HIGH VOLTAGE SUBNANOSECOND DIELECTRIC
BREAKDOWN

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ABSTRACT

Current interests in ultrawideband radar sources are in the microwave regime, which corresponds to voltage pulse risetimes less than a nanosecond. Some new sources, including the Phillips Laboratory Hindenberg series of hydrogen gas switched pulsers, use hydrogen at hundreds of atmospheres of pressure in the switch. Unfortunately, the published data of electrical breakdown of gas and liquid media at times less than a nanosecond are relatively scarce.

A study was conducted on the electrical breakdown properties of liquid and gas dielectrics at subnanosecond and nanoseconds. Two separate voltage sources with pulse risetimes less than 400 ps were developed. Diagnostic probes were designed and tested for their capability of detecting high voltage pulses at these fast risetimes.

A thorough investigation into E-field strengths of liquid and gas dielectrics at breakdown times ranging from 0.4 to 5 ns was performed. The breakdown strength dependence on voltage polarity was observed. Streak camera images of streamer formation were taken. The effect of ultraviolet radiation, incident upon the gap, on statistical lag time was determined.

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CHAPTER I

INTRODUCTION

Present interests in ultrawideband radiation sources are in the microwave regime, which corresponds to voltage pulse risetimes less than a nanosecond.¹ The high frequencies contained in the pulses provide opportunities to develop information rich radar systems. Some new sources, including the Phillips Laboratory Hindenberg series of hydrogen gas switched pulsers use hydrogen at hundreds of atmospheres of pressure in the switch.² Unfortunately, the published data of electrical breakdown of gas and liquid media at times less than a nanosecond are relatively scarce. This dissertation is a part of the research effort that is underway at the Phillips Laboratory and at a number of universities related to research problems in high power microwaves and sponsored by the Air Force Office of Scientific Research/MURI.

First, the theory of electrical breakdown is discussed. Topics such as Townsend breakdown, Paschen's law, and ionization coefficients are briefly described. Streamer theory is discussed in detail. Breakdown dependence on polarity and the statistical lag present in pulsed breakdown are characterized. Also, the mechanisms of liquid breakdown are discussed.

In the next chapter, the experimental setup is described. The operation and design of the voltage sources used are discussed. These sources include the SEF-303A pulser, with and without an added peaking gap, and a Marx bank driven pulse forming line. The setups of a UV effects and streak camera study are detailed. Also discussed is the design and 3D-field simulation of the test gap.

The next chapter is dedicated to the diagnostic scheme used in the experimental setup. An entire chapter is devoted to this subject due to the importance of accurate diagnostics at these fast pulse risetimes. An investigation into the bandwidth of the capacitive dividers utilized is described.

Next, the experimental results are presented. These results include E-field strengths obtained for various gas and liquid dielectrics at breakdown times from 500 ps to 5 ns. Additional data obtained include UV effect on statistical time lag, breakdown strength dependence on voltage polarity, and streak camera images of the arc formation.

Finally, conclusions drawn from data obtained in the previous chapter are presented.

CHAPTER II

THEORY OF ELECTRICAL BREAKDOWN

Introduction

Two major types of electrical breakdown are dc and pulsed. DC breakdown describes breakdown which occurs between electrodes which have had a voltage difference for a long time (steady state). Pulsed breakdown describes breakdown which occurs as a result of a fast voltage pulse between electrodes. The voltages required for pulsed breakdown are typically 20% greater than voltages in dc breakdown. The processes which comprise these two types of breakdown and related topics are described in this chapter.

Townsend Breakdown

A state of equilibrium exists in an ordinary gas between the rate of electron and positive ion generation and losses. However, when an external electric field is applied this equilibrium is upset. Townsend first studied the current generated in gases between two parallel electrodes.

The V-I characteristic for an ordinary gas between parallel plate electrodes is shown in Figure 2.1. As the gap voltage increases from zero to V_1 the current increases linearly. For a gap voltage between V_1 and V_2 the current remains constant at a value I_0 . This current, I_0 , is known as the saturation current and is the current generated when the cathode is irradiated with UV light.

Figure 2.1. Current-voltage relationship of gas gap.

Above a voltage V_2 , the electrons leaving the cathode are accelerated high enough to cause ionization upon collision with gas molecules. Townsend defined the number of electrons produced per unit length as the quantity α . Using Townsend's first ionization coefficient the incremental increase of electrons is given as

$$dn = \alpha n dx, \quad (2.1)$$

where n is the number of electrons at a distance x away from the cathode. Integrating this equation over the distance, d , from cathode to anode gives

$$n = n_0 e^{\alpha d}, \quad (2.2)$$

where n_0 is the number of primary electrons generated at the cathode. In terms of current at the anode

$$I = I_0 e^{\alpha d}, \quad (2.3)$$

where I_0 is the current leaving the cathode.

The ionization coefficient α is actually dependent on the electron energy distribution in gas, which depends only on E/P , where E is the applied electric field and P is the gas pressure. Therefore, α can be written as

$$\alpha = P f\left(\frac{E}{P}\right), \quad (2.4)$$

or

$$\frac{\alpha}{P} = f\left(\frac{E}{P}\right). \quad (2.5)$$

This dependence between α/P and E/P has been confirmed experimentally.

A number of other secondary processes contribute to the breakdown process. Some of these include secondary electrons produced at the cathode by positive ion impact, secondary electron emission at the cathode by photon impact, and ion impact ionization of the gas. In order to account for these processes the Townsend second ionization coefficient, γ , is introduced. The steady state current equation (2.3), accounting for both Townsend coefficients, can be rewritten as

$$I = I_0 \frac{e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)}, \quad (2.6)$$

where γ may represent one or more possible mechanisms ($\gamma = \gamma_i + \gamma_{ph} + \dots$).

Experimental values for γ can be determined from eqn. (2.6) for known values of E , P , gap distance, and α . Values for γ are highly dependent on cathode surface. Low work function materials will produce greater emissions. The value of γ is small at low values of E/P and higher at greater values of E/P . This is to be expected since at high

values of E/P there will be a greater number of positive ions and photons with energies high enough to eject electrons from the cathode.

Referring to equation (2.6)

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

Substituting eqn. (2.4) for α , eqn. (2.6) can be rewritten as

$$I = I_0 \frac{e^{(Pd)\left(\frac{V}{Pd}\right)}}{1 - \gamma \left(e^{(Pd)\left(\frac{V}{Pd}\right)} - 1 \right)}. \quad (2.7)$$

As the gap voltage increases, the electrode current at the anode increases according to equation (2.6). The current will increase until at some point the denominator of eqn. (2.6) becomes zero, or

$$\gamma(e^{\alpha d} - 1) = 1. \quad (2.8)$$

At this point, eqn (2.6) predicts that the electrode current becomes infinite. This is defined as the transition from self-sustained discharge to breakdown.

Theoretically, the value of the current becomes infinite, but in practice it is limited by the external circuit and voltage drop across the gap. A self-sustaining discharge occurs when the number of ion pairs produced in the gap by the passage of one electron avalanche is large enough that the resulting positive ions, on bombarding the cathode, are able to release one secondary electron and cause a repetition of the avalanche process. The discharge may also be self-sustaining as a result of the secondary electron photoemission process.

Paschen's Law

An analytic expression for breakdown voltage with respect to pressure and gap distance can be derived from eqn. (2.4). Since the first Townsend coefficient can be written as

$$\alpha = P f\left(\frac{E}{P}\right),$$

eqn. (2.8) may be expressed as

$$e^{f\left(\frac{E}{P}\right)Pd} = \frac{1}{\gamma} + 1. \quad (2.9)$$

Taking the natural logarithm of both sides of eqn. (2.9) results in,

$$\ln\left(e^{f\left(\frac{E}{P}\right)Pd}\right) = \ln\left(\frac{1}{\gamma} + 1\right) = K$$
$$f\left(\frac{E}{P}\right)Pd = \ln\left(\frac{1}{\gamma} + 1\right) = K. \quad (2.10)$$

For a uniform field, $V_b = Ed$, the breakdown voltage can be written as

$$f\left(\frac{V_b}{Pd}\right) = \frac{K}{Pd}$$
$$V_b = \phi(Pd), \quad (2.11)$$

which means the breakdown voltage is a function of the gas pressure and gap distance.

This relationship is known as the Paschen Law.

A Paschen curve for various gases³ is shown in Figure 2.2. Note that the breakdown voltage goes through a minimum value at a particular $(Pd)_{\min}$ value. This $V_{b\min}$ can be explained qualitatively. For $Pd > (Pd)_{\min}$, electrons crossing the gap make more frequent collisions than at $(Pd)_{\min}$, but the energy gained between collisions is less.

This results in a lower ionization level for a given gap voltage. For $Pd < (Pd)_{min}$, electrons crossing the gap make less frequent collisions than at $(Pd)_{min}$. Therefore, $(Pd)_{min}$ corresponds to the highest ionization frequency.

Figure 2.2. Paschen curve for various gases.³

Streamer Theory

Thus far, breakdown dependent mainly on electron ionization in the gas and ion bombardment of the cathode has been discussed. However, for over-voltaged gaps (typically 20% or higher of dc breakdown voltage) at pressures greater than 100's of Torr, much shorter breakdown delay times have been observed than what is predicted by the ion drift velocity. This discrepancy led to the development of the streamer theory of breakdown.

A streamer is started due to field enhancement at the head of the initial avalanche. A diagram¹⁰ of the electric field across the gap including the space charge distortion of the initial avalanche is shown in Figure 2.3. The average field across the gap is E_0 . The electron and positive ion clouds are separated due to the higher mobility of the electrons. The field at the anode side of the avalanche is enhanced. Between the electron and positive ion clouds the field strength is reduced due to shielding from the E-field across the gap. A field enhancement is also present at the cathode side of the avalanche.

Figure 2.3. E-field distribution across the gap including the effect of the space charge.¹⁰

When the carrier number in the initial avalanche reaches $n \approx 10^8$, the field enhancement becomes on the order of the applied field and may lead to the initiation of a streamer. Once the avalanche reaches this critical size, the electron density at the head of

the anode side of the avalanche, which is in a highly enhanced E-field, begins to grow rapidly towards the anode. This growth is due to photoionization, caused by ionizing radiation generated at the avalanche head, and is called a streamer. This progression moves at the speed of light due to the photon mechanism. At the cathode side of the avalanche a similar process occurs. Electrons produced by photoionization are accelerated toward the positive charge cloud head. This increases the size of the positive charge cloud towards the cathode. Once the cathode is reached, breakdown occurs. A schematic⁴ of the streamer process is shown in Figure 2.4.

Figure 2.4. Sketch of the propagation of a streamer due to ionized gas from radiation. (a) Anode directed (b) Cathode directed.⁴

Raether⁵ has developed an empirical expression for the streamer initiated breakdown formation

$$\alpha x_c = 17.7 + \ln x_c + \ln \frac{E_r}{E}, \quad (2.12)$$

where E_r is the field strength at the anode side of the avalanche, x_c is the length of the avalanche path in the field direction when it reaches the critical size. The condition for criticality is $E_r = E$, in which case eqn. (2.12) becomes

$$\alpha x_c = 17.7 + \ln x_c . \quad (2.13)$$

If x_c is larger than the gap length, then the initiation of streamers is unlikely. Therefore, the minimum breakdown value by streamer mechanism is when $x_c = d$, where d is the gap distance. Then eqn (2.13) becomes

$$\alpha d = 17.7 + \ln d , \quad (2.14)$$

which gives the minimum value of α for which streamer breakdown can occur.

Raether observed that a typical value for which streamer development can occur is

$$\alpha x_c = 20. \quad (2.15)$$

Using this value he developed a formative time for breakdown. Since the streamer propagation velocity is on the order of the speed of light, the formative time is the time it takes an avalanche to become critical, or

$$t_{cr} \cong \frac{x_c}{v_e} \cong \frac{20}{\alpha v_e} , \quad (2.16)$$

where v_e is the electron drift velocity.

Meek⁶ has developed a similar equation for streamer initiated breakdown. The transition from avalanche to streamer breakdown is taken to be when the enhanced field at the tail end of the avalanche due to the positive ions is on the order of the applied field. This radial E-field at the tail end of the avalanche can be calculated from the expression

$$E_r = 5.3 \times 10^{-7} \frac{\alpha e^{\alpha x}}{\left(\frac{x}{P}\right)^{\frac{1}{2}}} \text{ volts/cm} , \quad (2.17)$$

where x is the distance (in cm) which the avalanche has progressed and P is the gas pressure in Torr. As before, letting $E_r = E$ and $x = d$, a minimum breakdown from streamer occurs when

$$\alpha d + \ln \frac{\alpha}{p} = 14.5 + \ln \frac{E}{p} + \frac{1}{2} \ln \frac{d}{p}. \quad (2.18)$$

Felsenthal and Proud⁷ have taken a slightly different approach. They show analytically that under certain conditions, monopolar-pulsed and pulsed-microwave breakdown are directly comparable. It is assumed that the field in the gap is undistorted by the space charge. Also, effectively electrodeless monopolar-pulsed breakdown is assumed.

The formative lag time is then the measured characteristic time for buildup of ionization in the gap space. The electron continuity equation is used which relates the net rate of change of electron density to the generation and loss mechanism,

$$\frac{\partial n}{\partial t} = \nu_i n - \nu_a n - \nabla \cdot \Gamma, \quad (2.19)$$

where n is the electron density, ν_i is the ionization frequency, ν_a is the attachment frequency, and Γ is the particle flow. However, if the experimental design is such to fulfill the requirement for an effectively electrodeless system, then the $\nabla \cdot \Gamma$ term is neglected. Equation (2.19) is modified to formulate predicted curves of E/P versus $P\tau$, where τ is the formative time to breakdown, for each of the gases studied. Writing the ionization and attachment frequencies in terms of the Townsend first ionization coefficient α and attachment coefficient β , this formula is

$$P\tau = \frac{\ln(n_b/n_o)}{k(E/P)(\alpha/P - \beta/P)}, \quad (2.20)$$

where $k(E/P)$ is the electron drift velocity which is dependent on E/P and n_b/n_o is the ratio of breakdown and initial electron densities.

Experimental results by Felsenthal and Proud matched well with this theoretical model. Figure 2.5 shows formative time measurements in air compared with eqn. (2.20) and data reported.

Figure 2.5. Formative time measurements for air.⁷

T.H. Martin⁸ takes a more empirical approach to breakdown delay. He has developed a scaling relationship between the electric field and the breakdown time. Data

were taken from many diverse experiments including laser-triggered switches, sharp point to plane gaps, and uniform field gaps. The empirical relationship is given as

$$\rho\tau = 97800 \left(\frac{E}{\rho} \right)^{-3.44}, \quad (2.21)$$

where ρ is the gas density in gm/cm^3 , τ is the time delay to breakdown in seconds, and E is the electric field in kV/cm . One interesting observation can be made from this relationship is that breakdown times are highly dependent on E and ρ .

Martin describes a tentative model for the electrical breakdown in the following manner. A fast discharge closes the gap in a short time compared with the overall breakdown time. This fast discharge leaves behind a highly ionized channel. Electrical energy is converted to thermal energy during a heating phase. During this phase there is no significant change in the voltage across the gap. After many electron collisions, the gas temperature increases, thereby lowering the channel resistance. Finally, the gap resistance drops to a point where the electrical driving circuit heats the channel more efficiently. The gap resistance then drops rapidly along with the gap voltage to very low values and the gap closes. The scaling with gas density in eqn. 2.21 is expected since the relationship is one describing heating. Since the specific heats of most gases, except SF_6 , are similar, the gas density becomes the important scaling factor.

This tentative model is based particularly on a typical trigger pre-breakdown current for a trigatron, for which a waveform is shown in Figure 2.6. The fast discharge in this waveform is short compared to the heating phase (5 ns to 300 ns). Unfortunately, Martin does not speculate as to the nature of this fast discharge.

Figure 2.6. Typical breakdown trigger current of a trigatron.⁸

Figure 2.7 shows a plot of nitrogen, helium, SF_6 , and argon from the Felsenthal and Proud⁷ database and also a plot of J.C. Martin⁹ data for air at 1 atm. As the plot shows, the empirical relationship is rather good at long times and somewhat low at shorter times. In fact, for all the data examined by T.H. Martin, it is the short time Felsenthal and Proud data which are consistently above the predicted value. The remaining data, all of which were at greater values of the product of gas density and breakdown time, followed the empirical relationship closely.

Figure 2.7. Breakdown times for various gases (F&P⁷-N₂, He, Ar, and SF₆, JCM⁹-air).

Dielectric Breakdown Strength Dependence on Voltage Polarity

For point-plane like electrode geometries, the breakdown voltage is dependent on the voltage polarity applied to the point electrode. In Figure 2.8 is shown polarity dependence for SF₆, where V_b is the breakdown voltage.¹⁰ Notice that the breakdown voltage is independent of polarity up to approximately 1.5 bar. This is due to the establishment of a steady-state corona discharge about the positive point which acts to stabilize the gap against breakdown. Above this pressure the stabilization ceases and the breakdown for the positively charged point electrode falls to a consistently lower value.

Figure 2.8. D.C. breakdown voltage for SF₆ rod-plane gap (distance from rod to plane $d=20$ mm, rod radius $r=1$ mm).¹⁰

The difference between positively and negatively charged point electrode breakdown voltage is explained in the following manner. For the positively charged point case, ionization near the point will take place. The electrons will impact the anode while the positive ions will be left behind due to their lower mobility. This positive space charge will decrease the field enhancement, in effect, “rounding off” the point. A diagram of this process and a plot of the E-field with and without the space charge¹⁰ is shown in Figure 2.9. In time the positive ions move towards the cathode, thereby increasing the field strength. The field strength may become great enough at the head of the positive space charge to cause a cathode directed streamer, which will initiate breakdown.

Figure 2.9. Diagram of positive point with space charge including E-field strength distribution between positive point and grounded plane with and without space charge.¹⁰

For the negatively charged point, ionization will occur in the high field near the point. Electrons will immediately be repelled toward the anode due to their high mobility (Figure 2.10).¹⁰ The positive ions around the negative point cause an intense field, however, the ionization area is greatly decreased when compared with the positively charged point. So much so, that the ionization will stop. The space charge will be swept away by the applied field and ionization around the point will start again. In order to overcome this effect, a higher field strength is required. Therefore, a negatively charged point will have a higher breakdown voltage than a positively charged point.

Figure 2.10. Diagram of negative point with space charge including E-field strength distribution between negative point and grounded plane with and without space charge.¹⁰

Time Lag of Pulsed Breakdown

The time it takes for a gap to break down, once a pulsed voltage is applied at the gap, is comprised of a statistical lag time and a formative time. The latter is typically determined by the ion transit to the cathode and has been described in depth in this chapter. Statistical lag time is the time it takes for an initiating electron to begin an avalanche once the incident voltage arrives at the gap.

The statistical lag time is dependent on the density of free electrons present in the gap when the incident pulse arrives. The appearance of these electrons is statistically distributed in time. The width of this distribution can be greatly decreased, under certain conditions, when the cathode is illuminated by an external UV light or spark.

A voltage waveform of an over-voltaged gap is shown¹⁰ in Figure 2.11. The value V_s is the static or d.c. voltage under which the gap will break down after a long time. The overvoltage applied to a gap is

$$\text{overvoltage \%} = \frac{V_p}{V_s} \times 100\% \quad (2.22)$$

where V_p is the voltage pulse peak.

Figure 2.11. Time lag components under a step voltage.
 V_s static breakdown voltage, V_p peak voltage,
 t_s statistical lag time, t_f formative time.¹⁰

Kunhardt has done an extensive study of statistical lag time.¹¹ The experimental conditions include a 50 kV, 100 ns wide pulse incident upon a gap. An external spark illuminates the gap. Observational delay time histograms for brass and graphite

electrodes is shown in Figure 2.12. Notice that the statistical lag times are dramatically decreased for graphite compared to brass. This is due to the fact that apparent electron emission rates for graphite are an order of magnitude greater than for brass.

Figure 2.12. Histograms of observational delay time. (a) Brass, (b) Graphite.¹¹

Shown in Figure 2.13 are probability densities for different overvoltages. These are for graphite electrodes at 1 cm gap spacing. Note that the amount of statistical lag is highly dependent on the overvoltage percentage.

Figure 2.13. Histograms of observational delay time for various overvoltages.¹¹

Liquid Dielectric Breakdown

Unlike electrical gas breakdown, the mechanics of liquid breakdown is not as well established. Two general theories of liquid breakdown exist.¹⁰ One is an extension of gas breakdown in which avalanche ionization caused by electron collision is the main process. The electrons are introduced into the liquid gap from the cathode by either field

emission or field enhanced thermionic emission. This type of breakdown is reserved for liquids of high purity.

The other theory of liquid breakdown is derived from the presence of foreign particles in the liquid dielectric. These particles with radii, r , and permittivity, ϵ , will become polarized upon application of an E-field and a force will be applied, given by

$$F_e = r^3 \frac{\epsilon - \epsilon_0}{\epsilon + 2\epsilon_0} \vec{E} (\nabla \vec{E}). \quad (2.23)$$

For particles with $\epsilon > \epsilon_0$, this force will cause these particles to move to the region of highest field strength, which is the uniform gap. These particles in the gap will enhance field lines at the surface causing perturbations in the uniform field. The perturbations will influence particles to align in a bridge across the gap. This bridge will enhance the entire field to a point to allow breakdown to occur.

Other types of mechanisms leading to breakdown include cavity breakdown due to gas bubbles and electroconvection and electrohydrodynamic effects. Recall that the breakdown formative times of interest are primarily in the nanosecond regime. It is apparent that most of these theories require formative times of much longer periods, with the exception being the gas breakdown extension.

J.C. Martin has collected much empirical data on liquid breakdown.¹² One particular set of data consists of propagation velocities of high voltage streamers in several liquids. The experiments were conducted using a sphere-point electrode setup with gap voltages up to 1.3 MV. Liquids tested include transformer oil, carbon tetrachloride, glycerine, and deionized water.

The empirical expression resulting from this data relates streamer velocity to gap voltage. The general expression is

$$\bar{v} = k V^n, \quad (2.25)$$

where $\bar{v}$ is the mean streamer velocity, V is the gap voltage, and k and n are constants dependent on the liquid dielectric. As an example, for positive polarity voltage in transformer oil the streamer velocity expression is

$$\bar{v} = (90 \pm 12) V^{1.75 \pm 0.12}. \quad (2.26)$$

In Figure 2.14 are shown the plotted results for streamer velocity versus gap voltage in transformer oil for both positive and negative polarity.

Figure 2.14. Streamer velocity in transformer oil. (a) positive polarity, (b) negative polarity.¹²

Vorobyov et al.¹³ have conducted investigations into electrical breakdown versus time of exposure in transformer oil (Figure 2.15). Voltages applied ranged from .3 to 1 MV and pulse widths of 3 to 300 ns. Notice that the electrical strength of transformer oil increases about 2.5 times with a 10 times decrease of exposure time.

Figure 2.15. E-field strength versus breakdown time for transformer oil.¹³

Breakdown strength versus delay time for transformer oil² published by several investigators is shown in Figure 2.16. The Martin curve plotted is an adaptation for transformer oil by J. Wells.²

Figure 2.16. Various breakdown data for transformer oil.

CHAPTER III

EXPERIMENTAL SETUP

Introduction

The objective to be met by the experimental setup is to investigate electrical breakdown of liquids and gases at pressures greater than 100 atm. Breakdown time lengths to be observed range from 500 ps to 5 ns. This required a source to supply a pulse to a test gap area with a risetime as low as 400 ps. Peak electric field strengths required at these breakdown times are as high as 7 MV/cm. Hence, for a uniform gap length of 1 mm the required voltage of the incident pulse is 700 kV.

SEF-303A Nanosecond Pulser

The SEF-303A,¹⁴ shown in Figure 3.1, is a compact high-current pulsed power source capable of supplying 200 kV into a 50 ohm load. The backbone of the SEF-303A source is a Tesla transformer with an open core made of steel. The source is a Blumlein generator and comprises a high-pressure spark gap in the secondary circuit with a high-speed thyristor in the primary circuit. Output impedance of the generator is 45 Ω with a pulse risetime and width of 1 and 4 ns, respectively.

Figure 3.1. SEF-303A compact pulsed power source: 1-2, primary and secondary windings; 3-4, external and internal parts of the open core; 5, spark gap switch; 6, load (e.g., e-beam or x-ray tube); 7-8, capacitor dividers; A1-A4, timers; B1-B4, pulsed amplifiers; D, driver; S1-S2, output sync pulses.¹⁴

The compactness of the SEF-303A is derived from the fact that the voltage across the primary winding is held to a relatively low value (450-500 V). The low primary voltage is possible by use of a high-speed thyristor (10 kA, 0.9 kV, $di/dt = 5 \text{ kA/s}$) which acts as the primary switch.

Typical operation of the SEF-303A is as follows. A 500 V pulse is applied across the primary pulse transformer by way of the high voltage thyristor. The secondary winding and Blumlein generator are charged to 150 kV in 5 μsec (see Figure 3.2). At 5 μsec the spark gap breaks down. When the spark gap is shorted, voltage pulses are launched down each branch of the Blumlein, each being at an opposite polarity of the charging voltage and at half the magnitude. These pulses combine at the output of the pulser to form a voltage pulse of -150 kV, 4 ns wide, and 1 ns risetime into a matched load. Typical output voltage traces are shown¹⁴ in Figure 3.2.

Figure 3.2. Traces of charging voltage of the forming line, (A), and of the output voltage at different load resistances (B refers to 50 ohm, C to 150 ohm).¹⁴

An experimental setup using the SEF-303A pulser is shown in Figure 3.3. The output from the SEF-303A is applied to a test gap by way of a 4 ns delay line. The reason for its inclusion is to delay the return of the reflected pulse at the gap. After the incident wave at the gap is reflected, the delay line is made long enough so that breakdown will have occurred before its return. Physical dimensions of the delay line is 1 m long, 7.9 cm outer diameter, and 2 cm inner conductor diameter.

Figure 3.3. Experimental setup with SEF-303A pulser.

A typical waveform applied to the line from the SEF-303A is shown in Figure 3.4. This voltage pulse has a risetime of 1.5 ns and width of 4 ns. Notice that this waveform differs from the waveform in Figure 3.2 for a 50 ohm load. Both traces were recorded by way of the capacitive divider at the output of the SEF-303A. The reason for this variance is most likely attributed to the 50 ohm "matched" load supplied with the SEF-303A pulser. This load is in all likelihood not as matched as specified, resulting in a voltage pulse with a slightly faster risetime than actually being output.

Figure 3.4. Voltage output of SEF-303A pulser into experimental setup.

In order to decrease the risetime of the voltage pulse applied to the test gap a peaking gap was added. A schematic of the experimental setup with a peaking gap is shown in Figure 3.5. The oil-filled peaking gap is comprised of two brass electrodes at a gap distance of approximately 2 mm. A photograph of this setup is shown in Figure 3.6.

Figure 3.5. Experimental setup of SEF-303A with peaking gap.

Figure 3.6. Photograph of the SEF-303A with peaking gap experimental setup.

A comparison of the incident voltage to an open load between the SEF-303A with and without the peaking gap is shown in Figure 3.7. By including the peaking gap the risetime is decreased from 1.5 ns to approximately 400 ps. Notice that the pulsewidth and voltage magnitude remain essentially unchanged. The pre-pulse voltage in the peaking gap waveform is a result of capacitive charge across the oil-filled peaking gap.

Figure 3.7. Gap voltages from the SEF-303A with and without peaking gap.

Marx Bank Driven PFL Pulser

The second setup is a Marx bank driven pulse forming line (PFL) capable of delivering a 700 kV, 400 ps risetime, 3 ns wide pulse to an open test gap. A diagram of the pulser is shown in Figure 3.8. The higher voltage allowed for a larger test gap length thereby minimizing electrode surface effects. A photograph of this setup is shown in Figure 3.9.

Figure 3.8. Marx bank driven PFL subnanosecond pulser.

Figure 3.9. Photograph of Marx bank driven PFL pulser experimental setup.

The Marx bank used was originally constructed to study the effects of the low earth orbit (LEO) environment on high voltage insulators.¹⁵ Therefore, the Marx was originally designed to output a 500 kV pulse with a 1 μ sec risetime and an exponential decay with a time constant ~ 10 μ sec. The bank was originally a 10 stage Marx with a maximum charge voltage of 50 kV per stage. The switches are spark gaps made from 2.4 cm radius brass electrodes with a 3 mm gap. The entire circuit is inserted into a 20 cm diameter steel pressure tube, which is back-filled and pressurized with a 50/50 mixture of dry N_2 and SF_6 during operation. Gas pressure is typically 50 PSI above atmosphere. The output voltage of the Marx can be varied by either changing the spark gap lengths or gas pressure. The tube provides a ground return path as well as an EMI shield for the Marx bank, while the gas mixture acts as an insulator.

The Marx bank originally had a 3 k Ω lumped resistor at the output to the test gap. This resistor provided the desired overdamped response. For the subnanosecond pulser in Figure 3.8, this resistor was removed allowing the Marx to output an underdamped response. In addition the number of stages was increased from 10 to 13. This was motivated by the increased voltage requirement.

A circuit schematic of the Marx bank driven PFL pulser is shown in Figure 3.10.

Displayed is both the Marx bank in its DC and erected state.

Figure 3.10. Equivalent circuits of Marx bank driven PFL.
(a) DC state (b) erected Marx state.

Referring to Figure 3.10a, the capacitance of each stage is 1 nF and the resistance per stage is 100 k Ω . Therefore, the erected Marx capacitance is

$$C_M = \frac{C_{\text{stage}}}{N} = \frac{1 \text{ nF}}{13} = 77 \text{ pF},$$

where C_{stage} is the capacitance per stage and N is the number of stages. The effective erected Marx bank resistance is R_M . The erected Marx inductance, L_M , is designed into the arrangement of the Marx bank. Referring to Figure 3.8, this inductance is a result of the way in which each of the Marx stages were connected. Using the equation for the inductance of a solenoid

$$L_M = \mu_0 n^2 A h = 1.26 \times 10^{-6} \cdot 13^2 \cdot \pi \cdot 0.076^2 \cdot 1 = 2.3 \mu\text{H}, \quad (3.1)$$

where μ_0 is the permeability, n is the number of turns, A is the surface area per coil, and h is the length of the solenoid.

Recall that an underdamped response is desired from the Marx bank to the pulse forming line (PFL). In order to achieve a voltage doubling effect from the Marx the ratio between C_M and the capacitance seen at the output, C_S , and capacitance of the PFL, must be as high as possible. The stray capacitance, C_S , is between the Marx and the PFL. Referring to Figure 3.8, this is the stray capacitance of the Lexan feedthrough and the connector between the last gap of the Marx and the Lexan feedthrough. Using the equation for a cylindrical capacitor

$$C_s = \frac{2\pi\epsilon_0\epsilon_r l}{\ln\left(\frac{r_o}{r_i}\right)}, \quad (3.2)$$

where l is the coaxial length, r_o and r_i are the outer and inner radii, respectively. Taking into consideration the tapered Lexan feedthrough transition, the calculated stray capacitance is approximately 20 pF. Similarly, the stray inductance, L_s , of this region is calculated to be 50 nH. The calculated capacitance of the PFL is approximately 25 pF. A compromise had to be made between keeping the PFL capacitance as low as possible and designing the PFL electrical length to be on the order of 2 ns. This gives a total output capacitance, C_o , of 45 pF. Therefore, the ration between C_M and C_o is,

$$\frac{C_M}{C_o} = \frac{77 \text{ pF}}{45 \text{ pF}} = 1.71.$$

Figure 3.11 displays the charging voltage of the PFL, both simulated and actual. The Marx charges the PFL in approximately 25 ns. The peaking gap length is set for a breakdown time of 25 ns at voltage of 800 kV. Therefore, whenever the Marx voltage is varied the peaking gap length must be changed in order to optimize the charging of the PFL.

(a)

(b)

Figure 3.11. Charging voltage of the PFL. (a) simulated, (b) actual.

The actual voltage applied to the test gap is shown in Figure 3.12. A voltage of over 700 kV was achieved with a risetime of 400 ps and pulsewidth of 2 ns. This is over twice the voltage obtained with the SEF-303A pulser.

Figure 3.12. Test gap voltage from the Marx bank driven PFL

Several modifications were made to prevent breakdown from occurring inside the Marx bank chamber. The inner conductor between the final spark gap of the Marx and the Lexan feedthrough was enlarged in order to decrease field enhancement. Originally, this connection was made via a 12-gauge wire. Another modification was to change the profile of the Lexan feedthrough from a disc-type to a funnel shape. The funnel shape provided a lower E-field stress due to E-field curvature at the dielectric surface and also provided a longer path for tracking to occur.

UV Radiation Setup

The objective of this experiment was to introduce ultraviolet light to the test gap and determine its effect on statistical lag on breakdown time for various gas pressures. The major task was to design a UV rated window which could handle at least several tens of atmospheres. Therefore, a 1 cm thick ultraviolet grade synthetic fused silica window was chosen. The transmittance of this type window is shown¹⁶ in Figure 3.13. The UV was supplied by a 150 Watt Xenon arc lamp. An advantage of a Xenon arc lamp is that it produces a rather broad spectrum throughout the UV band.

Figure 3.13. Transmittance of a 1 cm thick ultraviolet grade fused silica window.

Streak Camera Setup

It is of interest to observe streamer formation across the gap. This requires imaging equipment with time resolution better than 1 ns for the breakdown times of interest. The Hamamatsu C979 temporal disperser is a picosecond streak camera capable of resolving time better than 10 picoseconds and producing a time profile of light events up to 100 nanoseconds.

The temporal disperser principle of operation¹⁷ is as follows (see Figure 3.14). Light incident on the input slit is focused onto the photocathode. The incident photons are converted to electrons and accelerated from the photocathode toward the sweeping electrodes via an accelerating mesh. Voltage across the sweeping electrodes is synchronized with the arriving electrons to decrease linearly in time, which sweeps the electrons from top down during the streak operation. The swept electrons are projected onto a micro-channel-plate where electron multiplication is accomplished. These electrons exit the micro-channel-plate and bombard the phosphor screen, and are converted into an optical image.

Figure 3.14. Schematic of the Hamamatsu streak camera.

Figure 3.15 shows a schematic of the experimental setup incorporating the streak camera. When the SEF-303A pulser is triggered a voltage is output from the microsecond detector several microseconds before the SEF-303A output pulse is applied to the test gap. This detector voltage is delayed by the delay generator and output to the trigger input of the streak camera. The streak camera requires a trigger approximately 10 to 20 ns before the event to be recorded. The gap is imaged on the slit of the camera via a

lens. When the voltage across the sweeping electrodes in the camera changes it is detected with a B-dot probe with 1 ns delay. This voltage is recorded with a 500 MHz sampling scope along with the voltage from the capacitive divider at the test gap. This makes it possible to determine when the streak occurred in relation to the gap voltage.

Figure 3.15. Schematic of the experimental setup with streak camera.

Once the streak image is incident upon the phosphor screen it is recorded by the highly sensitive image pickup tube Silicon Intensified Target (SIT) camera. The SIT camera works in conjunction with the temporal analyzer to digitize the image of the phosphor screen. The digitized image is 64 x 256 pixels in the spatial and time axes, respectively. The digitized intensity of the image is of 8-bit resolution. This digitized image is transferred to a PC laptop via a serial connection. Using the software program Matlab, the image was reconstructed.

Test Gap

A schematic of the test gap is shown in Figure 3.16. The chamber is made of schedule 40 stainless steel. Wall thickness is approximately 5 mm. Chamber diameter and length are 9 cm and 23 cm, respectively. The diameter of the view port is 2 cm. The O-rings are incorporated into the Lexan spacers. The chamber ruggedness was required to contain pressures up to 2000 PSI.

Figure 3.16. Test chamber for the experimental setup.

The electrode design used for a uniform field gap was a hemispherical shape with a 1 cm radius. A photograph of the electrodes is shown in Figure 3.17. The electrodes were made from highly polished brass.

Figure 3.17. Photograph of the hemispherical brass electrodes.

A point-plane electrode geometry was used to investigate breakdown dependence on polarity. The objective is to create a high field enhancement on the point electrode. A photograph of the electrodes is shown in Figure 3.18.

Figure 3.18. Photograph of the point-plane geometry electrodes.

Two hemispherical electrodes are used for a uniform field because of their close proximity, 2 mm, in relation to their radii, 1 cm. An expression for maximum field strength for two spheres at a distance, a , from each other is

$$E = 0.9 \frac{U}{a} \frac{r + a/2}{r} \frac{\text{kV}}{\text{cm}} \quad (3.3)$$

where U is the gap voltage, a is the distance between the spheres, and r is the radius of each sphere. For a $U=500$ kV and $r=1$ cm, the maximum field strength versus gap distance is plotted in Figure 3.19. Also plotted is the average E-field across the gap. Notice that for a gap distance up to 8 mm the max E-field and average E-field follow very closely. Above an 8 mm gap distance the max E-field approaches the E-field strength of two point charges.

Figure 3.19. Plot of maximum and average E-field versus gap distance.

The electrostatic fields for the test chamber geometry are calculated using a three dimensional field plotting program called Maxwell 3D. The geometry of the test chamber is drawn with appropriate material properties, such as conductivity and permittivity, assigned. Internally, the simulator creates a finite element mesh that divides the structure into thousands of smaller regions or tetrahedrons. The field in each sub-region can then be represented with a separate equation. The Maxwell 3D Field Simulator's electrostatic solver calculates and stores the value of the electric potential at each tetrahedron vertex (node) and at the midpoint of all edges. The electric field is solved using

$$\mathbf{E} = -\nabla V \quad (3.4)$$

where ∇V is the gradient of the electric potential.

A plot of the E-field strength using Maxwell 3D is shown in Figure 3.20. Plots are shown for various gap distances and different cross-sections. It should be noted that the max E-field strengths plotted follow the curve in Figure 3.19 fairly well.

(a)

(b)

(c)

Figure 3.20. E-field strength plot using Maxwell 3D for hemispherical electrodes and 500 kV gap voltage. (a) 5 mm gap, (b) 1 cm gap, (c) 2 cm gap.

The maximum E-field strength for a point-plane geometry can be calculated using an expression derived by Mason.¹⁸ This expression for the E-field at the tip is

$$E_{\max} = \frac{2V_0 t p_1}{\log q} \quad (3.5)$$

where

$$p_1 = \frac{(1 + R/t)^{1/2}}{R} \quad (3.6)$$

and

$$q = \frac{[2t + R + 2t^{1/2}(t + R)^{1/2}]}{R} \quad (3.7)$$

and V_0 is the voltage applied to the gap, t is the gap distance, and R is the tip radius of curvature.

A plot of max the E-field at the tip and the average E-field across the gap for $R=600 \mu\text{m}$ and $V_0=500 \text{ kV}$ is shown in Figure 3.21. When the gap distance is several mm, the E-field strength at the tip is approximately an order of magnitude higher than the average E-field across the gap.

Figure 3.21. E-field at point tip and average E-field across the gap versus gap distance.

The electrostatic field for the test chamber with a point-plane electrode geometry is calculated using Maxwell 3D. In Figure 3.22 are several plots for E-field strength at different gap distances and cross-sections. These E-field strengths compare well with those predicted in Figure 3.21.

Figure 3.22. E-field strength plots for test chamber with point-plane electrodes and 500 kV gap voltage. (a) 1 mm gap, (b) 2 mm gap, (c) 5 mm gap

E-field (MV/cm)

(b)

E-field (MV/cm)

(c)

Figure 3.22. Continued.

CHAPTER IV

DIAGNOSTICS

Introduction

Ultrawideband pulses with their fast risetimes (~150 ps) require diagnostics with high bandwidths (~4 GHz). The 150 ps risetime was an initial goal; however, risetimes ~400 ps were actually achieved. The four major components of the diagnostics setup are the high voltage divider, wide-band attenuator, wide-band cable, and the recorder. The chosen recorder is the Tektronix SCD-5000 transient event digitizer. The analog bandwidth of the SCD 5000 is approximately 4.5 GHz. This corresponds to recording risetimes of

$$t_r = \frac{0.35}{\text{Bandwidth}} = \frac{0.35}{4.5\text{GHz}} = 80 \text{ ps} \quad (4.1)$$

The wide-band cable used is semi-rigid with a bandwidth greater than 15 GHz. The wide-band attenuator has a bandwidth of 8 GHz and a rated peak power of 5 kW.

High Voltage Dividers

For the measurement of high voltage pulses there are two distinct types of attenuators to consider: a resistor divider and a capacitor divider. A schematic of a resistor divider circuit is shown¹⁹ in Figure 4.1. The R_H refers to the high impedance element and R_L refers to the low impedance element of the resistive divider. The R_d is a damping resistor included to attenuate the high frequency oscillation due to the stray capacitances and residual inductance. The capacitors shown represent capacitive coupling

between various points on the divider. The C_H refers to coupling between various points on the divider, and C_G refers to coupling between points on the divider and ground.

Figure 4.1. Equivalent circuit of a resistive divider.¹⁹

The step response of the circuit in Figure 4.1 is shown in Figure 4.2 for a damping resistor of zero ohms.¹⁹ It is obvious that such a device is unsuitable for the measurement of a signal which has significant variations on time scales shorter than about 10 μsec because high frequency oscillations would be induced on the output waveform that were not present on the input voltage. When a value of the damping resistor is increased, the oscillations are damped, however the response time of the divider decreases. For example, when $R_d = 57 \Omega$ the oscillations are successfully damped but the response time of the divider increases from 45 ns to 90 ns.

Figure 4.2. Step response of a resistive divider with $R_d = 0 \Omega$.¹⁹

It is evident that a resistor divider is not adequate for the measurement of nanosecond voltage pulses. Therefore a capacitor divider is the preferred attenuator. The schematic of a typical capacitive divider, often used in coaxial systems, is shown²⁰ in Figure 4.3. The capacitances C_1 and C_2 are not lumped elements but rather stray capacitances designed into the geometry of the system for desired values. A simplified equivalent circuit for this type of divider is shown¹⁹ in Figure 4.4. The impedance of the cable is assumed to match R_2 .

Figure 4.3. Schematic of a typical capacitive divider.²⁰

Figure 4.4. Circuit equivalent of a typical capacitive divider.¹⁹

The calculated unit step response of the circuit in Figure 4.4 is given by

$$V(t) = \left(\frac{C_1}{C_1 + C_2} \right) \left(\frac{R_2}{R_1 + R_2} \right) \exp(-t/\tau), \quad (4.2)$$

where the time constant, τ , is

$$\tau = (C_1 + C_2)(R_1 + R_2) \quad (4.3)$$

Choosing typical values,

$$C_2 = 10^{-8} \text{ to } 10^{-9} \text{ F} \gg C_1,$$

$$R_1 = R_2 = 50 \Omega,$$

yields a time constant of

$$\tau = 100 \text{ to } 1000 \text{ ns.}$$

A measured step response for this type of capacitive divider is shown¹⁹ in Figure 4.5. This was a low voltage measurement with the pulse being supplied to the gas-insulated test line through a mercury-wetted relay. The risetime of the pulse is on the order of 1 ns which was expected from the relay. It can be seen in Figure 4.5 that oscillations occur after 20 ns. These are not due to characteristics of the divider but rather are due to reflections in the high voltage circuit. A second observation is that there is significant droop in the output of the divider during the first 50 ns. The divider, therefore, could not be used without correction for an accurate measurement of voltages which have variations on these time scales. For measurements at these time scales, correction by either software or hardware would be required.

Figure 4.5. Measured step response of a capacitor divider at different time scales.¹⁹

Although the droop of a capacitive divider is an important characteristic, it is of less importance than the risetime when measuring nanosecond wide pulses. Recall that the time constant of this type of capacitive divider is typically between 100 and 1000 ns. The question then arises, what are the shortest risetimes that can be obtained from a capacitive divider.

Risetimes on the order of a 100 ps have been recorded. The behavior of a ground plane mounted transmission line E-field sensor, as shown in Figure 4.6, has been investigated by Buchenauer and Marek.²¹ The output pulse applied to the sensor was a

step with a 10 volt amplitude and 45 ps risetime. Acceptable performance is achieved only when the incident wave direction is perpendicular to the stripline axis or $\phi = 0^\circ$.

Figure 4.6. A dense dielectric supported stripline E-field sensor.²¹

Figure 4.7 shows the step response of this sensor constructed on teflon for $\phi = 0^\circ$ and L' of several lengths. The mid-trace aberration diminishes with increasing L' . This is an end effect that occurs on a dielectric strip of finite length because the electrode is not raised to a constant potential along its length after passage of the incident wave. Net longitudinal surface currents begin flowing near the end as the wave traverses the width of the line, thus generating the aberrant signal at time L/c_{eff} , where c_{eff} is the effective speed of light through the dielectric. This effect diminishes with increasing L' as electrical conditions approach those for a infinite dielectric strip. This effect has also been observed by the author using a similar type sensor.

Figure 4.7. Step response of the dense dielectric supported stripline E-field sensor.²¹

The risetime of the strip line step response is observed to be about 130 ps. Recall that the applied pulse risetime is 45 ps. The sensor response is altered by the dielectric. However, to accurately maintain sub-millimeter physical height, which is necessary to meet the high attenuation requirement, a solid dielectric must often be used.

Umbrella Probe

A variation of the strip line for a coaxial geometry is the umbrella probe.²² A cross-section of a coaxial line with an umbrella probe is shown in Figure 4.8. The attenuation of such a probe can easily be calculated.

Figure 4.8. Coaxial line with umbrella probe.

As a transverse electromagnetic (TEM) wave propagates along a coaxial line the electric field intensity is directed only along the radial axis normal to the cylindrical surface. The expression for the E-field intensity with respect to r for two concentric conducting planes can be found easily from applying Gauss law

$$E_r = \frac{\rho_s}{\epsilon}, \quad (4.4)$$

where ρ_s is the surface charge density and ϵ is the medium permittivity. The potential difference between the inner conductor and the outer conductor of the umbrella probe is

$$V_{ab} = - \int_{r=b}^{r=a} \mathbf{E}_l \cdot d\mathbf{l} = - \int_b^a \left(\mathbf{a}_r \frac{\rho_s}{\epsilon_1} \right) \cdot (\mathbf{a}_r dr) = \frac{\rho_s}{\epsilon_1} \ln \left(\frac{b}{a} \right), \quad (4.5)$$

where a is the inner conductor radius, b is the radius to the umbrella probe, and ϵ_1 is the permittivity of the coaxial line. Similarly, the potential difference across the umbrella probe is found to be

$$V_{bc} = \frac{\rho_s}{\epsilon_2} \ln\left(\frac{c}{b}\right), \quad (4.6)$$

where c is the radius of the outer conductor and ϵ_2 is the permittivity of the umbrella probe dielectric.

The voltage applied to the coaxial line, V_{ac} , is the sum of these two voltages

$$V_{ac} = V_{ab} + V_{bc}. \quad (4.7)$$

The probe attenuation is found to be

$$A = \frac{V_{bc}}{V_{ac}} = \frac{V_{bc}}{V_{ab} + V_{bc}} = \frac{\frac{\rho_s}{\epsilon_2} \ln\left(\frac{c}{b}\right)}{\frac{\rho_s}{\epsilon_1} \ln\left(\frac{b}{a}\right) + \frac{\rho_s}{\epsilon_2} \ln\left(\frac{c}{b}\right)} = \frac{\epsilon_1 \ln\left(\frac{c}{b}\right)}{\epsilon_2 \ln\left(\frac{b}{a}\right) + \epsilon_1 \ln\left(\frac{c}{b}\right)}. \quad (4.8)$$

The probe attenuation can also be found in terms of the capacitance. The capacitance between the inner conductor and the umbrella probe is

$$C_1 = \frac{2\pi\epsilon_1}{\ln\left(\frac{b}{a}\right)} w_{\text{probe}} \frac{l_{\text{probe}}}{2\pi b}, \quad (4.9)$$

where w_{probe} is the width of the probe and l_{probe} is the length of the probe. The capacitance between the umbrella probe and the outer conductor is

$$C_2 = \frac{2\pi\epsilon_2}{\ln\left(\frac{c}{b}\right)} w_{\text{probe}} \frac{l_{\text{probe}}}{2\pi b}, \quad (4.10)$$

where both capacitance calculations neglect fringing. Inserting eqns. (4.9) and (4.10) into eqn. (4.8) we get,

$$A = \frac{\epsilon_1 \frac{2\pi\epsilon_2}{C_2} w_{\text{probe}} \frac{l_{\text{probe}}}{2\pi b}}{\epsilon_2 \frac{2\pi\epsilon_1}{C_1} w_{\text{probe}} \frac{l_{\text{probe}}}{2\pi b} + \epsilon_1 \frac{2\pi\epsilon_2}{C_2} w_{\text{probe}} \frac{l_{\text{probe}}}{2\pi b}} = \frac{\frac{1}{C_2}}{\frac{1}{C_1} + \frac{1}{C_2}} = \frac{C_1}{C_2 + C_1} . \quad (4.11)$$

These probes are designed to detect voltages in the Megavolt range. For coaxial lines with radii in the cm range, an umbrella probe thickness, δ , of 10 to 100 μm will provide attenuation of about 1000. Another factor in determining δ is the typical voltage to be applied on the probe and the breakdown strength of the dielectric. Some common dielectrics used are polyethylene and kapton.

The geometrical shape of the umbrella can be, in principle, arbitrary, but its characteristic dimension (e.g., the radius of a round umbrella) must satisfy the condition of quasi-steadiness. According to this condition, the time of the wave path along the characteristic dimension must be significantly lower than the duration, T , of the registered pulse. For example, for a round umbrella

$$R \ll \frac{Tc}{\sqrt{\epsilon_2}} , \quad (4.12)$$

where R is the umbrella radius, c is the speed of light in vacuum, and ϵ_2 is the probe permittivity.

The advantages of the capacitive umbrella probe are the wide bandwidth due to the inherently vanishingly small inductance from the geometry and the ability to obtain a rough attenuation coefficient by measuring the probe capacitance and calculating from eqn. (4.11). The upper boundary of the bandwidth (several Gigahertz) is determined by the physical dimensions of the probe.

Probe Design

The actual probes used in these experiments differ slightly from that in the schematic of Figure 4.8. Issues such as available material, soldering connections, and durability had to be addressed. Figure 4.9 shows a schematic of a typical probe. This shows the probe at a close-up view at the cable connection. The hermetically sealed SMA connector is screwed into the external conductor. A layer of epoxy is added, filling the air gap between the end of the connector and the inside wall of the external conductor. Kapton-Aluminum foil is adhered to the inside of the external conductor. The foil is 1 mil thick Kapton deposited with 1mil thick aluminum. A hole is punched through the foil allowing the SMA inner conductor to pass through to the upper conductor without contacting the lower conductor. When the Kapton foil is cut, tiny abrasions are made exposing the aluminum side. High temperature Acrylic tape is sandwiched between the upper and lower conductors about the center hole. This assures that no electrical contact is made between the upper and lower plates. Copper tape is adhered to the Kapton. The SMA inner conductor is punched through the copper tape and soldered together. The Acrylic tape helps to isolate the connection thermally, allowing for a better solder joint.

Figure 4.9. Close-up view of a capacitive probe.

Diagnostic Setup

The diagnostic setup is shown in Figure 4.10. Typical attenuation values for the capacitive voltage dividers (CVD) and wide-band attenuators are 60 dB and 40 dB, respectively. The screen room provides protection from EMP noise.

Figure 4.10. Diagnostic setup.

Dimensions for a typical CVD were 2.4 cm wide by 4.8 cm long. The dielectric used was Kapton with a thickness of approximately 5 mil. Using eqn. (4.10), the calculated capacitance of the CVD is

$$C_2 = \frac{2\pi\epsilon_1}{\ln\left(\frac{c}{b}\right)} \times w_{\text{probe}} \times \frac{l_{\text{probe}}}{2\pi b} = \frac{2\pi \times 8.854 \times 10^{-12} \times 3.1}{\ln\left(\frac{0.03896}{0.03884}\right)} \times 0.024 \times \frac{0.051}{0.245} = 624 \text{ pF}.$$

The way in which the capacitive probe was adhered to the ground plane of the outer conductor made it difficult to maintain a 5 mil separation between the upper plate and the ground plane. Tiny pockets of air and adhesive made the average separation slightly greater than 5 mil. This results in a slightly lower capacitance than calculated. When measured with a LCR meter values ranged from 500 to 550 pF.

The coupled capacitance between the inner conductor and the CVD is calculated as

$$C_1 = \frac{2\pi\epsilon_o\epsilon_r}{\ln\left(\frac{b}{a}\right)} \times w_{\text{probe}} \times \frac{l_{\text{probe}}}{2\pi b} = \frac{2\pi \times 8.854 \times 10^{-12} \times 2.3}{\ln\left(\frac{0.03844}{0.00975}\right)} \times 0.024 \times \frac{0.051}{0.245} = 0.55 \text{ pF}.$$

The variable separation between the plates of the probe has a negligible effect on this capacitance. Inserting these values into eqn. (4.11), the calculated attenuation of the CVD is

$$A_{\text{dB}} = 20\log\left(\frac{C_1}{C_2 + C_1}\right) = 20\log\left(\frac{0.55}{550 + 0.55}\right) = -60.0 \text{ dB}.$$

As the risetime of the incident pulse is decreased, the bandwidth requirement of the diagnostic scheme increases. With the aforementioned diagnostic setup, a goal of detecting pulses with risetimes of ~300 ps would seem to be easily obtainable. However,

there are other issues, one of which is dispersion. The incident pulse consists of a band of frequencies. Waves of the component frequencies travel with different phase velocities, causing a distortion in the signal wave shape. The overall effect of this phase dispersion is to “round-off” the leading edge. The lossy dielectrics present in both the CVD and wide-band cable are dispersive media. This is a strong reason to keep the cable and CVD as short and small as possible.

As the wavelengths of the incident waves approach the dimensions of the CVD, the CVD begins to look more like a transmission line and less like a lumped element (Figure 4.11).²³ The effect on the divider is to show large resonances at quarter wavelength intervals of the incident wave. One way to decrease the resonant effects is to shift the resonances to higher frequencies by decreasing the dimensions of the divider. However, as mentioned before, the capacitive value of the divider must be large enough to prevent drooping of the pulse.

Figure 4.11. Input reactance of an open-circuited transmission line.

Probe Calibration

If the diagnostic setup is assumed to be a causal, linear-time-invariant system (LTI), the output $y(t)$ can be found from

$$y(t) = \int_0^t x(\tau) h(t - \tau) d\tau, \quad (4.13)$$

where $x(t)$ is the input and $h(t)$ is the impulse response of the system. A schematic of an LTI system in the time domain is shown in Figure 4.12.

Figure 4.12. Diagram of an LTI system in the time domain.

The impulse response of the system can be found by inputting a delta function. For example,

$$y(t) = \int_0^t x(\tau) h(t - \tau) d\tau = \int_0^t \delta(\tau) h(t - \tau) d\tau = h(t). \quad (4.14)$$

If an impulse could be applied to the system, a pulse of width on the order of tens of ps, one could obtain an approximation of the impulse response of the diagnostic setup. One could then obtain an approximation of the actual input pulse by knowing the output and impulse response. The practical limitation of this method is in obtaining and applying a known pulse with a width of several ten's of ps and of a voltage high enough to provide a CVD signal with an adequate signal to noise ratio.

Another approach would be to obtain the magnitude and phase frequency response of the diagnostic setup. For an LTI system

$$Y(f) = H(f)X(f). \quad (4.15)$$

A schematic of an LTI system in the frequency domain is shown in Figure 4.13.

Figure 4.13. Diagram of an LTI system in the frequency domain.

The input frequency response would be

$$X(f) = \frac{Y(f)}{H(f)}. \quad (4.16)$$

The input time response to the system can be found by taking the inverse Fourier transform

$$x(t) = \int_{-\infty}^{\infty} X(f) \exp(j2\pi ft) df = \int_{-\infty}^{\infty} \frac{Y(f)}{H(f)} \exp(j2\pi ft) df. \quad (4.17)$$

The frequency response of the diagnostic setup can be found experimentally by use of the HP8719C network analyzer. The HP8719C gives frequency magnitude and phase information for a simple two port network with a range from 50 MHz to 13.5 GHz. The sensitivity range of the network analyzer is greater than 100 dBm. A schematic of the frequency response test is shown in Figure 4.14. One advantage of this setup is that the divider response is tested in the actual coaxial line it will be used in rather than in a separate testing setup. The matched load is necessary to terminate the input signal from the network analyzer.

Figure 4.14. Calibration setup of frequency and phase response test.

The resulting frequency magnitude and phase response are shown in Figures 4.15 and 4.16, respectively. The magnitude response is relatively flat from dc to 1.5 GHz at an attenuation of -60 dB. At 1.5 GHz the response falls about 4 dB.

Figure 4.15. Frequency magnitude response of a CVD.

Figure 4.16. Phase response of a CVD.

In Figure 4.17 is displayed the frequency spectrum of a 400 ps risetime pulse detected by a CVD. Also shown in Figure 4.17 is the frequency spectrum of the same pulse after software compensation. This software compensation is an algorithm of eqn. (4.17) using the frequency and phase response of the CVD obtained from the HP8719C. Note the negligible change in frequency spectra between the compensated and uncompensated waveforms.

Figure 4.17. Normalized frequency spectrum of compensated and uncompensated waveforms.

The normalized gap voltage waveforms, both compensated and uncompensated, are shown in Figure 4.18. Note that the waveforms are nearly identical. It can safely be said that the response of the CVD is capable of following pulse waveforms with risetimes on the order of 400 ps.

Figure 4.18. Normalized voltage of compensated and uncompensated waveforms.

Another calibration method was performed on the CVD. A 1 kV, 800 ps risetime pulse from a reed switch pulser is applied to the coaxial line. The setup is shown in Figure 4.19. An advantage of this setup is that the input pulse can be recorded at the wide-band attenuator at the same time the output of the CVD is recorded.

Figure 4.19. Calibration setup with known input pulse.

The result of this calibration method is shown in Figure 4.20. Notice that the output signal from the CVD follows the input pulse fairly accurately at the front of the pulse. After 1 ns the output from the CVD begins to droop as compared to the input pulse.

Figure 4.20. Normalized voltage of the applied pulse and CVD pulse.

CHAPTER V

EXPERIMENTAL RESULTS

Introduction

This chapter presents the experimental results of the investigation into the breakdown characteristics in the nanosecond and subnanosecond time regime for several gases and liquids. These characteristics include electric field strength versus breakdown time, dielectric strength dependence on polarity, statistical time lag, and streak camera images of arc formation. The results are compared with data collected by others and existing theoretical predictions. Finally, an empirical fit for these data is presented.

E-field versus Breakdown Time for Gas

Initial investigations into E-field versus breakdown time in gases focused on breakdown times from 1 to 4 ns and pressures up to 11 MPa (1600 psi). The voltage source used in this experiment was the SEF-303A pulser without a peaking gap. This provided gap voltages up to 350 kV. Figure 5.1 shows typical voltage waveforms at the cathode and anode for high pressure gas with a time to breakdown of approximately 3 ns.

Figure 5.1. Voltage waveforms at the cathode and anode for H_2 at 9 MPa (1300 psi) and 1.8 mm gap spacing.

Figure 5.2 presents peak E-field versus time to breakdown measurements for various gases. Gas pressures were chosen as high as possible, limited only by bottle pressure. The E-field across the gap is essentially uniform between the hemispherical electrodes at the chosen gap distances of 1 to 5 mm. This assumption is verified by the field distribution calculated by the Maxwell 3D simulation program presented in Chapter 2. Therefore, the E-field is simply the voltage difference across the gap divided by the gap distance.

Figure 5.2. Peak E-field versus time to breakdown for various gases.

A common way in which this type of breakdown data is presented is scaled with pressure. The data in Figure 5.2 are presented in such a manner in Figure 5.3. Pressure is in units of pascal. Also, a log-log graph is used.

Figure 5.3. E-field versus breakdown time scaled with gas pressure for various gases.

The investigation of E-field versus breakdown time for gases was extended down to breakdown times of 600 ps and up to gap voltages of 350 kV. This was accomplished with a modification of the SEF-303A pulser in which a oil-filled peaking gap was added. Figure 5.4 shows E-field versus breakdown time for various gases at these shorter breakdown times.

Figure 5.4. E-field versus breakdown time for air with breakdown times down to 600 ps.

These data can also be presented in a Paschen curve. In Figure 5.5 is breakdown voltage versus pressure times gap distance for various gases. Also shown is the Paschen curves for these gases for dc breakdown. From these curves the overvoltage percentage in eqn. (2.24) can be calculated.

Figure 5.5. Paschen curve for various gases.

The ability to compare these data with data collected by others is limited. Breakdown data for gases at these pressures and fast times are nonexistent. Therefore, comparison can only be made on a relative basis. The only known empirical curve at these time lengths is that of Felsenthal and Proud.⁷ Their curve for air and the data collected by the author are displayed in Figure 5.6.

Notice the disparity between the two sets of data. The F and P values for E/P are lower than observed by the author. In actuality, the comparison between these two sets of data is not equal. The time to breakdown of this set of the F and P data are longer (>10 ns).

Figure 5.6. Comparison between F & P empirical and author's data of breakdown in air.

A comparison of the collected gas breakdown data can be made with the empirical relationship, eqn. (2.23), developed by T.H. Martin.⁸ This empirical formula is

$$\rho t = 97800 \left(\frac{E}{\rho} \right)^{-3.44}$$

where ρ is gas density in g/cc, E is average electric field kV/cm, and t is time to breakdown in seconds. Martin's curve fits a variety of gases including air, N_2 , He, and others. A comparison of observed breakdown data and the Martin curve is shown in Figure 5.7.

Figure 5.7. Collected gas breakdown data compared with the Martin curve.

There are two interesting observations to be made from this comparison. As the values for pt decrease, the observed E/ρ values are higher than predicted by the Martin curve. This discrepancy is also observed when the F and P data taken at breakdown times of < 5 ns is compared to the Martin curve (Figure 2.7). The question arises as to the cause of this discrepancy.

Clearly there will be a limit as to how fast breakdown can occur across a gap. This limit is the speed of light. In order to approach this limit the gap must be increasingly overvoltaged. As the breakdown times are decreased to < 5 ns, the formative times for breakdown shift to a different regime.

Recall classical streamer theory by Raether⁵ and Meek.⁶ The formative time lag is due to the creation of a critical avalanche. This time was speculated by Meek to be

$$t_{cr} \equiv \frac{x_c}{v_e} \equiv \frac{20}{\alpha v_e}, \quad (2.17)$$

where v_e is the electron drift velocity. Once the critical avalanche has formed a photoionization process takes place, which closes the gap with a highly ionized channel. This photoionization process is assumed to happen much faster than the creation of a critical avalanche, or $t_{av} \gg t_{photo}$ where t_{av} is the time for critical avalanche, t_{cr} , and t_{photo} is the time for photoionization to close the gap. A more accurate representation of breakdown time is the summation of t_{photo} and t_{av} , or $t_{break} = t_{av} + t_{photo}$.

As E/ρ increases, both α and v_e increase. As a result, t_{av} decreases. Once t_{break} reaches a value less than about < 5 ns, t_{av} is no longer much greater than t_{photo} . Therefore, higher values for E/ρ would be required to achieve a breakdown time than would be predicted by the F and P theoretical curve, eqn. (2.20), and the Martin curve, eqn. (2.21).

The second discrepancy between the data collected and the Martin curve is the large difference between the E/ρ values for H_2 . The Martin curve was developed for various gases, however, H_2 was not one of these gases. It is possible that the ionization coefficient, α , for H_2 is much less than α for the other gases observed for a given E/ρ . This would require higher E/ρ values for H_2 to obtain equivalent breakdown times for other gases.

An Empirical Relationship for Gas Breakdown

An empirical relationship for the relationship between E-field and breakdown time for gases is attempted. Figure 5.8 displays breakdown data for air, relating E/ρ versus ρt on a log-log scale. Also shown is the Martin curve of eqn. 2.23 and selected F and P data of breakdown of air at low pressures and fast breakdown time (~ 1 ns).

The expression for the curve fit shown in Figure 5.8 is

$$\frac{E}{\rho} = \left(\frac{\rho t}{0.9} \right)^{-\frac{1}{2.25}} \quad (5.1)$$

where E is in kV/cm, ρ is gas density in g/cc, and t is in nanoseconds. This expression fits the breakdown data for times less than 5 ns and gases tested which include air, N_2 , SF_6 , and He. The breakdown data collected on H_2 does not fit well with eqn. (5.1).

An additional expression has been fitted to the H_2 breakdown data. This expression is

$$\frac{E}{\rho} = \left(\frac{\rho t}{0.9} \right)^{-\frac{1}{2.05}} \quad (5.2)$$

Notice that the only change is in the value of the exponent.

Figure 5.8. Breakdown data for various gases including Martin curve. Also shows curve fit of selected data.

E-field versus Breakdown Time for Liquids

Initial investigations of liquid breakdown ranged from breakdown times of 1.5 to 4 ns. Liquids included were unfiltered and filtered transformer oil, castor oil, and freon-12. The experimental used for this investigation was the unmodified SEF-303A pulser described in Chapter 3.

The results of E-field versus breakdown time for these liquids are displayed in Figure 5.9. E-field strengths of over 4 MV/cm were obtained. The field between the electrodes at these gap distances is assumed uniform.

Figure 5.9. Peak E-field versus time to breakdown for various liquid dielectrics.

These investigations into liquid breakdown were expanded to cover breakdown times down to 500 ps. In order to obtain these fast breakdown times, the required E-fields are on the order of 7 MV/cm. For a gap distance of 1 mm, a gap voltage of 700 kV is required to obtain these high E-field strengths. Obviously, gap distances could be decreased below 1 mm to obtain higher field strengths. However, as the electrode

spacing is decreased, electrode surface effects begin to dominate the breakdown mechanism and comparison with previous data becomes questionable.

A subnanosecond risetime, high voltage pulser was built to meet the requirement for a higher gap voltage. This was achieved with a Marx bank driven pulse forming line pulser described in Chapter III. The results of this investigation are shown in Figure 5.10.

Figure 5.10. Breakdown data for transformer oil.

An Empirical Relationship for Transformer Oil Breakdown

A curve fit of the data for filtered transformer oil for time lengths of nanosecond and subnanosecond is attempted. In Figure 5.11 is displayed the collected data for transformer oil on a log-log scale for E-field versus time to breakdown. Also shown is the Martin curve developed for transformer oil from Figure 2.16.

Figure 5.11. Empirical curve fit for collected transformer oil breakdown data.

The expression relating E-field versus time to breakdown is

$$E = 7.9t^{-0.95} \quad (5.3)$$

where E is in MV/cm and t is in nanoseconds. This expression is only valid for times less than ~5 ns. At greater times, the Martin curve becomes valid. The J.C. Martin curve, shown in Figure 5.11, for breakdown voltage in transformer oil is

$$E^{\frac{3}{2}} = \frac{80}{t_{\text{eff}}} \quad (5.4)$$

where E is in MV/cm and t_{eff} is in nanoseconds. The effective time, t_{eff} , is the duration of the pulse between 63% and 100% of the peak voltage reached and ranged from 150 to 300 ns. This approach was one of measuring the threshold voltage before breakdown rather than breakdown time. The threshold voltage approach and the long duration times of the J.C. Martin curve result in the discrepancy of curves seen in Figure 5.11.

Dielectric Breakdown Strength Dependence on Polarity

The polarity dependence of dielectric breakdown was discussed in Chapter II. Polarity dependence is typically caused by the presence of space charge about the point in a point-plane electrode geometry. A point-cathode will typically have a higher breakdown strength than a point-anode for a given gap spacing, voltage, and gas pressure. The presence of this effect is investigated for nanosecond breakdown times.

The dielectrics investigated were transformer oil and air. The point-plane breakdown data for transformer oil are shown in Figure 5.12. The negative-point arrangement has a higher E-field breakdown strength, especially at the shorter breakdown times. The breakdown strength of the negative-point arrangement is approximately 50% greater than the positive-point. This value is in agreement with findings reported by J.C. Martin.¹²

Figure 5.12. Breakdown data for point-plane geometry in transformer oil.

Breakdown data of a point-plane geometry in air at different pressures are shown in Figure 5.13. Again, the negative point has a higher breakdown strength. The fractional increase in breakdown strength for the negative point seems to decrease with an increase in gas pressure. This amount varies from approximately 20 to 90%. Values reported by J.C. Martin¹² are as high as 100%.

Figure 5.13. Breakdown data of a point-plane geometry in air.

Streak Camera Images

Images of the arc formation during nanosecond and subnanosecond breakdown were recorded with a fast streak camera. The setup of this procedure was described in Chapter III. Dielectric media investigated were transformer oil and air. Of specific interest is the propagation velocity of the streamer and the time it takes for the channel to become highly ionized.

Streak images of a 1 mm wide transformer oil-filled gap were taken. The applied voltage pulse had a 400 ps risetime, a 4.5 ns width, and a magnitude of 300 kV. In Figure 5.14 is shown a 5 ns streak of the gap some time after the arc has been established.

Figure 5.14. 5 ns streak of 1 mm transformer oil filled gap after arc formation.

In Figure 5.15 a and b are streak images of the 1 mm transformer oil gap at the beginning of arc formation at streak lengths of 5 and 10 ns, respectively. The transition from the onset of ionization to gap closure appears to occur in approximately 500 ps. A closer view of the beginning of the arc formation in the 5 ns sweep is shown in Figure 5.16.

(a)

(b)

Figure 5.15. Streak images of the beginning of the arc formation of a 1mm transformer oil gap at time lengths of (a) 5 ns and (b) 10 ns.

Figure 5.16. Close up view of arc formation in the 5 ns streak.

An estimate of gap-closure velocity for oil can be made from Fig. 5.16. For a 1 mm gap and a 500 ps closure time, the gap-closure velocity for oil is

$$v_{\text{oil}} = \frac{0.1 \text{ cm}}{0.5 \text{ ns}} = 0.2 \frac{\text{cm}}{\text{ns}}. \quad (5.5)$$

Streak images of gas gaps have also been captured. Compressed air at a pressure of 400 psi was investigated. The first streak image is of a 4 mm gap at a 10 ns sweep (Figure 5.17).

Figure 5.17. Streak image of the beginning of arc formation of a 400 psi, 4 mm air gap at a 10 ns sweep.

The second streak image is of a 4 mm gap at a 5 ns sweep (Figure 5.18). A close up of the start of the streak is shown in Figure 5.19. The gap closure occurs in about 150 ps.

Figure 5.18. Streak image of the beginning of arc formation of a 400 psi, 4 mm air gap at a 5 ns sweep.

Figure 5.19. Close up view of the arc formation of the 400 psi, 4 mm air gap at a 5 ns sweep.

An estimate of gap-closure velocity for air can be made from Fig. 5.17. For a 4 mm gap and a 150 ps closure time, the gap-closure velocity for air is

$$v_{\text{air}} = \frac{0.4 \text{ cm}}{0.15 \text{ ns}} = 2.7 \frac{\text{cm}}{\text{ns}}. \quad (5.6)$$

Effect of Ultraviolet Radiation on Statistical Lag Time

Initial investigations into the effect of ultraviolet radiation of the test gap on statistical distribution of time lag were performed with the SEF-303A pulser without a peaking gap. The gases tested were H_2 , N_2 , and He . Pressures ranged from 1 to 17 atmosphere. The results of these investigations in H_2 are shown in Figure 5.20.

(a)

(b)

Figure 5.20. Distribution of breakdown times in H_2 for (a) 1 atm with a 4.5 mm gap, 50 kV gap voltage and (b) 17 atm with a 4 mm gap, 200 kV gap voltage.

Referring to Figure 5.20a, when the gap is radiated with UV the statistical lag time is decreased dramatically. This is due to the large number of free electrons present in the gap prior to the arrival of the incident gap voltage. However, when the gas pressure was increased (Figure 5.20b), the decrease in statistical lag time of a UV radiated gap does not occur. This effect was observed in all three gases.

The first possibility is that the radiated UV does not reach the gap due to photoabsorption or scattering by the high pressure gas. Therefore, the plethora of free electrons in the gap are not present as they are for the gaps at atmospheric gas pressures. After some simple calculations this is probably not the case.

Photoabsorption of ultraviolet radiation is caused by ionization of the medium. Recall Figure 3.13 which shows the transmittance of the fused silica window. Notice that smallest wavelength which can pass through this window is 160 nm. Assuming a uniform UV source across the UV spectrum from the Xenon lamp, the highest radiation energies which will be in the gap is 7.75 eV. The ionization potentials for H₂, He, and N₂ are 15.4, 24.6, and 15.6 respectively. Therefore, the ultraviolet radiation energy is not high enough to ionize the gases examined, however, with a work function of 4.5 eV for brass, the UV radiation is high enough to free electrons from the brass electrodes.

Another approach is to calculate the attenuation of UV radiation through the atmosphere and correlate it with the experimental setup. The transmittance of monochromatic radiation along a path in air can be expressed as²⁴

$$\tau = e^{-\gamma \Delta L}, \quad (5.7)$$

where γ is an attenuation coefficient and ΔL is the length of the path traversed by the radiation. The attenuation coefficient γ is given by

$$\gamma = \sigma + \kappa, \quad (5.8)$$

where σ is the scattering coefficient and κ is the absorption coefficient. For a wavelength of 300 nm, the attenuation coefficient at atmosphere is

$$\gamma = 0.0846 + 2.34 \times 10^{-4} \text{ km}^{-1} = 0.0848 \text{ km}^{-1}. \quad (5.9)$$

If the attenuation coefficient, γ , is assumed linear with gas pressure, then at 200 psi (13.6 atm) the attenuation coefficient is

$$\gamma_{200\text{psi}} = \gamma \frac{13.6 \text{ atm}}{1 \text{ atm}} = 0.0848 * 13.6 = 1.15 \text{ km}^{-1}. \quad (5.10)$$

Therefore, the transmittance of 300 nm radiation at 200 psi over a distance of 1 m is

$$\tau_{200\text{psi}}(1\text{m}) = e^{-1.15*0.001} = 99.9\%. \quad (5.11)$$

So, attenuation of 300 nm monochromatic radiation through 200 psi air over 1 m is approximately 0.1%. Of course, this is a very simplistic approach and does not take into account such factors as the entire spectrum of UV radiation and the different gases used experimentally. However, this gives a rough idea as to how much UV attenuation takes place.

A different approach was taken to observe statistical delay with and without UV radiation. First, statistical delay was investigated for H₂, N₂, and He at atmosphere. Then the gas pressure was increased in small increments up to 115 psi while the statistical delay was observed at each increment. This was done for each gas at gap length of 2, 4, and 6 mm. Figure 5.21 shows the median breakdown time of N₂ at a gap length of 4 mm for various pressures with and without UV. The error bars are 1 standard deviation.

Figure 5.21. Median breakdown time of N₂ at a gap length of 4 mm for various pressures with and without UV. Error bars are 1 standard deviation.

At each pressure and gap length 25 shots were taken with and without UV radiation incident upon the gap. The median breakdown time was calculated for each case. The percent difference between the median breakdown time with and without UV radiation was determined. This percent difference, $\% \Delta$, is plotted for nitrogen at various gas pressures and gap lengths in Figure 5.22. At low pressures the $\% \Delta$ is as high as 68% and decreases as the pressure is increased. At pressures above 100 psi the $\% \Delta$ becomes insignificant.

Figure 5.22. Percent difference of median breakdown time between a nitrogen gap with and without UV radiation at various gap lengths versus gas pressures.

As the pressure is increased the gap voltage is increased in order to obtain approximately the same breakdown time (~ 1.5 ns). The $\% \Delta$ is plotted with respect to E-field in Figure 5.23. As the E-field is increased, the $\% \Delta$ decreases.

Figure 5.23. Percent difference of median breakdown time between a nitrogen gap with and without UV radiation at various gap lengths versus E-field.

The interesting case is when $\% \Delta$ is plotted with respect to E-field/pressure as in Figure 5.24. The $\% \Delta$ is relatively independent of gap distance. When E/P is less than 5, the $\% \Delta$ becomes insignificant. However, when E/P is greater than 5, the $\% \Delta$ increases dramatically.

Figure 5.24. Percent difference of median breakdown time between a nitrogen gap with and without UV radiation at various gap lengths versus E-field/pressure.

A hypothetical explanation for these phenomena is presented. At high values of E/P the free electrons, due to the UV radiation, present in the gap contribute significantly to the initial avalanche which leads to breakdown. The high E/P of the gap allows these seed electrons to attain high enough energies to create the initial avalanche. As E/P is decreased, these seed electrons contribute less and less to the initial avalanche until E/P becomes so low that these seed electrons no longer contribute at all to the breakdown. In this case, the supply of electrons which lead to the initial avalanche is from explosive

emission on the cathode surface. The applied E-field in excess of 100 kV/cm makes the explosive emission process possible.

The $\% \Delta$ versus E/P for H₂ and He was also observed. These plots are similar to those for N₂. The plots are shown in Figures 5.25 and 5.26.

Figure 5.25. Percent difference of median breakdown time between a hydrogen gap with and without UV radiation at various gap lengths versus E-field/pressure.

Figure 5.26. Percent difference of median breakdown time between a helium gap with and without UV radiation at various gap lengths versus E-field/pressure.

CHAPTER V

CONCLUSIONS

An attempt has been made to investigate the breakdown characteristics of gas and liquid dielectrics at breakdown times ranging from 500 ps to 5 ns. Two different voltage sources were used to produce the fast risetimes (400 ps) and high E-fields ($>10\text{MV/cm}$) necessary to carry out these fast breakdown times. The experimental investigations were comprised of breakdown times versus E-field strengths, breakdown strength dependence on polarity, streamer formation analysis using a fast streak camera, and the effect of incident UV radiation on the statistical distribution of breakdown time.

The goals set for the specifications of the voltage sources were achieved. A simple modification of the SEF-303A (inclusion of a peaking gap) allowed for a fast risetime (400 ps) source with a variable voltage output that was easy to change. Another source, a Marx bank driven PFL, was designed and built and met the specification requirements of 400 ps risetime and 700 kV output. Modifications to the Marx bank and peaking gap could allow for faster risetimes ($<300\text{ ps}$) and higher voltage outputs ($>1\text{MV}$) in the future.

Experimental investigation into the E-field strengths achieved at various breakdown times were successful. Although E-field strengths at these breakdown times ($>500\text{ ps}$) have been attained by other investigators, nothing close to the high pressure gas dielectrics used here has been examined. It was found that the E-field strengths required to break down these high pressure gases at these short times ($\sim 500\text{ ps}$) is higher

than predicted by others. These fast breakdown times require different empirical formulas in order to predict breakdown strengths.

It was found that the breakdown strength of several gas dielectrics and transformer oil is dependent on gap polarity. As predicted, in a point-plane electrode geometry the negative point consistently attained higher breakdown strengths. The amount of this difference is on the order, though somewhat less, than those observed by other investigators.

The results of the streak camera investigation of the streamer formation were successful. Streamer formation of breakdown in transformer oil and air can be seen. However, streamer formation in gas occurs faster than in transformer oil and the time resolution is not as good. These results are most likely indicative of the breakdown times observed (the breakdown time in air was faster than in transformer oil) than any other factor. Streamer gap closure in transformer oil and air occurred in approximate times of 500 and 150 ps, respectively (0.2 cm/ns and 2.7 cm/ns, respectively).

The investigation of the effect of UV radiation on the statistical nature of breakdown time was successful. The effect of UV on statistical time lag on gases at atmosphere pressure was dramatic, but at pressures of 1.4 MPa (200 psi) and above the UV had no effect. A careful observation of statistical time lag with and without UV, as the gas pressure was incrementally increased, was made. It was found that UV effect on statistical delay time is dependent on E-field/pressure and relatively independent on gap length.

REFERENCES

1. D. Herskovitz, "Antennas and Transmission Systems: Wide, Wider, Widest," *Journal of Electronic Defense*, pp. 51-58, July, 1995.
2. F.J. Agee, D.W. Schofield, R.P. Copeland, T.H. Martin, J.J. Carroll, J. Mankowski, M. Kristiansen, and L. Hatfield, "A Review of Catastrophic Electromagnetic Breakdown for Short Pulse Widths," *Proceedings of SPIE '96*, pp. 172-182, August, 1996.
3. D.G. Fink, *Standard Handbook for Electrical Engineers*, New York: McGraw Hill, tenth edition, 1968.
4. L.L. Alston, *High Voltage Technology*, London: Oxford University Press, 1968.
5. H. Raether, *Electron Avalanches and Breakdown in Gases*, Washington D.C.: Butterworth, 1964.
6. J.M. Meek, *Phys. Rev.*, 57, 722, 1940.
7. P. Felsenthal and J.M. Proud, *Phys. Rev.*, 139, a1796, 1965.
8. T.H. Martin, "An Empirical Formula for Gas Switch Breakdown Delay," *Res. Sci. of Pulsed Power, Sandia National Labs*, pp. 73-79, 1991.
9. J.C. Martin, *Dielectric Strength Notes*, 15, first printed as SSWA/JCM/679/71, AWE internal publication, 1967.
10. E. Kuffel and W.S. Zaengl, *High Voltage Engineering*, Oxford, New York: Pergamon Press, 1984.
11. E.E. Kunhardt, "Nanosecond Pulse Breakdown of Gas Insulated Gaps," *NATO ASI Series, Series B: Physics*, Vol. 89a, New York: Plenum Press, 1983.
12. T.H. Martin, A.H. Guenther, and M. Kristiansen, *J.C. Martin on Pulsed Power*, Vol. 3, chap. 4, New York: Plenum Press, 1996.
13. A. Vorobyov, V. Ushakov, and V. Bagin, "Electrical Strength of Liquid Dielectrics at Voltage Pulses of a Nanosecond Duration," *Electrotechnika*, vol. 7, pp. 55-57, 1971.
14. *SEF-303A Compact High-Current Pulsed Power Source*, Description and Technical Manual, Ehaterinburg, Russia, Electrophysical Institute: 1991.

15. M. Mayerchak, *Pulsed High Voltage Insulator Flashover in a Simulated Low Earth Orbit Environment*, Master's Thesis, Texas Tech University, May, 1991.
16. V & L Products Inc, Optical Specifications, Berlin, NJ: 1997.
17. *Hamamatsu Temporal Disperser*, Description and Technical Manual, Middlesex, NJ: 1980.
18. J.H. Mason, "Breakdown of Solid Dielectrics in Divergent Fields," *Institute Monograph*, No. 127M, April, 1955.
19. R. Hebner, "The Measurement of High Current and Voltage Pulsed," *AF Pulsed Power Lecture Series*, No. 35, Texas Tech University, 1980.
20. W.A. Edson and G.N. Oetzel, "Capacitance Voltage Divider for High-Voltage Pulse Measurement," *Rev. Sci. Instrum.*, 52(4), pp. 604-607, 1981.
21. C.J. Buchenauer and R. Marek, "Antennas and Electric Field Sensors for Time Domain Measurements: An Experimental Investigation", *Ultra-Wideband Short-Pulse Electromagnetics 2*, New York: Plenum Press, 1994.
22. K. A. Zheltov, *Picosecond High Current Electron Accelerators*, Moscow: Energoatomizdat, 1991.
23. D. Cheng, *Field and Wave Electromagnetics*, Reading, MA: Addison-Wesley, 1989.
24. W. Driscoll and W. Vaughan, *Handbook of Optics*, New York: McGraw-Hill, pp. 14.9-14.11, 1978.