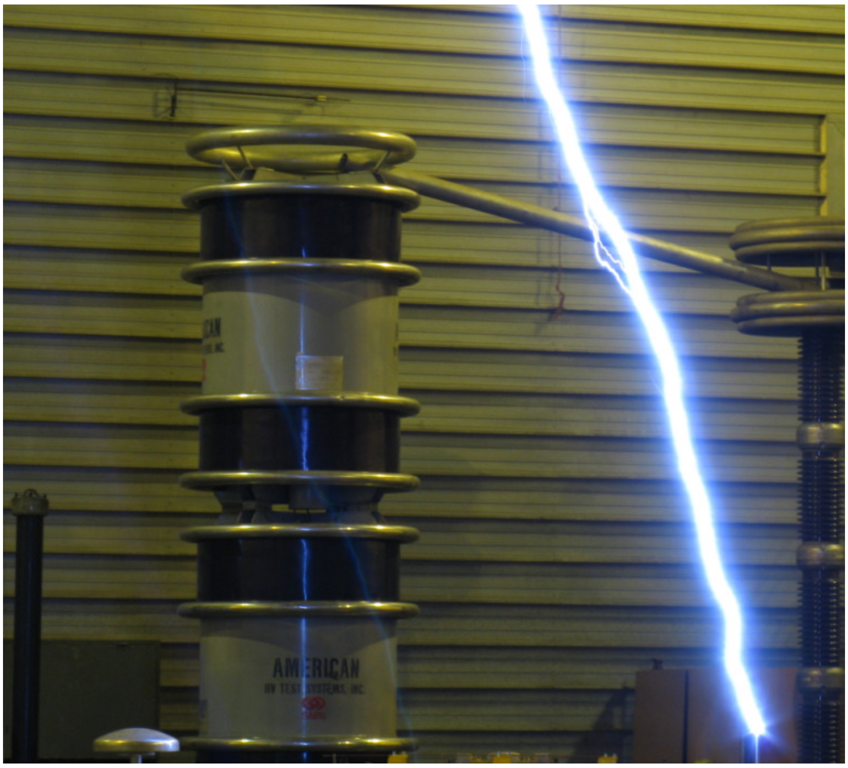
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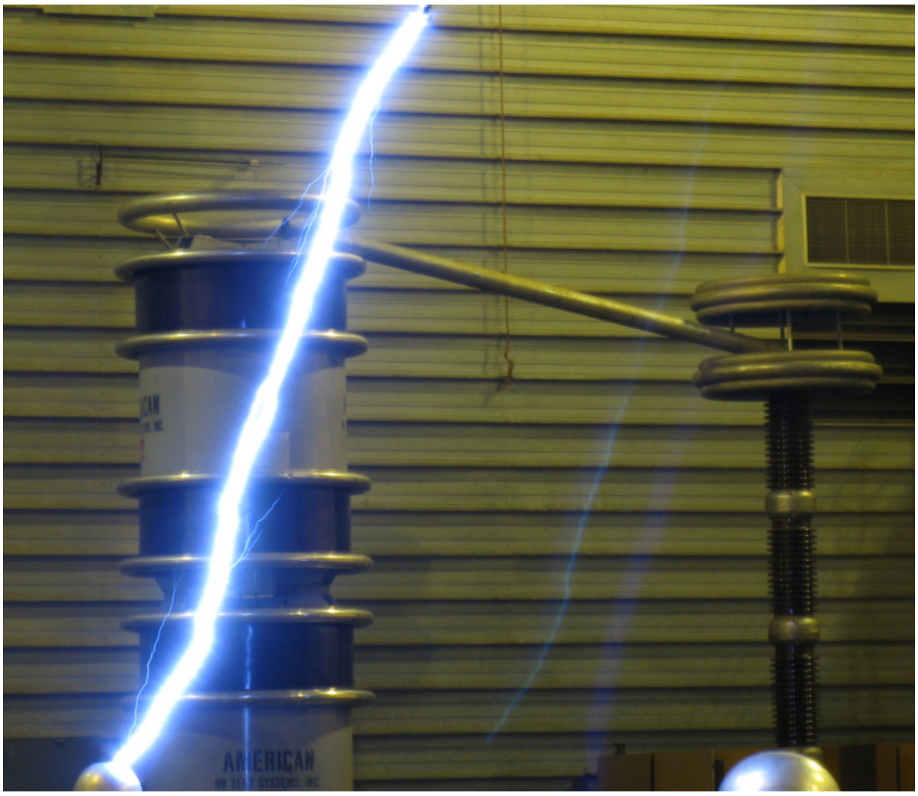
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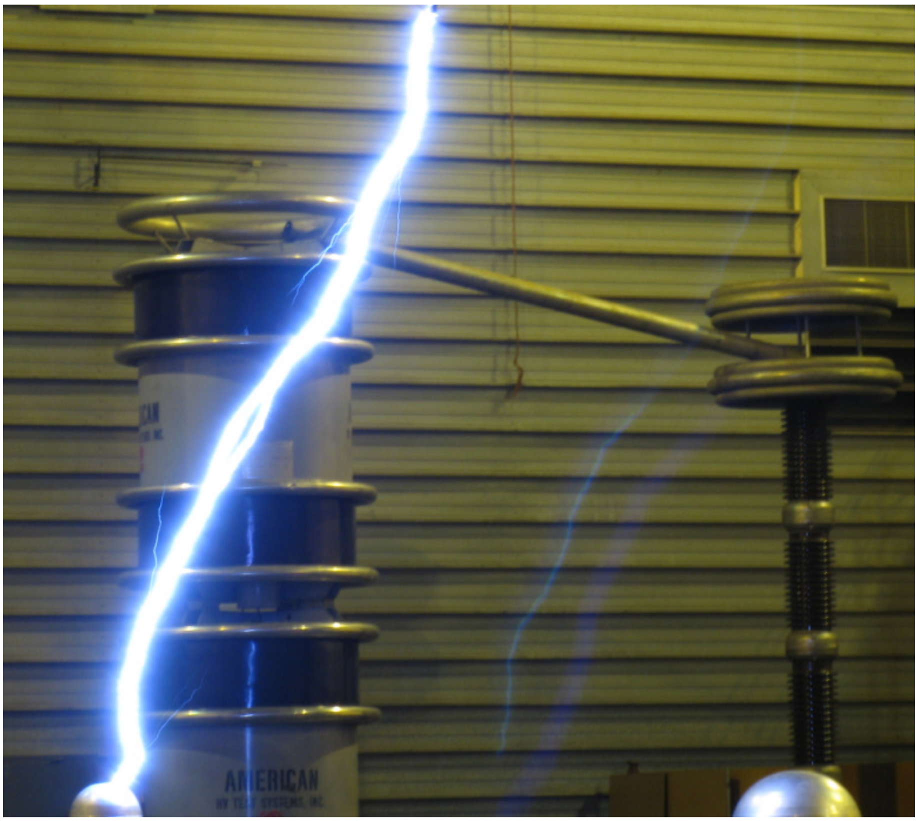
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Appendix B

Appendix B contains the photographs taken by the high speed gated camera during long air gap testing at the NETFA High Voltage Laboratory.