THE IMPACT OF FIELD ENHANCEMENTS AND CHARGE
INJECTION ON THE PULSED BREAKDOWN
STRENGTH OF WATER

by

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TABLE OF CONTENTS

ACKNOWLEDGMENTS	1
TABLE OF CONTENTS.....	iii
ABSTRACT.....	v
LIST OF TABLES.....	vii
LIST OF FIGURES	viii
CHAPTERS	
I. INTRODUCTION	1
II. BACKGROUND	4
2.1 Breakdown Initiation	4
2.1.1 Electric Field Enhancements.....	5
2.1.2 Electric Field Electron Emission (FEE).....	9
2.1.3 Explosive Electron Emission (EEE).....	26
2.1.4 Emission from Dielectric Inclusions.....	33
2.2 Breakdown Theories	35
2.2.1 Bubble Mechanism	35
2.2.2 Electronic Mechanism	37
2.3 Previously Documented Results	40
2.3.1 Effects of Electrode Surface Roughness.....	40
2.3.2 Effects of Electrode Surface Area.....	43
2.3.3 Effects of Various Electrode Materials and Coatings.....	45
2.3.4 Effects of Water Conductivity	49
III. EXPERIMENTAL SETUP.....	53
3.1 Electrode Sets.....	53
3.2 Ion Deposition Setup.....	56
3.3 Electrical Generation and Transmission of the Water Breakdown System.	60
3.4 Test Gap	63
3.5 Electrical Diagnostics	68
3.5.1 Capacitive Voltage Divider.....	68

3.5.2 Pearson Current Monitor.....	69
IV. EXPERIMENTAL PREPARATION AND PROCEEDURE.....	71
4.1 Surface Roughness and Area Preparation.....	71
4.2 Electrode Material Preparation	85
4.3 Water Conductivity Preparation	88
4.4 Aluminum Etched Surface Preparation	90
4.5 Shadowgraph Imaging Preparation.....	91
V. EXPERIMENTAL RESULTS.....	95
5.1 Typical Voltage and Current waveforms	95
5.2 Surface Roughness and Area Tests.....	97
5.3 Electrode Material Tests	100
5.3.1 Ion Deposited Surfaces	100
5.3.2 Additional Material Surfaces	101
5.4 Water Conductivity Tests	106
5.5 Aluminum Etched Surface Tests	112
5.6 Shadowgraph Imaging	114
5.7 Post Electrical Breakdown Imaging	115
VI. SUMMARY AND CONCLUSIONS.....	117
REFERENCES	119
APPENDIX A.....	122
Marx Generator Refurbishment	123
APPENDIX B.....	131
Surface Modeling using TurboCad.....	131

ABSTRACT

In any high voltage pulsed power system there is a need for a dielectric material to serve as a charge storage medium, switching medium, or insulator. Water, with its high dielectric constant, $\epsilon_r = 81$, and favorable physical properties is an ideal candidate for use in compact pulsed power systems. Several research efforts have been conducted over the last several decades to investigate possible ways of increasing water's dielectric strength [Joshi, Kun]. In the research documented here, experiments have been conducted in order gain further insight into the mechanisms that initiate the electrical breakdown of water.

With the application of a large enough pulsed electric field, any metal conductor will begin to emit electrons from its surface, especially from field enhancements on the electrode surface, into the dielectric region. This emission initiates the breakdown of water, though various theories of exactly what happens in the water prior to breakdown have been developed. Some suggest that the breakdown event is purely electronic where the emission enters the gap until a conductive channel is formed [1]. Others have suggested that the emission causes rapid heating within the water causing it to vaporize and a bubble to form [2,3,4]. Neither theory has been conclusively confirmed as the primary mechanism.

Several factors have been found to either increase or decrease the electric holdoff strength of water including the electrode surface roughness, the electrode material, the electrode surface area, and the water conductivity. Experiments have been conducted to test the effect each of these factors has on water's dielectric strength and in each experiment, a water gap was tested under pulsed conditions with pulse widths of roughly

2 μ s. Peak electric fields over 1 MV/cm and peak currents over 3.5 kA have been recorded across the gap. In all of the tests, electrodes machined with a Bruce profile were used on both the anode and cathode sides of the gap. Random and known surface roughness patterns were applied to the electrodes through mechanical sanding and etching processes. Surface roughnesses ranging from 0.26 μ m to 1.96 μ m and electrode surface areas ranging from 0.44 cm² to 75 cm² were tested. Electrodes constructed of various materials including Aluminum, Molybdenum, Copper, Tungsten, Nickel, Stainless Steel, and Zinc Oxide, all of which had a constant surface area of 5 cm², were also tested. The conductivity of the water was varied from 1 μ S/cm to 38.5 μ S/cm. Additionally, shadowgraph images of a point plane geometry were taken to further understand the breakdown processes that occur.

LIST OF TABLES

1	Effective B-factors and Emitting Areas for N Microprotrusions [7].....	9
2	Electrode Materials and their Work Functions	11
3	Electrode Material Properties	31
4	EBEST Treated Surface Parameters [21]	42
5	Water Breakdown Data Obtained by J.C. Martin [23]	44
6	Results Obtained using Various NaCl – Water Mixtures [31]	52
7	Large Area Electrode Specifications	55
8	Smaller Electrode Specifications	55
9	Surface Roughness Averages.....	72
10	Peak Surface Electric Field and β factor.....	75
11	Statistics of Locations on the Surface which have a β factor Greater than 1.....	76
12	Statistics of Locations on the Surface which have a β factor Greater than 5.....	77
13	Statistics of Locations on the Surface which have a β factor Greater than 10.....	77
14	Sputter Deposition Parameters.....	86
15	Conductivity Measurements	90
16	Peak Electric Field and β factor on the Etched Surface.....	92
17	Statistics of Locations on the Etched Aluminum Surface with Various Lower β Thresholds.....	92
18	Standard Deviations of the Surface Roughness and Area Test Results (units of MV/cm)	98
19	Standard Deviations of the Rough Smooth Test Results (units of MV/cm).....	98
20	Positive Side Wiring Description.....	129
21	Negative Side Wiring Description.....	129

LIST OF FIGURES

1	Flow chart of water's dielectric breakdown.....	5
2	Semi-ellipsoidal microprotrusion [5].....	6
3	β factor for various microprotrusion sizes and geometries [6]	6
4	Variation of β_{eff} as a function of electric field (calculated from independent arrays) [7].....	8
5	Fowler - Nordheim field emission vs. β	12
6	Spherical cloud of charge formed in front of an emitter as a result of high field emission	12
7	Electron density vs. β factor	14
8	Space charge generated electric field vs. charge radius.....	15
9	Applied and space charge generated electric fields vs. β	16
10	Single shielding event	18
11	Multiple shielding events for various β 's	20
12	Equilibrium of space charge generated field and enhanced tip field	20
13	Electric field simulations displaying the effect of a space charge generated electric field on the electric field at the tip of the emitter (a) E-field scale (b) no charged volume (c) $r = 0.840 \mu\text{m}$ (d) $r = 1.260 \mu\text{m}$ (e) $r = 1.680 \mu\text{m}$ (f) $r = 2.1 \mu\text{m}$ ($n_e = 2.84 \times 10^{19} \text{ electrons/cm}^3$).....	23
14	Graph of Fowler-Nordheim plot for positive and negative polarity. Open symbols: negative. Closed symbols: positive. Gap = 10 mm, Point/plane. Stage I resistive. Stage II tunneling. Stage III space charge saturation [12]	25
15	Current behavior of EEE (a) a transition from FEE (phase I) to EEE (phases II – IV) (b – d) Collector current waveforms at an explosion of a field emitter without over-voltage, (e) and with an over-voltage [9]	27
16	Explosion delay time of a tungsten field emitter as a function of a) electric field and b) current density [9].....	31

17	Time to emitter explosion for steady state mode vs. β	32
18	Schematic showing possible orientation of the water dipoles adjacent to.....	38
19	Surface field enhancement from lattice model [1].....	39
20	Breakdown results from various electrode surface treatments in vacuum environment [19].....	41
21	Breakdown strength of water for varying area and pressure [26].....	45
22	Schematic representation of the i - V curves obtained with different electrodes in pure water [28].....	46
23	Schematic Representation of a) the electron Fermi level for various regions of the i - V curve in Figure 22 and b) the transfer of electrons from the metal into the conduction band of water (between 0 and -1.2 eV) [28]	47
24	The dependence of breakdown potential (V_b) on the work function (ϕ) of the electrode material [28].....	48
25	Relationship between voltage and current for various NaCl concentrations [2] ..	50
26	Bruce profile template [33].....	53
27	Electric field simulation of Bruce profiled electrodes	54
28	Varying area electrode sets	54
29	5cm ² Bruce profiled electrode	55
30	5cm ² Bruce profiled electrode with material insert	56
31	Space simulation facility.....	57
32	Schematic of the ion deposition setup	58
33	Photograph of the ion deposition setup.....	58
34	Tantalum tip hollow cathode [37].....	59
35	Block diagram of the experimental setup	60
36	Photograph of the water breakdown experimental setup.....	60

37	Schematic of the peaking gap	62
38	Schematic of the water test gap	63
39	3D View of the water test gap.....	64
40	Photograph of the water test gap.....	64
41	Anode design (a) fixed anode inner conductor and (b) hole pattern used to mount the anode to the Lexan endcap.....	65
42	Electrostatic field simulation of the revised test gap	66
43	Water flow diagram	67
44	Capacitive voltage divider schematic	69
45	Pearson current monitor (model 110A) [39].....	70
46	Large Bruce profile stainless steel electrodes.....	71
47	Veeco NT1100 optical profiler [40]	72
48	3D contour plots of each of the various surface roughnesses (a) 36 grit, (b) 60 grit, (c) 80 grit, (d) 100 grit, (e) 400 grit, and (f) buffing compound.....	73
49:	Electric field simulation plots of mechanically finished surfaces (a) scale (b) untreated (c) 36 grit (d) 60 grit (e) 80 grit (f) 100 grit (g) 400 grit (h) buffing compound	74
50	Hitachi S-4300SE/N electron microscope [41].....	78
51	SEM images of the various surface roughnesses (a) 36 grit, (b) 60 grit, (c) 80 grit, (d) 100 grit, (e) 400 grit, and (f) mirror (45X magnification at 10kV)	79
52	Zoomed in images of the various surface roughnesses (a) 36 grit, (b) 60 grit, (c) 80 grit, (d) 100 grit, (e) 400 grit, and (f) mirror (1200X magnification at 10kV)	80
53	X-Ray microanalysis of the 36 grit sandpaper.....	81
54	X-Ray microanalysis of the 60 grit sandpaper.....	81
55	X-Ray microanalysis of the 80 grit sandpaper.....	82

56	X-Ray microanalysis of the 100 grit sandpaper.....	82
57	X-Ray microanalysis of the 400 grit sandpaper.....	82
58	Typical elemental spectrum of the stainless steel electrodes.....	83
59	Location of Al, O, and C embedded in the surface of an electrode conditioned with 36 grit sandpaper.....	83
60	Location of Al, O, and C embedded in the surface of an electrode conditioned with 60 grit sandpaper.....	84
61	Location of Si, O, and C embedded in the surface of an electrode conditioned with 80 grit sandpaper.....	84
62	Location of Al, O, and C embedded in the surface of an electrode conditioned with 150 grit sandpaper.....	84
63	Location of Si and O, and C embedded in the surface of an electrode conditioned with 400 grit sandpaper.....	84
64	Ion deposition (a) Photograph of the electrode which was half covered in polyimide tape, (b) surface contour image, and (c) x,y data plot of the surface...	87
65	Various material electrodes.....	88
66	Copper and stainless steel electrodes used in the conductivity tests	89
67	Uniform field enhancement pattern applied through chemical etching and b) and though milling (c and d).....	91
68	Optical interferometer images of the uniform field enhancement pattern that was applied using a PC board endmill (a) contour map and (b) x,y profile	91
69	Electric field simulations of the router etched surface (a) scale and (b and c) surface images.....	92
70	Shadowgraph imaging setup	93
71	Electrodes used in the point – plane geometry (a) point and (b) plane.....	94
72	Typical voltage and current waveform	95
73	Dielectric strength vs. electrode surface area	97

74	Dielectric strength vs. electrode surface area	98
75	Dielectric strength vs. work function of the ion deposited surfaces	101
76	Dielectric strength vs. material work function.....	103
77	Dielectric strength vs. material melting point.....	104
78	Dielectric strength vs. material hardness	104
79	Dielectric strength vs. material density.....	105
80	Dielectric strength vs. specific heat	105
81	Voltage recorded during testing of the 1, 3.5, 11, 20, and 38.5 $\mu\text{S}/\text{cm}$ conductivities on the (a) cathode and (b) anode sides of the gap	107
82	Dielectric strength vs. R_A (1 $\mu\text{S}/\text{cm}$ conductivity).....	108
83	Dielectric strength vs. R_A (3.5 $\mu\text{S}/\text{cm}$ conductivity).....	108
84	Dielectric strength vs. R_A (11 $\mu\text{S}/\text{cm}$ conductivity)	109
85	Dielectric strength vs. R_A (20 $\mu\text{S}/\text{cm}$ conductivity).....	109
86	Dielectric strength vs. R_A (38.5 $\mu\text{S}/\text{cm}$ conductivity).....	110
87	Dielectric strength vs. water conductivity (stainless steel electrodes with various R_A 's).....	110
88	Dielectric strength vs. water conductivity (copper electrodes with various R_A 's).....	111
89	Dielectric strength vs. R_A (stainless steel electrodes tested in various conductivities).....	112
90	Dielectric strength vs. R_A (copper electrodes tested in various conductivities) .	112
91	Etched aluminum surface test results.....	113
92	Cathode point discharge development at time before breakdown (a) reference, (b) 300 ns, (c) 195 ns, (d) 95 ns, (e) 70 ns, and (f) 10 ns.....	114

93	Anode point discharge development at time before breakdown (a) reference, (b) 305 ns, (c) 283 ns, (d) 275 ns, (e) 270 ns, and (f) 200 ns.....	115
94	Interferometry images of breakdown locations	116
95	SEM images of breakdown locations	116
96	Marx generator capacitor stacks	123
97	Charging components	123
98	Marx control panel.....	124
99	Charging configuration	126
100	Connection between charging components and the capacitor stacks	126
101	Capacitor Stack lifted out of the tank	127
102	Potted resistor.....	128
103	Remains of a destructed electrode	128
104	Wiring diagram of the Marx control panel and charging components	130

CHAPTER I

INTRODUCTION

Over the last several decades, water has become an increasingly popular dielectric medium in high voltage pulsed power systems. This is primarily due to water's high dielectric constant, $\epsilon_r = 81$, which provides for increased energy storage density, making it an ideal candidate for use in compact pulsed power systems. While water's strongest quality is its high dielectric constant, it also possesses several other qualities making it a good choice as an insulating material in pulsed power systems. One such quality is water's self healing nature, enabling it to be reused after an electrical discharge has occurred. Other qualities are that water is readily available, environmentally safe, and easy to handle. Water is also the insulator of choice in large pulsed power machines. For example, many of the large machines at Sandia National Laboratories employ water as the primary insulating and switching media. It is the desire of Sandia National Laboratories to learn more about water breakdown that has made this research possible.

There are two leading theories about the general breakdown mechanisms in water which include charge injection at the electrode/water interface [1] and electron impact ionization in a low-density region of the water, i.e., a bubble mechanism [2,3,4]. Both of these theories are heavily dependent on the magnitude of the field enhancements present on the surface and the subsequent charge that is injected into the dielectric via Fowler-Nordheim field emission.

As the surface roughness of an electrode is increased, the number of microprotrusions on the surface is increased and the magnitude of the peak electric field

enhancement is increased as well. This increases the number of emission sites and the overall probability of a breakdown event initiating thereby lowering the dielectric strength. A larger surface area also increases the number of microprotrusions which exist on the surface, for a given average surface roughness, resulting in a lower dielectric strength as the surface area gets larger. The work function of the electrode also has a dramatic impact on water's dielectric strength. This is because as the work function is decreased, the amount of charge injected into the water is increased. Water's conductivity is another factor that impacts its dielectric strength due to its impact on the current density at the electrode water interface as well as the mobility of the emitted electrons once they have been injected into the dielectric medium.

Several experiments have been conducted in order to develop further insight into how each of these factors affects the dielectric strength of water. In each experiment, a water gap was tested under pulsed conditions with pulse widths of roughly 2 μs where peak electric fields over 1 MV/cm and peak currents over 3.5 kA have been recorded across the gap. In all of the tests, electrodes machined with a Bruce profile were used on both the anode and cathode sides of the gap. In the first set of tests, which were conducted to determine the impact of electrode surface roughness and area, six sets of stainless steel electrodes, with varying surface roughness averages, ranging from 0.26 μm to 1.96 μm , and varying effective surface areas, ranging from 0.44 cm^2 to 75 cm^2 , were tested. In order to test electrode materials with varying work functions, ion beam deposition was performed to apply various thin film coatings of several metals and oxides, including copper, tungsten, and zinc oxide, to Bruce profiled stainless steel

electrodes with an effective area of 5 cm^2 . The coating thickness of each surface layer is roughly a few hundred nm. Electrodes that were not put through ion beam deposition but rather were fabricated from copper, molybdenum, nickel, aluminum, and stainless steel were also made to include in this set of tests so that a wider range of work functions could be tested. In the next set of tests, electrodes constructed of copper and stainless steel with a single surface area of 5 cm^2 , were tested with various surface roughnesses, ranging from $0.26 \text{ }\mu\text{m}$ to $1.96 \text{ }\mu\text{m}$, in water with varying conductivity, ranging from $1 \text{ }\mu\text{S/cm}$ to $38.5 \text{ }\mu\text{S/cm}$. In the final set of tests, aluminum electrodes were etched on a PCB router so that two different known surface roughness patterns could be tested. Additionally, shadowgraph images of a point plane geometry were taken to further understand the breakdown processes that occur.

A further look at the previously conducted research in that area of water breakdown is given in Chapter II. A description of the experimental setups used to conduct the research is documented in Chapter III, a closer look at the tests performed is detailed in Chapter IV, an analysis of the data and results obtained are presented in Chapter V, and some conclusions are drawn in Chapter VI.

CHAPTER II

BACKGROUND

As mentioned in the introduction, water has many strong electrical and physical properties that make it an excellent intermediate storage material and switching medium in high voltage pulsed power systems. Several past research efforts have been conducted to further understand the electrical properties of water under pulsed conditions, as well as to develop new methods for improving its dielectric strength. In order to better understand the results that are being presented in this paper, a look at some of the earlier work that has been performed in this area of research will be discussed here.

2.1 Breakdown Initiation

Before any of the previously documented results or theoretical models is presented, it is important to explain the mechanism of field enhancement and subsequent electron emission which is believed to initiate the bulk breakdown of a liquid dielectric. Figure 1 displays a flow chart of events which result in the dielectric breakdown of liquid dielectrics. As expected the main branch of the chart occurs after the initial application of the electric field at which point electron emission into the water dielectric occurs. The manner in which this occurs is dependent upon the electrode surface conditions, electrode material, and water conductivity. Each of the electron emission mechanisms will be discussed in greater detail in the upcoming sections.

Figure 1: Flow chart of water's dielectric breakdown

2.1.1 Electric Field Enhancements

On any metallic electrode surface there exist irregularities or asperities on the electrode surface, more commonly referred to as microprotrusions, which are present in the form of peaks and valleys. At peaks in the surface, the electric field flux lines become more concentrated, as shown in Figure 2, and the enhancement of an otherwise moderate and uniform electric field results. The magnitude of this enhancement, which is a function of the electrode shape, height, and radius, is represented by β , and is therefore referred to as the beta factor. The electric field at the tip is then calculated using the beta factor and the uniform electric field strength according to Equation (1). In Figure 3, a chart displaying the different shapes and resulting beta factors as a function of their height and radius is shown.

$$E_{tip} = \beta E_{uniform} \quad (1)$$

Figure 2: Semi-ellipsoidal microprotrusion [5]

Figure 3: β factor for various microprotrusion sizes and geometries [6]

As an example, the enhancement of the semi-ellipse shaped microprotrusion, like the one displayed in Figure 2, is calculated using Equation (2) [6] with $\lambda = h/b$, where h is the height of the microprotrusion and b is the base radius.

$$\beta = \frac{(\lambda^2 - 1)^{1.5}}{\lambda \ln \left[\lambda + (\lambda^2 - 1)^{\frac{1}{2}} \right] - (\lambda^2 - 1)^{\frac{1}{2}}} \quad (2)$$

Across any electrode surface, there exist many different types of microprotrusions which will all have different shapes and β values. There is of course an increased likelihood that the dielectric breakdown will initiate from the one particular irregularity on the electrode surface which creates the largest electric field strength. This is because when the electric field at a small tip is raised, there is an increased probability that volume heating, high electric field electron emission, and even explosive electron emission will occur fastest from that point. These give rise to either a bubble or electronic mechanism which directly results in the liquids bulk breakdown. All of these possibilities will be discussed further in upcoming sections.

The β factor is usually considered at individual emitters on the electrode surface and it is primarily believed that it is the single largest electric field enhancement on the surface which initiates dielectric breakdown, however the concept of an effective β factor across the entire electrode surface has been considered in the past by Farrall [7] at the General Electric Research and Development Center. Through computer simulation, where he calculated the current density that is emitted from various microprotrusions on different electrode surfaces, he concluded that an effective β factor is formed across the entire surface. The simulated surface had N emitters or microprotrusions on it and as the electric field which he applied to the electrode was increased, the value of the effective β factor he recorded on the surface was decreased and the effective emission surface area was increased. Some of the results he documented are shown graphically in Figure 4.

Figure 4 :Variation of β_{eff} as a function of electric field (calculated from independent arrays) [7]

Additionally, Table 1 shows data collected by Farrall for high and low electric field strengths applied to a surface with various numbers of microprotrusions. The subscripts indicate, in kV/cm, the applied electric field used during testing, and the subscript “max” indicates the maximum value within the microprotrusion subset. In the results where electric fields of 120 kV/cm were tested, it should be observed that the effective β factor increases substantially as the number of emitters on the surface increases. This is contrary to when electric fields of 480 kV/cm were applied. In those tests, the effective β factor remains nearly constant as the number of emitters on the surface is increased and each is less than that recorded when electric fields of 120 kV/cm were applied for the same number of emitters.

Table 1: Effective B-factors and Emitting Areas for N Microprotrusions [7]

N	β_{120}	$A_{120} \times 10^{10}$	β_{480}	$A_{480} \times 10^{10}$	$\beta_{\max}''$
5	173	1.27	170	1.97	174
10	173	1.27	167	2.49	174
20	175	2.35	166	6.21	183
50	181	5.40	173	12.7	191
100	198	4.07	179	22.8	201
200	198	8.37	179	45.6	206

Farrall believes that this decrease in the β factor occurs because at larger electric fields, the field emission occurs primarily from the majority of microprotrusions on the surface which have a more average individual β factor rather than a select few which have a significantly larger individual β factor. This is what gives rise to an increased emitting surface area. According to Farrall, under low field strengths the single highest β -factor microprotrusion contributes between 42% and 90% of the total prebreakdown current supplied to the gap; whereas under high field strengths the single highest β -factor microprotrusion contributes between 10% and 50% of the total prebreakdown current. This implies that the prebreakdown current under high field stress is sourced by a larger number of microprotrusions, and the overall β -factor is dictated by a weighted average of the microprotrusions on the surface of the electrode.

2.1.2 Electric Field Electron Emission (FEE)

If any microprotrusion creates a large enough β factor, the possibility exists for a substantial current density to be emitted from its tip and injected into the water dielectric. The field emission theory, in vacuum, was first documented by Fowler and Nordheim

back in the 1920's in which they state that electrons are assumed to be emitted from the tip of a microprotrusion, at an isolated site on the surface of a broad-area cathode [NEUBER]. The model, which was first formulated in 1928, is called the Metallic Microprotrusion (MM) Model. In it they document the “Metallic” Field Electron Emission (M-FEE) mechanism which describes the quantum mechanical tunneling of electrons through a potential barrier. In tunneling, an electron wave function penetrates across a potential barrier, thus accounting for a certain probability of an electron to exist beyond the potential barrier [5,8]. It has been documented by Fowler and Nordheim that a theoretical threshold field of 2×10^9 V/m is required for the M-FEE mechanism to provide significant electron emission. In most cases, the uniform field between two electrodes is much less than this threshold value and thus it is believed that these fields can only be obtained at localized field enhancements, microprotrusions, on the electrode surface. Equation (3) and Equation (4) [9] were empirically developed by Fowler and Nordheim to calculate the steady state current density that is emitted for a certain electric field.

$$j = \frac{1.54 \cdot 10^{-6} (\beta E)^2}{\phi} \exp\left(\frac{-6.83 \cdot 10^7 \phi^{3/2} \theta}{\beta E}\right) \left(\frac{A}{cm^2}\right) \quad (3)$$

In Equation (3), ϕ is the metallic work function in eV, E is the electric field strength in V/cm, and

$$\theta \approx 0.956 - 1.06 \left(3.84 \cdot 10^{-4} \sqrt{\beta E} / \phi\right)^2 \quad (4)$$

In addition to the β factor of an emitter, it should be noticed from Equation (3) and Equation (4) that the work function of the metal used to make the electrodes also impacts

the amount of current density that is injected into the dielectric region. This is shown in Figure 5 which displays plots of the emitted current density, for each of the electrode materials tested in this paper, as a function of β factor which emits it. In the figure, the uniform electric field is assumed to be 1.5 MV/cm. Table 2 lists the work functions of each of the materials.

Table 2: Electrode Materials and their Work Functions

Electrode Material	Work Function
Aluminum	4.2
Molybdenum	4.2
Copper	4.5
Tungsten	4.55
Nickel	4.9
Stainless Steel	5.05
Zinc Oxide	5.3

As shown in Figure 5, a substantial current density can be emitted if the electric field at the surface is large enough. Since the mobility of electrons in water is quite low, $2 \times 10^{-7} \text{ m}^2/\text{V}\cdot\text{s}$ [10], it takes a substantial amount of time for the electrons which are emitted into the gap to drift. For example, at this mobility it takes 2.2 ns for an electron to travel 2 μm in an electric field of 45 MV/cm.

Figure 5: Fowler - Nordheim field emission vs. β

It is assumed here that the electrons which are emitted from a tip will initially be concentrated in a spherical volume in front of the tip from which they were emitted, similar to that shown in Figure 6.

Figure 6: Spherical cloud of charge formed in front of an emitter as a result of high field emission

If the magnitude of the current density, and consequently the electron density, is large enough, then the space charge generated electric field developed from the presence of electrons in front of the tip can approach that of the enhanced applied electric field. When this occurs, the space charge shields or grades the electric field at the tip, lowering the future emitted current density until such time has passed for the electrons within the charged volume to drift away from the tip. Once enough time has passed for the electrons to drift, the process is restarted and this occurs until the gap is either flooded with electrons or a bubble has formed leading to bulk breakdown. It could be best described by thinking of the emitter being ‘switched on’ when the space charge generated field in front of the tip is lower than the applied field and ‘switched off’ when the space charge generated electric field becomes equal to that of the applied field. The density of the electrons collected in front of the tip can be calculated from the current density using Equation (5) [10,11] where q is the charge of an electron, 1.602×10^{-19} C, β is the electric field enhancement factor, and μ_e is the electron mobility. It is shown graphically in Figure 7 that the resulting electron density increases as the β factor is increased.

$$n_e = \frac{j}{q \cdot \mu_e \cdot \beta \cdot E} \quad (5)$$

The electric field generated by the space charge can be calculated using Equation (6) where V is the volume of the sphere in which the charge in front of the tip is contained and $r_{\text{space_charge}}$ is the spherical radius.

$$E_{\text{Space_Charge}} = \frac{n_e \cdot V \cdot q}{4\pi \cdot \epsilon \cdot r_{\text{space_charge}}^2} \quad (6)$$

Figure 7: Electron density vs. β factor

As electrons are emitted into the gap, the radius of the spherical charge volume gets larger and the electric field generated from the space charge increases. For any emitter, which has a certain β factor and emits a certain electron density, there exists a single radius at which the electric field generated by the space charge becomes equal to the applied field. This is shown in Figure 8 where the emitter is assumed to have a β factor equal to 30. In the plot, it is shown that once the charged volume expands to a radius of $2.1 \mu\text{m}$, then the space charge generated electric field becomes equal to the applied field and shielding of the electric field at the tip occurs. Since this is a space charge limited model, electric fields above the uniform field cannot be generated in steady state and for that reason space charge generated fields greater than the applied field are considered hypothetically and are dashed in the plot.

Figure 8: Space charge generated electric field vs. charge radius

As shown earlier, as the β factor increases, the number density increases as well and consequently a smaller radius is needed to develop electric fields on the order of the applied field. It is shown in Figure 9, where it is assumed that a uniform field of 1.5 MV/cm is applied to a copper surface, that if a β factor of 27 is on the surface then a number density of 1×10^{19} electrons/cm³ is emitted and a charged sphere with a radius of 6 μm is required for shielding to occur. This is opposed to when a β factor of 37 is present at which a number density of 3×10^{20} electrons/cm³ is emitted and a radius of 0.2 μm is required for shielding to occur.

Figure 9: Applied and space charge generated electric fields vs. β

Though it would seem that the likelihood of a shielding event occurring increases as the required radius of charge decreases, since the time required for a smaller radius of charge to develop, it may not be the case. This is because as the electron number density increases, the repulsive forces felt by the charged volume increases, inhibiting the charge volume from holding together. Additionally, as the coulombic forces increase, the time it takes for the charge to drift apart once the emission is turned off is decreased as well. Equation (7) represents the force, F , exerted on an electron, with charge q , when it is placed within an electric field, E . However, Equation (7) does not account for the mobility of electrons in the water dielectric so it is more useful to use the Equation for mobility, seen in Equation (8), where μ_e is the electron mobility, v is the velocity the electron is traveling at, and E is the electric field which the electron is present in.

$$F = qE \quad (7)$$

$$\mu_e = \frac{v}{E} \quad (8)$$

The electric field, E , is approximated here as being equal to the enhanced field at the emitter tip, since that is ideally the largest electric field that can exist in the space charge region due to space charge limitation. Ideally the electric field in this region is less than the tip field until the volume expands such the electric field created by the charged volume is equal to the applied field. In order to more accurately calculate the electric field, it requires a sort of super positioning of the fields present as a result of the tip field and those present due to the space charge, which is a much more complicated evaluation. With this in mind, Equation (8) can be rearranged to solve for the velocity of the traveling electrons since the mobility and the electric field values are known. The velocity is then integrated over time using Equation (9) to solve for the distance which the electron travels over the time interval from t_{initial} to t_{final} . Equation (4) is then solved with the updated charged volume radius to calculate the electric field created by the space charge's presence.

$$d = \int_{t_{\text{initial}}}^{t_{\text{final}}} \mu_e E_{\text{tip}} dt \quad (9)$$

When the space charge generated electric field approaches the applied tip field, the emission is turned off, or is at least very substantially reduced since the tip field is so low, and the number density and volume terms of Equation (4) are replaced with a constant

charge value, which is equal to the charge of the total number of electrons within the charged sphere prior to the emission turning off. At this point the radius of the charge continues to expand, because of the electric field as well as coulombic forces, and the electric field created by the space charge decreases. As the charged volume expands and the electric field produced by it increases, the electric field at the tip is reduced until the two begin to approach one another. As the charged volume expands and its electric field reduces, the electric field at the tip begins to grow again since the effect of the charged volume is reduced. Figure 10 shows what a typical turn on and off transition would look like, for a copper electrode with a β factor of 30 and a uniform applied field of 1.5 MV/cm. The electric field due to space charge increases until roughly 2.5 ns when the charge approaches the applied field and the emitter turns off. At this time the radius continues to expand due to the electric field as well coulombic forces and a decay of the electric field created by the charged volume occurs.

Figure 10: Single shielding event

It should be kept in mind that once the electric field drops below the externally applied field, the tip field increases and the emission will turn back on. This causes the electric field present as a result of space charge to grow and the electric field at the tip to be lowered again. Figure 11 shows what multiple switching events might look like. The figure shows a space charge generated electric field which grows and then gets smaller as the emission is turned on and off. The electric field at the tip has been described in the figure as going through a sort of oscillation where it is reduced as the space charge generated field increases and returns to its initial value as the generated field decreases. However, this is not really a realistic situation. In reality it would be expected that as the tip field is reduced from the presence of space charge, the emission from it is lowered as well. After some time, a certain number of electrons must be swept out of the charged volume, far from the tip. It is believed that some sort of equilibrium is reached where the reduced amount of charge entering the volume in front of the tip is roughly equal to the number of electrons leaving the charged volume maintaining a near constant charge and near constant reduced tip field. The exact time over which this process occurs is difficult to calculate without some type of particle-in-cell solver that can accurately model the electrical properties of water and that can update the tip field as the charged volume grows while keeping track of the electrons which are emitted from the tip. A very rough guess of what this process may look like is shown in Figure 12. The time scale has been left off the figure since it is not known exactly how much time this process may take to develop, though it is believed that the process does unfold in the time range of 10's of nanoseconds making it applicable to the time scales tested in the experiments that are

discussed in this dissertation. The electric field scale has also been left off since the exact value of any of the steady state electric fields is not known either. The space charge electric field and the tip field are believed to never exactly equal each other but as the figure shows, they come close and reach equilibrium. The steady state electric field at the tip, E_{ap} , is believed to be between 60 and 85 percent of the initial enhanced value, βE_{ap} .

Figure 11: Multiple shielding events for various β 's

Figure 12: Equilibrium of space charge generated field and enhanced tip field

In both of the figures above, it is shown that the time that it takes for shielding to occur will of course change when the β factor is raised or lowered. What this implies is that there is a range of β factors, which depends upon the electrode work function and the magnitude of the applied uniform field, for which the shielding effect due to high field electron emission could occur. Individual emitters which have a very small β factor will not emit a large enough current density for an electric field on the order of the applied field to develop. As the β factor is increased, the current density becomes sufficient for a space charge generated electric field on the order of the applied field to be reached and the time required for the space charge generated electric field value to reach that of the applied field decreases. For emitters which have an extremely large β factor, the current density emitted by them is much larger and the time required for the space charge generated field to approach the applied field appears almost instantaneous and the repulsive forces are more than likely too large for the charged volume to hold together for any substantial length of time or shield the emitter once the emission is turned off. For a uniform external field of 1.5 MV/cm, applied in the microsecond time regime, it is estimated that shielding is possible on lower work function metals such as copper and molybdenum for individual β factors ranging from the middle 20's to upper 30's. In the case of β factors larger than 40, it becomes more probable that other processes such as FFE occur, which will be shown later. As the electrode work function is increased, as the case with stainless steel, the lower range of β shifts up to the middle 30's and the upper range shifts to the upper 40's. Thus far, the effect of shielding has been considered as an event that occurs in front of a single emitter. Since almost all electrode surfaces have a

countless number of emitters on them, most of which are in close proximity to one another, the phenomena is in reality believed to be one that occurs in front of an entire surface. All of the emitters emit charge into the dielectric and this forms a collective cloud of charge in front of the entire surface. The result is shielding in front of the whole surface. If the surface roughness is large, the magnitude of individual emitters is also large and the likelihood of a bubble or electronic mechanism, which will be discussed later, initiating before substantial shielding can occur increases. Additionally if the work function of the electrodes is large, the likelihood of shielding occurring in front of smoother surfaces, where shielding may occur before the development of a bubble or electronic mechanism, is decreased.

As the electron mobility is increased, or as the water becomes more conductive, the electron density in the water decreases, and consequently a larger charged volume radius is required for electric fields on the order of the applied field to form due to space charge. From the equations above, the time required for shielding to occur in either case remains essentially the same, which makes sense but then it doesn't, so the question arises of just how large can the radius reasonably expand to and still shield the emitter before it gets to close the anode and conduction occurs.

In order to verify the effect that a spherical space charge generated electric field has on the enhanced electric field at the tip of an emitter, electric field simulations, shown in Figure 13, were performed in Ansoft's Maxwell 3D. In the simulation, the tip is a copper emitter and the spherical charge volume in front of the tip is a charged volume of water. The charge volume has been simulated to have various sized spherical radii, but each

contains the same electron density of $2.84 \times 10^{18.5}$ electrons/cm³. An applied electric field of 1.5 MV/cm has been applied and the tip has a beta factor equal to roughly 30 producing an enhanced field of approximately 45 MV/cm.

Figure 13: Electric field simulations displaying the effect of a space charge generated electric field on the electric field at the tip of the emitter (a) E-field scale (b) no charged volume (c) $r = 0.840 \mu\text{m}$ (d) $r = 1.260 \mu\text{m}$ (e) $r = 1.680 \mu\text{m}$ (f) $r = 2.1 \mu\text{m}$ ($n_e = 2.84 \times 10^{19}$ electrons/cm³)

The radius of the charged volume was varied from 0.84 μm to 2.10 μm with increments of 0.42 μm . As shown already in Figure 9, as the charged volume radius increases, the electric field created by the charged volume increases. It should be noticed, that shielding of the tip begins to occur as the radius of the charge approaches 1.68 μm and the shielding effect that the charge has on the field at the tip is increased further as the radius increases to 2.1 μm , where the electric field at the tip is reduced substantially to between 20 and 35 MV/cm.

The results indicate that it only requires electric fields created by the space charge that are within a significant percentage of the applied field, and not necessarily exactly equal to it, for significant shielding to occur. The electric field inside the charged volume appears lower in the simulation than expected from calculations, using Equation (6), and this is more than likely due to the electrical properties assigned to water in Maxwell 3-D or interactions between the two charged volumes that has not been accounted for in the calculations.

A similar concept on charge mechanisms in transformer oil has been presented by Michael Butcher in his dissertation research [12], shown graphically in Figure 14 below.

Figure 14: Graph of Fowler-Nordheim plot for positive and negative polarity. Open symbols: negative. Closed symbols: positive. Gap = 10 mm, Point/plane. Stage I resistive. Stage II tunneling. Stage III space charge saturation [12]

Three stages of charge conduction that lead to the dielectric breakdown of oil are shown in the figure. Stage 1 is characterized by a resistive region at low electric fields. Conduction through this region is dominated by the bulk resistivity of the liquid. Stage 2 consists of a rapid rise in the injection current associated with quantum mechanical “tunneling” phenomena, similar to Fowler-Nordheim tunneling or emission through a Schottky barrier, at the liquid/metal interface. Stage 3 is a region of high applied fields and the current behaves like a space charge saturation region at voltages very near to self-breakdown for non-uniform fields.

2.1.3 Explosive Electron Emission (EEE)

The Electrical Explosion of Conductors (EEC) is defined by Mesyats as “an abrupt change in the physical state of the metal caused by intense deliberation of energy in the conductor, when passing through it a pulsed current of high density ($10^6 - 10^9$) A/cm², which disrupts the metallic conduction” [13]. Explosive Electron Emission (EEE) is a process which is believed be essentially the same as that of EEC. As implied by their names, each process involves the physical explosion of a metal conductor within an electrical system. The process occurs when an extreme current density is applied to the conductor which causes intense localized heating of the surface discontinuities causing the metallic surface temperature to approach its own melting temperature. Once this temperature is reached, the molten metal is lifted from the surface and injected into the dielectric which separates the cathode and anode. The cathode ejecta propagates into the dielectric region with a velocity dependent on the thermal and electrical properties of the bulk cathode material and the mobility of the particles in the dielectric itself. As this process unfolds, a gas, consisting of both plasma and cathode material, in both solid and vapor form, expands into the dielectric where it becomes further ionized. The plasma is responsible for emitting additional electrons into the dielectric [14]. As mentioned, the process is immediately preceded and thereby initiated by high electric field electron emission. Like the electric field electron emission theory presented earlier, this is also a space charge limited model.

Since such high current densities, ($10^6 - 10^9$) A/cm², are required for the cathode temperature to approach its melting point, it is only possible for this process to initiate

from microprotrusions on the electrode surface where the electric field is significantly enhanced. It has been experimentally shown in vacuum that the process can evolve within 10's of nanoseconds enabling this process to occur when pulses in the microsecond and sub-microsecond time regimes are applied. Figure 15 displays four phases which describe the evolution of EEE.

Figure 15: Current behavior of EEE (a) a transition from FEE (phase I) to EEE (phases II – IV) (b – d) Collector current waveforms at an explosion of a field emitter without over-voltage, (e) and with an over-voltage [9]

Phase I is the prebreakdown phase when electric field electron emission occurs. Phase II is the transition phase associated with the explosive destruction of an emitter. Phases III and IV are the subsequent electron emission phases that occur once the tip has exploded. In Figure 15, this is shown on several different time scales to better describe the transition phases. The transition is also described when a gap is heavily over-voltaged to show the lack of any clear transitions. Note that the graph was presented by Mesyats in

a vacuum scenario and that the current values are not representative of the experiments tested here.

One of the primary models which have been described by Mesyats is referred to as the Joule model since it is Joule heating of the cathode tip which results in the explosion. Two criterions have been specified for EEE to occur. The first is associated with the steady state mode and is shown in Equation (10).

$$j = \text{const}_1 \quad (10)$$

The second is shown in Equation (11) and is associated with the non-steady state mode.

$$\int_0^{t_d} j^2 = \text{const}_2 \quad (11)$$

Equation (12) can be used to describe the heating of a cathode emitter by flowing current through it. In the Equation, ρ , c , σ , and κ are the emitter density, heat capacity, heat conductivity, and resistivity. The first term on the right hand side describes the heat transferred by conduction and the second represents the heat released through Joule heating.

$$\rho c \frac{dT}{dt} = \nabla(\sigma \Delta T) + j^2 \kappa \quad (12)$$

Though most of the material parameters are temperature dependent, the resistivity is the most greatly influenced and is represented in Equation (13).

$$\kappa = \kappa_o T \quad (13)$$

In the steady state, Mesyats describes a temperature distribution, $T(x)$ across a cylindrical microtip with height h as shown in Equation (14).

$$T(x) = T_o \frac{\cos(bx)}{\cos(bh)} \quad (14)$$

In the equation, T_o is the temperature at the protrusion base, x is the distance measured from the protrusion apex, and $b = j(\kappa_o / \sigma)^{1/2}$. The temperature at the protrusion apex, $x = 0$, goes to infinity when $bh = \pi/2$ and the limiting current density that an emitter can have, assuming pulses long enough to enable a steady state current density to develop, can be found using Equation (15). Current densities on the order of 10^8 A/cm² are typical limiting values.

$$j = \frac{1}{h} \sqrt{\frac{\sigma}{\kappa_o}} \quad (15)$$

The time delay to explosion in the steady state mode can be approximated using Equation (16) where f is dependent upon the work function, the protrusion geometry, and the way in which the explosion criterion is defined. According to Mesyats, f can be approximated by setting it equal to 1 in most cases.

$$t_d = \frac{f \rho c}{\kappa_o j^2} \quad (16)$$

The value of the limiting current density has the potential of being larger when short pulses are used. Pulse lengths shorter than those required for a steady state current density to develop will fit the criteria shown below, Equation (17) where t_p is the pulse duration and h is the protrusion height.

$$t_p \ll h^2 \rho c / \sigma \quad (17)$$

If the condition shown in Equation (17) is valid and the current density remains unchanged in time then the temperature of the emitter increases exponentially as shown in Equation (18).

$$T = T_o \exp \left[\frac{\kappa_o}{\rho c} \int_0^{t_d} j^2 dt \right] \quad (18)$$

If it assumed that the protrusion explodes once a critical surface temperature is reached, more than likely equal to the material's melting point, then the time delay to explosion in the non steady state mode can be found by simplifying Equation (19), as shown in Equation (20).

$$\int_0^{t_d} j^2 dt = \left(\frac{\rho c}{\kappa_o} \right) \ln \left(\frac{T_{cr}}{T_o} \right) \quad (19)$$

$$t_d = \frac{\rho c \ln \left(\frac{T_{cr}}{T_o} \right)}{j^2 \kappa_o} \quad (20)$$

It has been experimentally shown in vacuum that this process is more than capable of evolving in only a matter of nanoseconds. Figure 16 displays the relationship between the time delay to explosion in vacuum to both the microtip current density and the electric field. Figure 17 displays the time to electrical explosion for each of the materials listed in Table 3, considered in the steady state time regime. The plot was generated using Equation (16). It can be seen that, this mechanism is not solely

dependent upon materials current density but more upon the material's thermal and resistive properties.

Figure 16: Explosion delay time of a tungsten field emitter as a function of a) electric field and b) current density [9]

Table 3: Electrode Material Properties

Electrode Material	Resistivity ($\mu\Omega\cdot\text{cm}$)	Hardness (Vickers)	Melting Point (K)	Thermal Conductivity ($\text{W/m}\cdot\text{K}$)	Density (g/cm^3)	Specific Heat ($\text{J/K}\cdot\text{kg}$)
Aluminum	2.67	42	933	237	2.7	900
Molybdenum	5.7	250	2890	138	10.22	251
Copper	1.69	87	1356	401	8.96	385
Tungsten	5.4	500	3683	173	19.3	133
Nickel	6.9	200	1726	90.9	8.9	444
Stainless Steel	71	190	1698	16.3	7.93	500
Zinc Oxide	6900	535	2248	Unknown	5.67	Unknown

Figure 17: Time to emitter explosion for steady state mode vs. β

It is important to remember that in these experiments being performed here, the electrodes being tested are in a liquid water environment and not in a vacuum so the time delay to electrical explosion could be larger than the times displayed in the figure above. Since pulse lengths in the microsecond time regime are being considered here, with time to breakdowns occurring between 200 and 400 ns, it is only possible for EEE to occur prior to bulk breakdown if the time delay to explosion occurs within roughly 100 to 300 ns. Looking at the steady state explosion delay times of copper for instance, shown in Figure 17, it appears that β values greater than 45 satisfy these conditions. This is in agreement with ranges of β defined earlier for emitter shielding. Similarly, β 's in the upper 50's begin to satisfy the conditions mentioned earlier for stainless steel and the

other higher work function materials. It is not believed that emission from this mechanism contributes to any surface shielding.

2.1.4 Emission from Dielectric Inclusions

Another model, which has been presented by Latham, is based on the assumption that the onset of field enhanced emission at low electric fields can be attributed to micron sized insulating inclusions embedded in the cathode surface. Electrons emitted from the bulk cathode into the conduction band of the insulator are accelerated towards the anode and collisions with electrons in the valance band of the insulator causing an electron avalanche to form within the dielectric inclusion [14,15]. It is assumed that electrons are emitted from the insulator by the thermionic process and the temperature is described in terms of the electric field that has accelerated them through the insulator. Documented experimentation of this model yields a close match to many experimental measurements of high field emission.

The current density emitted from the inclusion can be calculated using Equation (21) [16], where A is a constant, k is Boltzmann's constant, ΔV is potential drop across the insulating inclusion, and χ is the height of the potential barrier at the insulator-dielectric region.

$$j = A \left(\frac{2e\Delta V}{3k} \right)^2 e^{-\frac{3\chi}{2\Delta V}} \quad (21)$$

The potential drop across the high field surface region can be approximated using Equation (22) where ε is the inclusion's dielectric constant, V is the gap's applied voltage, d is the electrode separation, and Δd is the thickness of the micro-inclusion.

$$\Delta V \simeq \frac{1}{\varepsilon} \frac{\Delta d}{d} V \quad (22)$$

The apparent beta factor as a result of the dielectric inclusion can be calculated using Equation (23) [15] where χ and ϕ_o are measured in eV, and Δd is measured in m.

$$\beta = \frac{1.89 \times 10^9 \phi_o^{3/2} \Delta d}{\chi \varepsilon} \quad (23)$$

Extensive research into this mechanism of electron emission has not been performed here. It has been brought up since it is possible that sandpaper residue or buffing compound, composed of aluminum-oxide and silicon-oxide may remain imbedded in the electrode surface after the mechanical conditioning process is performed. Though this is possibly a substantial emission mechanism on all surfaces, in conjunction with the other mechanisms already discussed, it could well be the primary electron emission mechanism from surfaces with low R_a values. It is possible that electrons emitted from dielectric inclusions combine with those emitted from high field emission and for shielding to occur as a result. In order to investigate the possible presence of these materials in the electrodes tested here, conditioned electrodes were observed under a scanning electron microscope to detect their presence. The results of those tests will be discussed in Chapter 3.

2.2 Breakdown Theories

As mentioned in the introduction, there are two leading mechanisms which occur prior to the bulk breakdown of a liquid dielectric. These are the bubble mechanism and the electronic mechanism and each will be discussed next.

2.2.1 Bubble Mechanism

One of the more significant theoretical water breakdown models that have been documented involves the formation of a low density region, or bubble, at the tip of a microprotrusion that exists on the electrode surface. Jones and Kunhardt [2,3,4] are among those who have extensively documented this breakdown theory in water for both microsecond and sub-microsecond time regimes. The model is based on bubble dynamics where a bubble is formed due to volume heating, proton hopping, or localized heating due to field emission currents from a microprotrusion on the electrode surface.

Jones and Kunhardt have cited previous models of the bubble mechanism which include both an “electronic” and a “thermal” mechanism [4]. In the electronic model, ionization and current growth begin in the liquid phase. When an avalanche reaches a critical size, the field at the front of the avalanche is large enough for electrons at the front of the avalanche to heat the liquid at which point bubble formation begins. This model is believed to be most valid in the sub-microsecond time regime. In the thermal model, the electron avalanche is initiated in pre-existing bubbles or bubbles which are formed due to volume heating or localized heating at the tips of microprotrusions on the cathode surface. The bubbles expand under coulombic forces until a critical size is

reached or until it bridges the gap. The thermal model is most likely responsible for microsecond breakdown.

From these models, Jones and Kunhardt have developed a model which they believe is valid for both microsecond and sub-microsecond time scales. Initially, a bubble nucleates in the liquid near an asperity on the cathode whose density decreases with time due to continuous heating by field emission current. An electron avalanche is assumed to develop when the density reaches a critical value, $n_c = 10^{20}/\text{cm}^3$. Additionally they believe that the growth of the avalanche is retarded when the space charge generated fields are on the order of the external field. Electrons continuously heat the liquid directly in front of the avalanche thereby lowering the density below n_c . New avalanches can subsequently form in this region. The power input to the liquid by the electrons at the front depends on the resistance of the trailing ionized channel. The resistance of this channel must be sufficiently low to permit the energy flow from the electrode to heat the liquid at the front. This cycle of heating, density lowering, and avalanche growth and retardation propagates the ionization front across the gap until it is bridged to the anode [2,3].

The breakdown model developed can be broken up into four stages: (i) formation of a low density site (nucleation) in the liquid near the electrode, (ii) growth and expansion of this site until local density is reduced below a critical density for electron impact ionization to take place, (iii) growth of an electron avalanche and its transformation into an ionizing front, and (iv) propagation of the ionization front via a sequence of processes

occurring in the region ahead of the front; namely, heating by electron injection, lowering of the liquid density, and avalanche growth and retardation [4].

Jones and Kunhardt list three experimental observations that support this theory. First, they state that the breakdown strength of liquids decrease with increasing water temperature. Second, bubbles have actually been observed at sharp tips on the electrode surface within a few microseconds. Third, the dielectric strength of water has been observed to increase as the pressure within the liquid gap is increased. This increased pressure is believed to both remove bubbles that are initially present in the water as well as suppress any that form due to localized heating.

This model is very heavily dependent on the current density produced by a microprotrusion. As the current density is increased, the probability of a low density region forming increases and the nucleation time is decreased. It has been documented in research conducted at Texas Tech that this mechanism is more than likely responsible for dielectric breakdown of transformer oil tested with negative polarity pulses [17].

2.2.2 Electronic Mechanism

It has been documented that electron avalanches are more than likely incapable of occurring in water's liquid phase [1,2] however, another method of electron amplification has been presented by Lewis. As expected, he says that electrons are injected into the liquid from a micro-protrusion on the cathode. He believes that the electrons collide with the liquid molecules, locally heating the liquid through collisional impacts. The heating of the liquid reduces the density allowing future electrons to obtain more energy from the field before colliding with another molecule. The impacts that ionize a molecule will

leave two slow electrons to drift in the field. The build up of low energy electrons at the front of the streamer “marks the onset of spherical expansion under the coulombic forces of the consequent cloud of negative charge” [18].

Another electronic model has been presented by Joshi and others at Old Dominion University, in which they argue that the mechanisms of bubble formation and localized heating do not apply for time durations less than $10\mu\text{s}$ [1]. In their model two mechanisms lead to the dielectric breakdown. The first mechanism involves the formation of electric field enhancements, which are in addition to those typically formed by microprotrusions, formed due to the collective orientation of the dipole water molecules at the water/electrode interface. This is shown visually in Figure 18. The second mechanism is dictated by all of the electric field enhancements and the subsequent injection of electrons at the interface which modulates the conductivity of the gap and leads to the eventual bulk breakdown.

Figure 18: Schematic showing possible orientation of the water dipoles adjacent to the electrode due to high fields [1]

In their analysis of a four-layer water lattice model, Joshi documented the field enhancement factors obtained at the electrode interface versus the electric field itself at the interface. This can be seen in Figure 19. The results display enhancement factors as large as 70 which they believe can lead to electric fields as high as 2×10^9 V/m in their particular test setup. This value is right at the lower threshold for field emission documented by Fowler and Nordheim.

Figure 19: Surface field enhancement from lattice model [1]

This enhancement in addition to those formed by microprotrusions can well exceed the electric field strengths required for substantial electron emission to occur. As the amount of current density injected into the water is increased, either from the large electric field enhancements or from a lower work function metal, there is an increased likelihood of the gap becoming more quickly modulated thereby initiating the breakdown process. It has been documented in research conducted at Texas Tech that an electronic

mechanism of some sort is responsible for dielectric breakdown of transformer oil tested with positive polarity pulses [17].

2.3 Previously Documented Results

In the following sections, research that has already been conducted in each of the areas under investigation here will be discussed.

2.3.1 Effects of Electrode Surface Roughness

As already mentioned, the roughness of the electrode surface has a dramatic impact on the magnitude of the field enhancements that are present on an electrode surface under electrical stress. One measurement of surface roughness is the called the roughness average, R_A . This is the average distance measured above and below the arithmetic mean of the measured points. Equation 24 is used to compute the roughness average of a surface.

$$R_A = \frac{1}{n} \sum_{i=1}^n |Z_i - \bar{Z}| \quad (24)$$

Mechanical conditioning involves sanding the surface with a series of sand papers and possibly buffing the surface with different buffing compounds if a smoother surface is desired. The sanding process removes irregularities from the surface which are larger than the grit size of the paper being used. The mechanical sanding process is best executed when the grit size of the paper is started out low and then increased to provide a smooth surface. The buffing stages are implemented upon completion of sanding the

surface and remove the periodic grit lines that are left by the finer sand papers. Finishes with roughness averages under $0.25\text{ }\mu\text{m}$ can easily be obtained using this method.

Considerable research into the effect of electrode surface roughness on vacuum breakdown has been performed by Williams and Williams at University College of Swansea [19]. In their tests they applied various electrode surface treatments to four sets of Bruce profiled molybdenum electrodes, including unpolished, a hand polish, a lapping process, and an electropolishing process. Their results show a dramatic impact on the high field electron emission into the gap and consequently the holdoff voltage. Their breakdown results are shown in Figure 20.

Figure 20: Breakdown results from various electrode surface treatments in vacuum environment [19]

As expected, the unpolished surface shows the worst holdoff performance. The hand polished electrode surface displays the best performance though the lapped and electropolished surfaces are not too far below. They attribute all of these results to the

amount of field emission which is given off by each surface, which is smallest for the hand polished surface and larger for the unpolished surface, as well as the shape of the microprotrusions on the surface, which are sharp on the unpolished surface and smaller and rounder on the hand polished surface.

Another form of electrode conditioning is called electron beam conditioning since it subjects the surface of the electrode to a high energy beam of electrons which results in rapid heating of the electrode surface. This in effect melts the surface developing new surface properties. Ion Beam Surface Treatment [IBEST] has similar results in treating the surface [20]. Tests involving electron beam treatment have been conducted in a vacuum environment by David Johnson and others at Sandia National Laboratories [21]. In these tests large area stainless steel electrodes, with surface areas of 50 cm² and 100 cm², were given an electron beam enhancing surface treatment, EBEST, and tested with pulse amplitudes of roughly 220 kV and FWHM of 50 ns. The treatment process increased the surface roughness average of the electrodes as seen in Table 4, however it was concluded that the EBEST of the surface of the electrodes increases the peak electric field measured by a factor of 1.5–2 compared to that for electrodes with the initial surface resulting from machining.

Table 4: EBEST treated surface parameters [21]

Electrode Material	Original Roughness, μm	EBEST Roughness, μm	Crater Density, mm^{-2}
304L rod	0.120 ± 0.07	1.46 ± 0.26	10
304L plate	0.188 ± 0.02	0.37 ± 0.07	1
HVFF 304L Plate	0.193 ± 0.02	0.35 ± 0.1	0.1
304L HDII	0.193 ± 0.02	0.4 ± 0.2	0.5
316L Rod	0.366 ± 0.07	0.57 ± 0.08	5

2.3.2 Effects of Electrode Surface Area

As the surface area of the electrodes or transmission line structures used within an electrical system is increased there is an enlarged probability of a large microprotrusion existing on the surface. This enlarged probability also increases the probability of a breakdown event initiating, implying that as the surface area is increased, the dielectric holdoff strength is decreased.

In his Master's thesis, Keith Truman documented many good sources which tested the impact electrode surface area has on the dielectric strength of water [22]. Most of these are represented here.

The most well known set of area dependency experiments in water were performed by J.C. Martin in the early 1960's. From his experimental results he empirically derived Equations that predict the breakdown strength of water using the area of the electrodes and the effective time of the voltage pulse applied to the gap [23]. Two Equations were developed from his work, one each for positive polarity, shown in Equation (25) and negative polarity, shown in Equation (26).

$$F \cdot t_{eff}^{1/3} \cdot A^{1/10} = 0.3 \quad (25)$$

$$F \cdot t_{eff}^{1/3} \cdot A^{1/10} = 0.6 \quad (26)$$

In each of the Equations F is the electric field across the water gap in MV/cm, t_{eff} is the effective time of the voltage pulse in μ s taken at 63% of the maximum voltage, and A is the area of the electrodes in cm^2 . These Equations calculate the electric field necessary for breakdown to occur in water for a given set of test conditions.

Table 5 lists some of the data collected by Martin for a range of experimental variables for water breakdown used to determine the electric field and area relationship.

Table 5: Water Breakdown Data Obtained by J.C. Martin [23]

Area (cm ²)	Voltage (MV)	distance (cm)	t _{eff} (μs)	E _{exp} (kV/cm)	F _{pp} (kV/cm)
2200	0.3	1.5	0.5	200	130
120	0.3	1.0	0.3	280	170
400	1.0	4.0	0.4	260	200
50	0.4	0.6	0.02	700	700
1000	0.9	5.0	0.6	180	160
100	1.5	7.0	0.35	230	220
6	0.4	1.0	0.2	420	230
3000	1.85	10.5	0.75	160	150
55000	2.1	15.0	0.5	150	175
1000	0.63	0.6	0.0085	1050	1250
1000	0.53	0.6	0.01	870	870
1000	0.98	0.95	0.016	1030	970
1000	1.1	1.27	0.027	870	770

Additional research efforts in this area were performed by Buttram and O'Malley. In their experiments they tested a water gap with varying electrode surface areas under long term stress conditions [24]. The water they used was chilled to 2°C, deionized, and deaerated producing a water resistivity of 70 MΩ-cm. For their experiment, a Marx generator charged a water capacitor using stainless steel electrodes with areas of 80, 400, 2000, and 10000 cm² for pulsed durations as long as several hundred microseconds. During testing no substantial relationship was found between the breakdown strength of the water gap and time. The area of the electrodes, however, influenced the breakdown strength of the water gap by a factor of Area^{-0.08}. Ian Smith has documented this same area dependence factor as well [25].

Miller performed water breakdown experiments in which he applied microsecond pulses to a water gap under varying water pressures using electrodes of various surface areas [26]. As expected there is an increase in the water's dielectric strength as the pressure is increased, similar to results documented by Jones and Kunhardt [2,3], and a decreasing dielectric strength as the effective surface area of the electrodes is increased by a factor of $\text{Area}^{-0.58}$. Figure 21 shows the variation of water breakdown strength versus area for different pressures as documented by Miller. VanDevender has documented results in which he believes the area term to be $\text{Area}^{-0.6}$ [27].

Figure 21: Breakdown strength of water for varying area and pressure [26]

2.3.3 Effects of Various Electrode Materials and Coatings

As indicated earlier, the material from which the electrodes used in a water gap are made has an impact on the overall dielectric strength of the water. This is because as the work function of the conductors used in the system is decreased, the current density, and consequently the amount of charge injected into the dielectric, from high field electron

emission is increased as well. In their look at the breakdown strength of water, Szklarczyk and others [28] found that the electrode work function had a strong impact on the dielectric breakdown strength of water under DC conditions. In their studies, they observed the current to voltage relationships of various electrode materials including Pt, Cu, Fe, Ni, Au, and Co. In all of their curves, they observed five stages that lead up to catastrophic breakdown, as shown in Figure 22. Stage A is the application of the electric field to the gap. In Stages B and C they believe that there is a formation and eventual build up of a hydrogen gas layer at the electrode water interface in which plasma is formed. At Stage D, electrons build up enough energy to transfer into the conduction band of the water and at Stage E, electrical breakdown is believed to occur.

Figure 22: Schematic representation of the i - V curves obtained with different electrodes in pure water [28]

When a potential is applied to the electrode surface, they believe that it causes a shift in the electron Fermi level. The shift continues until the Fermi level in the metal reaches the conduction band of the liquid dielectric at which point streamers begin to

develop in the liquid [28]. Figure 23 schematically describes the shift in the Fermi level with respect to each of the five stages observed in Figure 22.

Figure 23: Schematic Representation of a) the electron Fermi level for various regions of the i - V curve in Figure 22 and b) the transfer of electrons from the metal into the conduction band of water (between 0 and -1.2 eV) [28]

In all of their tests, the breakdown event typically occurred when the current density reached a few A/cm^2 in all of the materials that were tested. Their breakdown results,

shown in Figure 24, indicate a decreasing trend in holdoff voltage as the work function of the electrode is increased. They document a couple of reasons for the material variation. First, there is an inverse relationship between the exchange current density and the work function such that, with increase of work function, the current density for hydrogen evolution reaction increases. Second, each material requires a different applied potential for the Fermi level to reach that of the conduction band of water.

Figure 24: The dependence of breakdown potential (V_b) on the work function (ϕ) of the electrode material [28]

In earlier water breakdown experiments conducted at Texas Tech University, Lojewski attempted to coat stainless steel electrodes with a thin layer of poly(ethersulfone), poly(carbonate), and Apiezon-W black wax in order to determine its impact on the dielectric strength of a water gap [29]. Decreases in the maximum voltage of 25.6% and 19.6% respectively were obtained when the PES and PC coatings were applied to both the cathode and anode of the gap. No significant impact was noticed with

the application of the black wax. Under DC conditions, Szklarczyk [28] tested the impact of adding a sulfide layer, a paraffin film, and black wax. In the case of the sulfide layer, which was added to a Pt tip, a 2kV increase in the breakdown potential was observed. With the addition of the paraffin layer, a 3 to 4 kV increase in the breakdown strength was observed in comparison to a bare Pt electrode. The black wax greatly increased the breakdown potential and was heavily dependent upon the thickness of the layer of wax added, with the thicker layer providing the greatest holdoff strength. They believe these additions to the electrode surface inhibit the hydrogen evolution.

Gehman and others at the Naval Surface Weapons Center [30] tested the effect of adding a cuprous oxide coating to copper electrodes on the dielectric breakdown strength of ethylene glycol / water mixtures. Their results show a strong decrease in the charge injection into the dielectric as well as a decrease in the dielectric strength. They also document a further decrease in the dielectric strength as the oxide layer thickness is increased.

2.3.4 Effects of Water Conductivity

Past research efforts investigating the impact of water conductivity have been mixed. While some have shown that water conductivity has little to no impact on the dielectric strength [2,3], others have shown that the dielectric strength is increased as the conductivity is reduced [28,31]. It could be expected for several reasons that the conductivity of the water would have a significant effect on the breakdown strength of water. First, as the conductivity is increased, current more easily flows through the medium making the gap look less resistive as the voltage is initially applied. In

experiments conducted by Jones and Kunhardt in the sub-microsecond time regime [2.3], an increased magnitude of steady prebreakdown current is observed across a water gap as the water conductivity is increased, as shown in Figure 25.

Figure 25: Relationship between voltage and current for various NaCl concentrations [2]

As the conductivity is increased, the current density in the water is increased as well as shown in Equation (27). Under pulsed conditions, the increased prebreakdown current and current density should raise the possibility of a bubble or low density region forming. Second, if the breakdown initiation is considered to be purely electronic, it would be expected that an increased prebreakdown current would increase the likelihood of a conductive channel forming across the gap.

$$J = \sigma E \quad (27)$$

Third, the electron mobility in water is also impacted by the water's conductivity as shown in Equation (28) [32] where n is the electron density and q is the electron charge.

As the conductivity is increased, the mobility of the electrons is increased. It would be expected that this could make it harder for the spherical volume of electric charge mentioned earlier to form in front of an emitter and hold together. This could reduce the likelihood of a shielding event occurring and in effect reduce the dielectric strength of water as the conductivity is increased.

$$\mu_e = \frac{\sigma}{n|q|} \quad (28)$$

All of these factors would indicate that as the water conductivity is increased, the breakdown would be more dependent upon events which occur in the water between the gap rather than solely at the electrode / water interface. Thus as the water conductivity is increased, it would be expected that the electrode surface roughness and material would have less of an impact on the dielectric strength.

In the tests performed by Jones and Kunhardt, where 80 kV pulses with a 3 ns risetime and a 100 ns pulse width were applied, they say that they have observed little impact on the time to breakdown when distilled water was tested in comparison with various concentrations of molar NaCl ranging from 0.001 to 1.0 [2,3]. From their results they believe that bulk ionic heating of the water dielectric has no impact on breakdown initiation. It has been experimentally shown under DC conditions by Szklarczyk, that there is a decreasing holdoff strength as the water conductivity is increased [28].

Bernardes and Rose at the Naval Surface Weapons Center [31] investigated the breakdown characteristics of various NaCl - water mixtures. Their mixtures ranged from

pure de-ionized water, with a conductivity of 10 $\mu\text{S}/\text{cm}$, to a saturated salt solution, with a conductivity of 67 mS/cm . The mixtures were tested in the microsecond time regime with a point - plane geometry and gap separations ranging from 1 mm to 3 mm. The experimental setup involved discharging a capacitor across the resistive gap. After voltage application, the gap initially looks resistive until such time has passed, that catastrophic breakdown occurs. They refer to this time difference as the time to breakdown. From Table 6, which displays their results, it should be noticed that there is a decrease in the time to breakdown as the conductivity of the gap is increased. The breakdown electric field has a mildly decreasing trend but suggests that even at high conductivities, water maintains its substantial dielectric strength.

Table 6: Results Obtained using Various NaCl – Water Mixtures [31]

Conductivity ($\mu\text{S}/\text{cm}$)	Gap distance (mm)	Gap Resistance (Ω)	E_{bd} (MV/m)	Time to Breakdown (s)
10	1.14	2800	2.7	1.6×10^{-2}
769	1.14	68.6	1.4	1.4×10^{-4}
769	3	85.7	0.86	3.6×10^{-4}
4.7×10^3	1.14	9.7	1.4	2×10^{-5}
4.7×10^3	3	12.6	1.3	17×10^{-6}
6.6×10^4	1.14	0.86	1.58	4×10^{-6}
6.6×10^4	3	1.23	1	20×10^{-6}

CHAPTER III

EXPERIMENTAL SETUP

3.1 Electrode Sets

In all of the experiments conducted, Bruce profiled electrodes [33, 34] were used on both the anode and cathode sides of the gap. The profile provides a taper which follows a cosine function from the edge of the disk's effective area, a flat portion, to the outer diameter of the disk where a circular or rounded edge is located. This taper removes field enhancements from the edge of the electrode's effective area. Figure 26 displays a template used for constructing a Bruce profile electrode.

Figure 26: Bruce profile template [33]

In the figure, AB is the effective area or flat portion of the electrode mentioned earlier. BC is the cosine tapered edge and CD is the rounded edge, centered at O, which further removes field enhancements from the electrodes edge. All of the electrodes were attached to the system's inner conductors with 1/2"-20 all-thread, providing a strong electrical connection. Figure 27 displays an electrostatic field simulation of the electric field between two electrodes.

Figure 27: Electric field simulation of Bruce profiled electrodes

In the experiments where the electrode surface roughness and area were tested, six sets of Bruce profiled electrodes, with a common overall diameter and varying cosine taper functions, were used. The common overall diameter was used to minimize the capacitance changes between the different sets. The varying cosine function was used to change the overall diameter of the electrodes effective surface area. The effective areas tested ranged from 0.44 cm^2 to 75 cm^2 . Figure 28 displays drawings of all of the different electrodes used in this set of tests. Each of the electrodes has a thickness at the flat portion of 1.27 cm and an overall base diameter of 14.94 cm. Table 7 displays the taper function, area, and 2 mm gap capacitance of all six electrode sets.

Figure 28: Varying area electrode sets

Table 7: Large area electrode specifications

Bruce Slope	Area (cm ²)	Capacitance (nF)
cos(.27x)	0.44	2.463 nF
cos(.30x)	3.50	2.687 nF
cos(.50x)	39.00	3.802 nF
cos(.60x)	53.97	4.158 nF
cos(.70x)	66.24	4.452 nF
cos(.80x)	76.31	4.677 nF

In the experiments where the electrode material, conductivity, and aluminum etched surfaces were tested, a single Bruce profile design was used in all of the tests. A schematic of the smaller electrode is shown in Figure 29. Table 8 details the taper function, area, and capacitance of this electrode set with a 2 mm gap separation

Figure 29: 5cm² Bruce profiled electrode

Table 8: Smaller Electrode Specifications

Bruce Slope	Area (cm ²)	Capacitance (nF)
cos(.7x)	5.00	1.426 nF

Some of the metallic alloy and oxide layers tested initially, Cu, W, and ZnO, were deposited onto stainless steel electrodes using an ion deposition system which will be discussed later. Other materials tested were either completely fabricated from the metal to be tested, Al and Cu, or a 0.0625 cm thick by 5 cm diameter insert of the material to be tested, Mo and Ni, was inset into the center of a 1.25 cm thick by 8.28 cm diameter piece

of aluminum before the profile was machined. This ensured that the material to be tested well exceeded the effective surface area of the electrode. This is shown schematically in Figure 30.

Figure 30: 5cm² Bruce profiled electrode with material insert

Some of the electrodes fabricated entirely from aluminum were given a mirror finish and were put through a chemical etch process so that a known field enhancement pattern could be applied to the electrode surface. The details of this process will be presented later.

3.2 Ion Deposition Setup

As mentioned earlier, an ion beam sputter deposition setup was constructed so that thin film coatings of higher and lower work function material could be deposited onto the stainless steel electrodes which were already machined. A 1 kW Hall Effect thruster with anode layer (TAL) [35] was used as the primary ion deposition source while a smaller magnetic layer Hall Effect ion source with an operating range between 100 W and 300 W, was used to clean the electrode surface prior to deposition. The 1 kW ion source was developed, tested, and documented by John Walter at Texas Tech University. The second

is a modified design of the KM-20M, developed by Kaufmann and Robinson Inc. in Fort Collins, Colorado, and it was constructed for these tests [36].

All of the deposition was performed in the Space Simulation Facility at Texas Tech University which is shown in Figure 31. Vacuum is primarily provided by two large (0.91 m diameter) Varian NHS 35 diffusion pumps with an operational pumping speed of 50,000 l/s. The chamber is roughed from atmosphere to about 1×10^{-2} Torr using a Stokes 912-10 Microvac rotary piston mechanical foreline pump. Utilizing one diffusion pump, the system can achieve minimum pressures around 1×10^{-6} Torr and a pressure near 1×10^{-5} Torr during deposition. An overall schematic of the deposition system is shown in Figure 32 and a picture of the actual setup is shown in Figure 33. Grade 5 Xenon gas was used as the neutral gas in all of the conducted tests.

Figure 31: Space simulation facility

Figure 32: Schematic of the ion deposition setup

Figure 33: Photograph of the ion deposition setup

The cathode used to neutralize the sources in all of the tests is a SHC1000 Electron Source designed by Kaufman and Robinson Inc., shown schematically in Figure 34 [37]. It is a Tantalum tip, hollow cathode electron source that can provide an electron current up to 8 A with a 1 sccm flow of Xenon and a keeper discharge of 1.5 A at 20 V.

Figure 34: Tantalum tip hollow cathode [37]

As indicated, prior to depositing the various materials, which include copper, tungsten, and zinc oxide, the electrodes were subjected to an ion beam from the smaller ion source to clean the surface. This cleaning process removed any oxide layer or contaminants that were present on the surface, allowing the material to be deposited the ability to properly attach itself to the electrode surface. This proved to be a vital step in obtaining a successful material deposition. The electrodes were mounted from a vertically positioned motor so that the electrodes could be rotated from in line with the cleaning ion source to in line with the sputter target after the cleaning process was completed. The sputter target was positioned roughly 15 cm from the sputter ion source at a 45° angle and

roughly 10 cm from the cleaning ion source at a -45° angle. The details of the deposition procedure will be discussed in the next chapter.

3.3 Electrical Generation and Transmission of the Water Breakdown System

A block diagram of the experimental setup used to conduct the water breakdown tests is shown in Figure 35 and a photograph is shown in Figure 36. The system can be broken into three important sections including the primary energy storage, the secondary storage, and the test gap. The first two sections were constructed and used by other students prior to myself on other experiments. The test gap was designed for these experiments and will be discussed in great detail in the next section.

Figure 35: Block diagram of the experimental setup

Figure 36: Photograph of the water breakdown experimental setup

The primary energy used in the system is stored in a Marx generator. The most extensive documentation on this particular Marx generator is found in Blake Ausburger's master's thesis [38] though extensive changes were made during these tests which are documented in Appendix A. To refresh the reader, a Marx generator is a collection of capacitors that are charged in parallel and discharged in series resulting in a multiplication of the charge voltage at the output. The components of the Marx generator are stored in a large oil filled tank to prevent breakdown. The Marx generator consists of 31 stages, with an erected capacitance of roughly 6 nF, that is both positively and negatively charged to provide an erected voltage of roughly -1 MV when fully charged. The capacitor charging is accomplished using two 50kV power packs located inside the tank. The switches used to throw the capacitors into a series connection are air filled spark gaps pressurized to roughly 27 psi. To erect the Marx generator, the air pressure is released from the first four gaps, which are pressurized independent of the other twelve gaps, using a 120V AC solenoid valve attached to a momentary switch. The decrease in pressure lowers the holdoff voltage of the gaps causing them to breakdown. The remaining twelve switches are self breaking and get thrown in series as the erection process proceeds. After the final switch has been thrown, the erected voltage is discharged through a charging inductor, 25 μ H, into a pulse forming line which serves as the secondary storage section of the system.

The pulse forming line is an oil filled coaxial transmission line with a characteristic impedance of 20 Ω . At the end of the pulsed forming line is an adjustable self breaking oil filled switch that shapes the output pulse. The switch is made of two stainless steel

hemispheres with one being fixed, the cathode, and the other being adjustable, the anode. The cathode side of the gap is attached directly to the inner conductor of the pulse forming line and the anode is attached to a 3/4"-16 bolt that protrudes from the front of the pulse forming line's Plexiglas endcap. A nut around the bolt can be turned to adjust the gap separation. Six prepulse resistors at the anode of the gap are used to prevent the cathode of the load from floating up with the pulsed forming line. This enables the eventual bulk breakdown of the gap. The resulting pulse is then delivered to the load. When the peaking gap is open, pulses with roughly a 20 ns risetime and 80 ns pulse width are formed. When the gap is shorted, the direct output of the Marx, which is an RLC response pulse with a risetime of roughly 250 ns, is applied. Figure 37 displays a graphical image of the peaking gap just discussed.

Figure 37: Schematic of the peaking gap

3.4 Test Gap

The test gap was placed inside a cylindrical chamber which has normally served as a vacuum port on previous experiments. The walls of the chamber were coated in a very heavy layer of epoxy paint to prevent rusting of the chamber and any contamination of the water with metallic particles. Schematics of the design are shown in Figure 38 and Figure 39. A photograph of the gap is shown in Figure 40.

Figure 38: Schematic of the water test gap

Figure 39: 3D View of the water test gap

Figure 40: Photograph of the water test gap

The chamber is 813 cm in diameter and is located directly at the output of the peaking gap. A 12.5 cm thick section of Plexiglas, which has a rigid face design to lengthen the electrical path length, isolates the inner conductor of the water chamber from the outer conductor while containing the oil within the pulse forming line. Since

breakdown across the Plexiglas insulator surface was a concern, 2 cupric sulfate water resistors, with an equivalent resistance of roughly $75\ \Omega$, were placed just prior to the cathode electrode of the gap. These were included to prevent voltage doubling at the gap, reduce reflected power to the Marx generator, and minimize the E-field stress across the large Plexiglas interface. A 7 cm diameter aluminum inner conductor was machined for the cathode side of the gap providing a $20\ \Omega$ impedance up to the gap itself. At the far end of the chamber, a 36 cm cylindrical opening is present to work within the chamber. A Lexan endcap, to which the anode of the gap is mounted, is bolted on to this opening with an o-ring to seal the water within the chamber. Figure 41 contains a schematic of the anode design and bolt hole pattern used to secure it to the Lexan endcap.

Figure 41: Anode design (a) fixed anode inner conductor and (b) hole pattern used to mount the anode to the Lexan endcap

The same setup of two resistors that was placed on the cathode side of the gap was also placed on the anode side of the gap to serve as a load once the gap had broken down. These helped to limit the current out of the Marx Generator and prevent all the energy in the gap from returning to the generator itself. Two view ports, which are parallel to the ground, are also present to provide visual access through the gap. Electric field simulations, seen in Figure 42, were run to ensure that there were no major field enhancements which could have resulted in the destruction of the Plexiglas insulator. In the simulation, the only field enhancements are noticed at the junction of the Plexiglas insulator and the conductive ring surrounding the cathode feed through. However, since the distance to the outer conductor is so large, it was not considered to be serious enough to cause a catastrophic problem.

Figure 42: Electrostatic field simulation of the revised test gap

In order to assure that the water being used in all of the tests was clean and fresh, a reverse osmosis system was purchased and used to purify domestic water. The system puts domestic water through both a carbon filter and reverse osmosis membrane and then stores the water in a 45 gallon tank. Pressure built up inside the tank during the filling is then used to release the water from the tank for use. Two de-ionization columns were put in line with the reverse osmosis tank and the fill port of the water chamber. Since, the pressure from the tank is used to release the water, there was no need for any additional pumps. This removed the possibility of any contaminants getting into the water from a pump head. Plastic tubing was used for all of the water transport, again removing the possibility of rust or other metallic contaminants. The water directly out of the de-ionization columns had a measured conductivity as high as $0.6 \mu\text{S}/\text{cm}$. A schematic diagram of the water flow system is shown in Figure 43.

Figure 43: Water flow diagram

3.5 Electrical Diagnostics

In order to measure the voltage and current across the gap, a capacitive voltage divider was placed on the cathode side of the gap and a Pearson current monitor, model 110A, was placed around one of the load resistors on the anode side of the gap. Coaxial cables, with a 50Ω impedance, were run in shielded conduit from the location of the test gap to a Faraday cage where an oscilloscope is located to record the measured waveforms.

3.5.1 Capacitive Voltage Divider

A capacitive voltage divider was implemented to monitor the electric field across the gap. To construct the divider, a strip of polyimide tape, that is 5 cm wide and $88.9\ \mu\text{m}$ thick, was placed 170° along the inner diameter of the chamber. Polyimide tape is used due to its high dielectric strength, as well as because of its dielectric constant of 3.6. A 2.54 cm wide strip of copper tape was then placed on top of the polyimide tape, forming a capacitor between the inner conductor of the system and the copper tape, C_1 , as well as between the copper tape and the system's outer conductor, C_2 . Water serves as the dielectric of the first capacitance and the polyimide tape serves as the dielectric of the second capacitance. A schematic of the divider is shown in Figure 44. A radial distance of 170° was chosen to keep the strip of copper tape below the view ports on either side of the chamber and it was placed on the bottom to remove any air pockets the could form along the upper end of the chamber.

Figure 44: Capacitive voltage divider schematic

The capacitance of C_2 was measured, using an LCR meter, to be roughly 5 nF. To obtain the capacitance value of C_1 , and thus the attenuation factor of the probe, a known voltage pulse was input to the anode side of the gap, which was shorted, from a mini Marx generator. The output of the generator was recorded on the scope and an attenuation factor of -67.2 dB was obtained by comparing the input and output pulses, thus C_1 was found to have a capacitance value of roughly 2.2 pF. When the direct output of the Marx generator was applied to the gap, a 1 k Ω resistor was placed at the output of the probe to remove the droop that the divider introduced.

3.5.2 Pearson Current Monitor

In all of the tests conducted, a current monitor manufactured by Pearson Electronics Inc., model 110A, was used to monitor the current through the gap. The coil was placed inside the chamber, in a Lexan encasement, around one of the cupric sulfate load resistors. The monitor has a usable rise time of 20 ns, a maximum peak current of 10 kA, and a sensitivity of 0.1 V/A [39] when it is terminated into a 1 M Ω impedance. A graphical description of the coil can be seen in Figure 45.

Figure 45: Pearson current monitor (model 110A) [39]

CHAPTER IV

EXPERIMENTAL PREPARATION AND PROCEEDURE

4.1 Surface Roughness and Area Preparation

The first set of tests that were conducted were those intended to determine the impact of both electrode surface area and surface roughness on the dielectric strength of water. The larger stainless steel Bruce profiled electrode sets, which are displayed in Figure 46, were used in these tests.

Figure 46: Large Bruce profile stainless steel electrodes

Prior to each test, every set of electrodes was sanded mechanically with a different sandpaper grit to obtain a different surface roughness average. Additionally, after each sanding process and prior to testing, a WYKO NT1100 optical profiler manufactured by Veeco Instruments [40] which is shown in Figure 47, was used to measure the surface roughness average that each of the sandpaper grits created on the surface. The profiler is

capable of recognizing sub-nanometer up to millimeter elevation changes. The software accompanying the profiler computes a roughness average across the full measured surface, R_A , a peak to valley difference across the full measured surface, R_T , provides a 3-D contour mapping of the surface, and plots an (x,y) profile of the surface. Ten random measurements, of a 1mm by 1mm area, were taken of each electrode and an average of the measurements, shown in Table 9, was calculated. Figure 48 compares 3-D contour plots of the five mechanical finishes that were applied for this set of tests as well as a plot of a surface that was additionally buffed to a mirror finish using buffing compounds.

Figure 47: Veeco NT1100 optical profiler [40]

Table 9: Surface Roughness Averages

Grit Size	Roughness Average R_A (μm)	Peak to Valley Distance R_T (μm)
400	0.26	3.98
100	0.60	7.96
80	1.13	14.96
60	1.53	16.18
36	1.96	19.48
Mirror	0.11	1.83

Figure 48: 3D contour plots of each of the various surface roughnesses (a) 36 grit, (b) 60 grit, (c) 80 grit, (d) 100 grit, (e) 400 grit, and (f) buffing compound

An additional feature of the interferometer is the ability to export the surface data in x,y,z coordinates for use in other software packages. This feature was used so that actual surfaces could be simulated in Ansoft's Maxwell Electrostatic Field Simulation software. However, prior to importing the data into Maxwell, a 3-D solid model of the data has to be created. TurboCAD v.11 was the best software found to accomplish this task. The software was very useful in creating a solid object from the data, one limitation is the processing time needed to create the solid surfaces with either a high image resolution or surface size. Processors have a tendency to lock up when attempting to create solids from data consisting of more than ten thousand points or sometimes the solids are created with defects. To get around this, a subregion of the sample size, 1 mm x 1 mm, was taken and

surfaces with a width and length of 0.27 mm, 6048 points, were modeled. The simulation results are shown in Figure 49. A detailed procedure for generating solids using the TurboCAD v.11 software package can be found in Appendix B.

Figure 49: Electric field simulation plots of mechanically finished surfaces (a) scale (b) untreated (c) 36 grit (d) 60 grit (e) 80 grit (f) 100 grit (g) 400 grit (h) buffing compound

Analysis of each of the surface simulations displayed in Figure 49 is listed in Table 10 through Table 13 below. To perform the analysis, the electric field values at each of the points used to create the surface was exported to Microsoft Excel. First it should be noticed from the simulations that there is clear evidence of enhanced electric fields along the outer perimeter of all of the simulations resulting from edge effects. Attempts at shielding all of the edges were made though it shielded the surface too much resulting in fields well below the average field along the edges. In order to more accurately interpret the results of the simulations, only the points which are more than 25 μm in from each edge were used in the analysis. This makes the effective area under consideration 225 μm x 225 μm , 4153 points, rather than the full 275 μm x 275 μm , 6048 points. After exporting the data, it was noticed that on each surface there were points where the fields did not converge and thus no data was obtained. These points were also removed from the analysis so as not to introduce a bias. Table 10 displays the maximum electric field and corresponding maximum β factor that was recorded on each surface. As expected, the maximum electric field values decrease as the surface gets smoother, though the drop is very small as the surface roughness varies from 1.53 μm to 0.60 μm .

Table 10: Peak Surface Electric Field and β factor

Surface	E_{Max} (MV/cm)	β_{Max}
36G (1.96 μm)	28.69	19.13
60G (1.53 μm)	18.70	12.47
80G (1.13 μm)	18.31	12.20
100G (0.60 μm)	18.05	12.04
400G (0.26 μm)	16.72	11.15
Mirror (0.065 μm)	15.19	10.12

Table 11 contains analysis of all of the data points on each surface that possess electric fields larger than the expected uniform electric field of 1.5 MV/cm, $\beta > 1$. In the table four properties are listed including the total number of points, which is the number of points on the surface for which valid data was obtained, the number of sites, the average electric field, and the average β factor, which are the number of sites on the surface which have electric fields above the lower threshold and the average electric field and β factor of all those sites. It should be noticed that there are a fewer number of valid data points on the 36 grit and 80 grit surfaces than on any of the other surfaces. This is believed to be due to their complex structure.

Table 11: Statistics of Locations on the Surface which have a β factor greater than 1

Surface	Total Number of Sites	Number of Sites	E_{Avg} (MV/cm)	β_{Avg}
36G (1.96 μm)	3932	3895	6.54	4.36
60G (1.53 μm)	4127	4121	7.02	4.68
80G (1.13 μm)	3940	3923	6.74	4.49
100G (0.60 μm)	4128	4124	7.08	4.72
400G (0.26 μm)	4119	4115	7.23	4.82
Mirror (0.065 μm)	4140	4136	7.55	5.03

It should be noticed in Figure 49 that the rougher surfaces contain a number of points in the surface where the electric fields are quite low, as indicated in blue. These lower fields are a result of the large valleys which are created in those surfaces. This is evident in Table 11 where it should be noticed that there are more sites on the rougher surfaces, in relation to the total number of sites, which do not meet the electric field criteria set. In addition the presence of these lower fields tends to offset the average electric field and β factor values so that they fall slightly below those calculated from the

smoother surface data. In the data presented in Table 12 and Table 13, the lower threshold has been raised to 5 and 10 respectively.

Table 12: Statistics of Locations on the Surface which have a β factor greater than 5

Surface	Total Number of Sites	Number of Sites	E_{Avg} (MV/cm)	β_{Avg}
36G (1.96 μm)	3932	1157	9.32	6.21
60G (1.53 μm)	4127	1424	9.15	6.10
80G (1.13 μm)	3940	1111	9.12	6.08
100G (0.60 μm)	4128	1398	9.17	6.11
400G (0.26 μm)	4119	1472	9.09	6.06
Mirror (0.065 μm)	4140	1728	9.00	6.00

Table 13: Statistics of Locations on the Surface which have a β factor greater than 10

Surface	Total Number of Sites	Number of Sites	E_{Avg} (MV/cm)	β_{Avg}
36G (1.96 μm)	3932	20	17.81	11.87
60G (1.53 μm)	4127	8	16.63	11.09
80G (1.13 μm)	3940	7	16.25	10.83
100G (0.60 μm)	4128	9	16.25	10.84
400G (0.26 μm)	4119	7	16.03	10.69
Mirror (0.065 μm)	4140	1	15.19	10.12

In Table 12, the trend in the number of sites is still slightly unexpected however; the average electric field and β factor trends start to decrease as the surface roughness decreases and in Table 13 all of the trends are decreasing, as expected. From all of the data in the tables above it appears that β factors in the teens and possibly the lower twenties are common. On stainless steel surfaces, significant shielding probably does not occur in front of individual emitters and it is even unlikely that the effect would occur across the surface since the work function and localized field enhancements are so high. The results do indicate that rougher surfaces expose larger electric field enhancements to

the gap than do those with a smoother surface. It should be remembered that only small samples of each surface were simulated and that a number of β factors larger than the maxima displayed in each table could, and almost certainly do, exist on any of the surfaces.

Additionally, though after testing, each electrode surface was observed using a scanning electron microscope, SEM, to find out if any trace of aluminum or silicon oxide from the sandpaper used to sand the surface was imbedded into the surface. A Hitachi S-4300SE/N electron microscope, shown in Figure 50, was used. The microscope has a resolution down to 1.5 nm operating at 30 kV, can observe a 120 mm specimen diameter, and has a fully automated stage [41].

Figure 50: Hitachi S-4300SE/N electron microscope [41]

Secondary electron detection was initially used to image each of the surfaces, shown in Figure 51. In the images of all the sanded surfaces, several black spots appear spread out across the surface. These spots appear to be something other than stainless steel. It is possible that these are imbedded particles of the sandpaper used to sand the

surface. Further zoomed in images of each surface are shown in Figure 52. From these images, it is clear to see that each surface has very complex structures which act as field enhancements.

Figure 51: SEM images of the various surface roughnesses (a) 36 grit, (b) 60 grit, (c) 80 grit, (d) 100 grit, (e) 400 grit, and (f) mirror (45X magnification at 10kV)

(a)

(b)

(c)

(d)

(e)

(f)

Figure 52: Zoomed in images of the various surface roughnesses (a) 36 grit, (b) 60 grit, (c) 80 grit, (d) 100 grit, (e) 400 grit, and (f) mirror (1200X magnification at 10kV)

X-Ray microanalysis was also performed on a few electrodes, using a detector manufactured by EDAX, in order to discriminate the elemental composition of the electrodes which had been sanded with each of the sandpaper grits. Additionally, each of the sandpaper grits were analyzed to determine their elemental content as shown in Figure 53 through Figure 57. From the figures it should be noticed that the 36, 60, and 100 grit sandpapers are composed of aluminum oxide while the 80 and 400 grit sandpapers were composed of silicon oxide. In the images, the red cross marks the spot where the spectrum of the figure was taken. When the spectrum of the whole image was taken, rather than just a spot, there were traces of other several other elements such as carbon, sulfur, and calcium which are believed to make up the binding material and the paper backing that hold the sandpaper together.

Figure 53: X-Ray microanalysis of the 36 grit sandpaper

Figure 54: X-Ray microanalysis of the 60 grit sandpaper

Figure 55: X-Ray microanalysis of the 80 grit sandpaper

Figure 56: X-Ray microanalysis of the 100 grit sandpaper

Figure 57: X-Ray microanalysis of the 400 grit sandpaper

Figure 58 contains the spectrum that was obtained when stainless steel was observed under the EDAX detector. As expected the main elements which make it up are chromium and iron. Additionally, one electrode that had been sanded using each sandpaper grit was also analyzed. The surface was scanned and on all of them, elements making up the sandpaper were located on the surface. Images which contain particles

believed to be part of the sandpaper, along with their spectrum, are shown in Figure 59 through Figure 63. Of course it should be mentioned that with regards to all of the surfaces, it took a considerable amount of time to locate a very small number of irregularities in the surface. Each element was by no means present in any great quantity on any of the surfaces but none the less it does show that there are traces of dielectric inclusions present which could contribute to the total electron emission into the gap. One interesting thing to notice from the plots is that the contents of both the iron and chromium increase, in relation to the elements that make up the dielectric inclusion, as the grit gets larger suggesting that the smaller and rougher papers leave behind a more significant portion of their elemental composition than do the smoother ones.

Figure 58: Typical elemental spectrum of the stainless steel electrodes

Figure 59: Location of Al, O, and C embedded in the surface of an electrode conditioned with 36 grit sandpaper

Figure 60: Location of Al, O, and C embedded in the surface of an electrode conditioned with 60 grit sandpaper

Figure 61: Location of Si, O, and C embedded in the surface of an electrode conditioned with 80 grit sandpaper

Figure 62: Location of Al, O, and C embedded in the surface of an electrode conditioned with 150 grit sandpaper

Figure 63: Location of Si and O, and C embedded in the surface of an electrode conditioned with 400 grit sandpaper

Each set of electrode sets was tested inside the water gap where the direct output of the Marx generator was applied. The peaking gap remained closed for all of these tests since the gap capacitance of these electrode sets is large. The gap separation was set to 2 mm for each test and the de-ionized water had a measured conductivity of roughly 1 $\mu\text{S}/\text{cm}$. Ten test shots were taken with each electrode set and fresh water was used when each electrode set was tested. Once each surface roughness had been tested, two additional tests which have been called the rough – smooth tests were performed. In the first of these tests, the electrode placed on the cathode side of the gap was sanded with the 36 grit sandpaper and the electrode placed on the anode side of the gap was sanded with 400 grit sandpaper. In the second of these tests, the order was reversed so that the cathode had a smooth surface while the anode had a rough surface. These tests were performed to determine the impact surface roughness has on a particular polarity. Ten test shots were taken with each electrode set in each of the two configurations. The results obtained from each electrode set and configuration will be documented and discussed in the next chapter.

4.2 Electrode Material Preparation

The second set of tests that were conducted are those that were intended to determine the impact of electrode material on the dielectric strength of water. The smaller Bruce profiled electrodes, which were mentioned earlier and shown in Figure 29, were used for these tests. All of the electrodes were machined from stainless steel and the ion deposition setup discussed earlier was used to apply a layer of the various metallic and oxide materials to the surface. Prior to depositing each layer, all of the electrodes were

mechanically sanded with a 2000 grit aluminum oxide paper and buffed with buffing compounds so that a 50 – 200 nm surface roughness was obtained. The electrodes were then cleaned with both acetone and methanol to mechanically clean the surface of any contaminants. Once vacuum was pulled, each electrode was then subjected to an ion beam from the cleaning thruster for roughly 15 minutes. Keep in mind that Xenon was used as the neutral gas in both the ion sources and the neutralizer. The cleaning ion source was operated with a discharge voltage and current of 225 V and 0.73 A. Once the cleaning process was completed, the larger ion source was operated to apply the layer applications. Table 14 displays each of the materials that were deposited, its work function, the discharge voltage and current that the ion source was run at, and the time that each electrode was subjected to the deposition.

Table 14: Sputter Deposition Parameters

Target Material	Work Function (eV)	Discharge Voltage (V)	Discharge Current (A)	Time (hr)
Cu	4.5	300V	1.66	2
W	4.55	300V	1.66	3
ZnO	5.5	300V	1.66	6
Ion Beam Only (SS)	5.05	225V	0.73	0.75

In each case it is believed that a surface layer of roughly a few hundred nm was applied to the surface. Early in the setup process, when a small ion source like the one used for cleaning the surface was used as the deposition source also, copper was deposited onto an electrode that was half covered with Polyimide dielectric tape. This was done to obtain an edge of deposited material and the edge was then looked at using the NT1100 interferometer to measure the height of the deposition layer. Figure 64

displays an image of the electrode, a 3D contour plot of the surface, and an x,y plot of the surface which shows a deposition layer that is roughly 155 nm high.

Figure 64: Ion deposition (a) Photograph of the electrode which was half covered in polyimide tape, (b) surface contour image, and (c) x,y data plot of the surface

After the material tests were conducted and a trend was noticed, it was desired to test additional materials, however the sputter deposition setup had been disassembled so the electrodes with a material insert mentioned earlier as well as some fabricated entirely from the desired material were made. Those made with an insert include Molybdenum, Mo, which has a work function of 4.2 eV and Nickel, Ni, which has a work function of 4.9. These were chosen to fill in the work function gap below copper and between

tungsten and stainless steel. Electrodes fabricated entirely from aluminum, with a work function of 4.2 eV, and copper, with a work function of 4.5 eV were also tested. Images of all the electrodes are shown in Figure 65. Five test shots were taken with each electrode set and a statistical average of the breakdown data was calculated. The results of all the material tests will be discussed later.

Figure 65: Various material electrodes

4.3 Water Conductivity Preparation

The third set of tests that were conducted were those that were intended to determine the impact of water conductivity on the dielectric strength of water. In this set of tests the smaller Bruce profiled electrodes fabricated entirely from stainless steel and copper were used. The surface roughness of each electrode was also varied so that the impact of water conductivity in conjunction with surface roughness could be tested. The 36 grit, 80 grit, and 400 grit sandpapers were used to test the surface roughness equal to

roughly 1.96 μm , 1.13 μm , and 0.26 μm . Figure 66 contains a photograph of all of the electrodes used in these tests.

Figure 66: Copper and stainless steel electrodes used in the conductivity tests

The water conductivities under test ranged from 1 $\mu\text{S}/\text{cm}$ to 38.5 $\mu\text{S}/\text{cm}$ and are listed in Table 15. Cupric Sulfate, CuSO_4 , crystals were diluted in roughly 40 gallons of water to increase its conductivity. The amount of CuSO_4 used to create each water conductivity value is also listed in Table 15. An Orion, model 162, benchtop conductivity meter was used to measure the conductivity of the water prior to each test. The device can accurately measure conductivities that fall in the range of 0.0 $\mu\text{S}/\text{cm}$ to 500,000 $\mu\text{S}/\text{cm}$ with a resolution of 0.1 $\mu\text{S}/\text{cm}$ [42]. Five test shots with each electrode set were tested with each water conductivity value and a statistical average of the results were taken. The results will be presented in the next section.

Table 15: Conductivity Measurements

Conductivity ($\mu\text{S/cm}$)	Cupric Sulfate (g)	Gap Resistance (Ω)
1.0	0.00	40000
3.5	0.25	11430
11.0	1.35	3636
20.0	2.35	2000
38.5	5.25	1039

4.4 Aluminum Etched Surface Preparation

The last set of tests were intended to test the impact of electrodes with a uniform field enhancement pattern as opposed to the random ones that were applied through mechanical sanding. Trenches across the electrode surface area, that are roughly 25 μm apart and 100 μm deep, make up the uniform field enhancement pattern. The trenches were applied to the electrode in two manners. In the first, a chemical etch process was used. In the second, the trenches were milled out using an endmill bit on a conventional PC board router. Pictures of the electrodes, to which the uniform field enhancement patterns were applied, are displayed in Figure 67. Under a profilometer, the chemically etched electrode has what appears to be a structured trench pattern though; to the eye the electrode had a very odd appearance and texture. The surface did not reflect enough light to take any images with the optical interferometer however the surface of the router etched electrode did, seen in Figure 68. It should be noticed that this method of application provides a very uniform trench pattern with sharp peaks. In order to quantify the enhancement that such a pattern creates, an electric field simulation of the surface was performed. Images of the electric field simulations are shown in Figure 69.

Figure 67: Uniform field enhancement pattern applied through chemical etching (a and b) and through milling (c and d)

Figure 68: Optical interferometer images of the uniform field enhancement pattern that was applied using a PC board endmill (a) contour map and (b) x,y profile

Figure 69: Electric field simulations of the router etched surface (a) scale and (b and c) surface images

Oddly enough, the trench pattern does not provide field enhancements that are all that large. As shown in Table 16 and Table 17, the peak β factor is roughly 54 and there are only a few sites on the surface where β 's greater than 25 exist. In the statistics shown in the tables, the edge effects were removed in a fashion similar to that used earlier. Five test shots were taken with each surface and a statistical average of the results will be shown in the next section.

Table 16: Peak Electric Field and β factor on the Etched Surface

Surface	EMax (MV/cm)	β Max
Etched Al	82.02	54.68

Table 17: Statistics of Locations on the Etched Aluminum Surface with Various Lower β Thresholds

Etched Al	$\beta > 1$	$\beta > 5$	$\beta > 10$	$\beta > 25$
Total Number of Sites	7415	7415	7415	7415
Number of Sites	3896	667	84	4
E_{Avg} (MV/cm)	5.3	11.83	21.08	54.49
β_{Avg}	3.54	7.89	14.06	36.32

4.5 Shadowgraph Imaging

The last sets of tests conducted were intended to possibly capture evidence of bubble formation prior to breakdown. A shadowgraphy setup was put together to capture images of the gap during pulse application and prior to bulk breakdown. A schematic of the experimental setup is shown in Figure 70.

Figure 70: Shadowgraph imaging setup

As seen in the schematic, the output of the capacitive voltage divider was used to trigger a pulse generator and gate the camera. The pulse generator also provided the ability to delay the signal so that images at various times after pulse application could be taken. The setup was contained within a mobile Faraday cage to prevent interference from the pulse into the camera setup. An Andor ISTAR ICCD camera was used to image the gap. A filter, which is not shown in the schematic, was put inline with the camera lens and the gap to filter out the light from the laser. The images were taken of a point – plane

geometry, which is shown in Figure 71. The point had a diameter of roughly 1.5 mm and the plane electrode is one of the smaller Bruce profiled stainless steel electrodes. The captured images will be shown in the next chapter.

(a)

(b)

Figure 71: Electrodes used in the point – plane geometry (a) point and (b) plane

CHAPTER V

EXPERIMENTAL RESULTS

5.1 Typical Voltage and Current waveforms

Figure 72 displays typical voltage and current waveforms recorded using the capacitive voltage probe and Pearson current monitor discussed in the experimental setup. These were measured when the direct output of the Marx was applied to the test gap.

Figure 72: Typical voltage and current waveform

In Figure 72, the arrival of the pulse at the gap occurs at roughly 200 ns. The gap is charged up until roughly 600 ns when bulk breakdown occurs and a rise in the current seen at the anode is increased to follow the remaining voltage pulse. This particular shot was taken when the smaller electrode sets were used across a 2 mm gap. It is representative of all the shots recorded in which the direct output of the Marx was

applied, however the one factor that varied between the smaller and larger electrode sets is the amount of displacement current that was visible prior to breakdown. When the smaller sets were used, the anode side of the gap floated up to roughly 45 kV through displacement current but remained nearly the same for all of the tests in which they were used and was essentially neglected. In order to accurately measure the effect of electrode area, the current measured at the anode prior to breakdown must be taken into account. As the effective area of the electrodes is increased, the capacitive coupling across the gap increases and therefore a larger amount of current was measured at the load prior to breakdown. The peak voltage across the gap was recorded as the difference between the maximum value of the voltage measured by the capacitive probe at the cathode and the voltage at the anode prior to breakdown, which is the product of the current measured by the Pearson current monitor and load resistor it is placed around. Similar increases in the current were observed at the anode when the smaller electrode sets were used and the water conductivity was increased. As the conductivity is increased an increased amount of conduction current is measured in conjunction with the normal displacement current. In these tests, the current measured was normalized to the current recorded during the de-ionized water tests and the breakdown voltage was recorded as the difference between the peak voltage recorded at the load due to conduction current and the maximum voltage recorded by the capacitive probe prior to breakdown.

5.2 Surface Roughness and Area Tests

As mentioned already, there is an increase in the displacement current seen at the load as the electrode's effective surface area is increased. The average voltage seen at the load preceding breakdown was roughly 55 kV for the smallest area electrode set and roughly 95 kV for the largest area electrode set. Figure 73 displays the results obtained from the six larger electrode sets when the surface roughness average was varied and Figure 74 displays the results obtained from the rough-smooth tests. Table 18 and Table 19 list the standard deviations of each of the data points shown in Figure 73 and Figure 74, respectively. The equations describing the area dependence of each surface finish are also displayed in the tables.

Figure 73: Dielectric strength vs. electrode surface area

Figure 74: Dielectric strength vs. electrode surface area

Table 18: Standard Deviations of the Surface Roughness and Area Test Results
(units of MV/cm)

Area	36 G	60 G	80 G	100 G	400 G
0.44	0.113	0.118	0.070	0.157	0.139
3.50	0.124	0.109	0.086	0.173	0.161
39.00	0.100	0.112	0.081	0.099	0.083
53.97	0.110	0.093	0.043	0.147	0.146
66.24	0.139	0.081	0.055	0.091	0.091
76.31	0.087	0.088	0.121	0.082	0.126
Area Term	$1.03A^{-0.0315}$	$1.06A^{-0.0309}$	$1.09A^{-0.0301}$	$1.14A^{-0.0276}$	$1.17A^{-0.0186}$

Table 19: Standard Deviations of the Rough Smooth Test Results
(units of MV/cm)

Area	RC – SA	SC- RA
0.44	0.154	0.088
3.50	0.175	0.089
39.00	0.113	0.110
53.97	0.166	0.075
66.24	0.134	0.065
76.31	0.095	0.082
Area Term	$1.07A^{-0.032}$	$1.11A^{-0.0247}$

In analysis of the data shown in Figure 73 there is clearly a decreasing holdoff voltage trend as the electrode surface roughness and surface area increase. As expected there is also a moderate increase in the area dependence as the surface roughness is increased. The average electric field difference between the smoothest and roughest electrodes is roughly 175 kV/cm and the area dependence term is increased by roughly 1.7 times. As stated in the introduction, the increasing surface roughness and areas impact should be closely related. As the electrode surface area increases, the number of microprotrusions that exist on the surface, which are substantial enough to initiate a breakdown event, increases. The increased surface roughness only amplifies the likelihood of such a microprotrusion existing thereby decreasing the dielectric strength. On the smoother surfaces, it is possible that shielding plays some very minor role in their higher dielectric strength because these surfaces have a more uniform electric field across their surface and a reduced number of localized field enhancements. From the field simulations performed earlier, there is a decreasing trend in the peak field enhancements which are localized across the surface as the surface roughness is decreased resulting in an increased dielectric strength. It was shown earlier that there are embedded particles of each of the sandpaper grits used to mechanically condition the surface. In all of the tests it is possible that emission from those materials contributed to the breakdown event, though it was probably not a dominant effect by any means under these conditions.

With regards to the rough – smooth tests, there is again both a decrease in the holdoff electric field and an increase in the exponential area dependence as the surface roughness is increased on the cathode side of the gap. The smooth cathode – rough anode

tests show both a decreased holdoff electric field and an increased exponential area dependency term from that obtained in the original smooth tests. The data appear to almost fit the trend obtained from the 100 grit surfaces. The data obtained from the rough cathode – smooth anode tests show an increased holdoff voltage and an increased exponential area dependency term from that obtained from the original rough tests. These results appear to almost mirror the data obtained from the 60 grit surfaces. All of the results, except for the increased area dependency on the rough cathode – smooth anode tests, indicate that the effect of surface condition is most dominant on the cathode but also show that the anode surface condition has a significant impact.

5.3 Electrode Material Tests

Two sets of tests were conducted into the effect electrode material has on the dielectric strength of water. The first set involved testing the material surfaces which were applied to stainless steel electrodes through ion beam deposition. The second set tested some of the ion deposited materials as well as those which were fabricated entirely of or had an insert of the material to be tested. The results of these tests are discussed in the following sections.

5.3.1 Ion Deposited Surfaces

Figure 75 displays the results that were obtained from the various electrode materials which were deposited onto stainless steel electrodes using the ion deposition setup. The dielectric strength has been plotted versus material work function and the results show a strong decreasing trend in the dielectric strength as the electrode work function is increased. Almost a 15% decrease is noticed between copper electrodes and

those coated with zinc oxide. It should be remembered that these surfaces were deposited onto stainless steel electrodes which had a mirror finish giving the deposited surface a mirror finish as well. Since the surface is mirrored, the peak β factors should be small and the emission into the gap from field emission should be low as well. The results suggest that as the work function is lowered, there is a better chance of shielding occurring across the surface. These results prompted additional materials tests which will be discussed next.

Figure 75: Dielectric strength vs. work function of the ion deposited surfaces

5.3.2 Additional Material Surfaces

The results of the material tests discussed in the previous section revealed an interesting trend suggesting that the dielectric strength of water could be increased even further if a metal which has a work function lower than that of copper, 4.5 eV, is used. Because of this, additional tests were carried out to test materials which have a lower work function than copper. Prior to conducting these tests, the ion – deposition setup used

to conduct the earlier material tests was disassembled and so the material insert electrodes, constructed of molybdenum and nickel, as well as others fabricated entirely from the material to be tested, stainless steel, copper, and aluminum, were used in addition to some of those already created using ion deposition, tungsten and zinc oxide. It was desired to test a material with a work function lower than 4 eV however, the majority of materials with this property are in the Lanthanide series and are heavily reactive with water. Molybdenum and aluminum were chosen to fill in the curve below copper and each have a work function of 4.2 eV. Nickel was also added to fill the gap between tungsten and stainless steel which has a work function of 4.9 eV.

Two sets of tests were performed. In the first, all of the materials were tested with a mirror finish. In the second, all of the electrodes, with the exception of tungsten and zinc oxide, were tested with a rougher surface which was applied through sanding the surface with an 80 grit sandpaper. The surface roughness average of all the surfaces was roughly 1.13 μm when sanded with this grit of sandpaper. The results of the tests are shown in Figure 76 through Figure 80. In all of the plots, the triangular symbols represent the data collected from testing the mirror surfaces while the circular symbols represent the data collected when testing the rougher surfaces sanded with the 80 grit sandpaper. Additionally, the red trendline and error bars correspond to the data obtained from the mirror surfaces, while the black trendline and error bars represent the data collected from the surfaces sanded with the 80 grit sandpaper.

Figure 76: Dielectric strength vs. material work function

For the most part, the results obtained in Figure 76 are as expected. First, there is a decrease in the dielectric strength for each material as the surface roughness average was increased. Also, there is still a strong decreasing trend in the dielectric strength as the work function is increased. Almost a 24% decrease was recorded between the electrodes with a molybdenum insert and those coated with zinc oxide while an 8% decrease was observed between the molybdenum and copper electrodes. The only material that severely disrupts the trend is nickel. Nickel had a poor performance in both tests and the reason for this is unclear. The highlight of these tests is the strong performance of molybdenum. As hoped, it provided a much higher dielectric strength than that of copper. It is again believed that on these smoother surfaces, the lower work function enables shielding to occur in front of the electrode surface thereby raising the water's dielectric strength. As the surface roughness is increased, from the mirror to 80 grit surfaces, more localized field enhancements are present across the surface, increasing the likelihood of a bubble or electronic mechanism initiating from those points. This, in conjunction with a

reduced shielding effect, reduces their holdoff strength with respect to the mirror surfaces, however the shielding effect is still visible as the work function is decreased. In order to determine if there is another significant material property which impacts the dielectric strength, other material properties were considered. Some of the possible properties that were considered are the material's melting point, hardness, density, and specific heat. Plots of the holdoff electric fields for each material versus each of these material properties are shown in Figure 77 through Figure 80.

Figure 77: Dielectric strength vs. material melting point

Figure 78: Dielectric strength vs. material hardness

Figure 79: Dielectric strength vs. material density

Figure 80: Dielectric strength vs. specific heat

From Figure 77 and Figure 80, it appears that there is a small upward trend in the holdoff electric field strength as the melting point and density of the material is increased. A near level trend is present when plotted with respect to the material hardness and a downward trend is present with respect to increasing specific heat. The melting point, density, and specific heat have a significant impact on the time delays to electrical explosion which could explain their impact though it should be expected that dielectric strength is increased as both get larger though the trend observed with respect to specific

heat is decreasing. The reason for this is not quite clear. There is no trend observed in any of the ladder plots which indicate a more dominant impact on water's dielectric strength than that of the materials work function.

5.4 Water Conductivity Tests

In this set of tests, the impact of water conductivity in conjunction with various electrode surface roughness was tested. First as the water conductivity was increased, the gap became less resistive and an increased amount of conduction current was observed prior to breakdown, which is in addition to the usual gap displacement current. With each water conductivity tested, between 1 $\mu\text{S}/\text{cm}$ to 38.5 $\mu\text{S}/\text{cm}$, the conduction current across the gap increased but remained small enough that a significant differential voltage across the gap was observed prior to breakdown.

Figure 81 displays typical voltage waveforms obtained at the cathode and anode sides of the gap when water with conductivities of 1, 3.5, 11, 20, and 38.5 $\mu\text{S}/\text{cm}$ were tested. The figure is hard to read but two things should be observed from the plots. First, as the water conductivity is increased, the gap initially looks less resistive and it appears that the water conducts the charge longer before it can no longer handle the current and breakdown occurs. This results in an increased time to breakdown and breakdown voltage. Second, as the water conductivity is increased, the voltage observed at the anode side of gap prior to breakdown gets larger as well. When water conductivities of 1, 3.5, and 11 $\mu\text{S}/\text{cm}$ were tested, the increase in the breakdown voltage recorded at the cathode is larger than the voltage increase observed at the anode prior to breakdown, thus the differential breakdown strength increased as the conductivity was raised within this

range. When the conductivity was tested above 11 $\mu\text{S}/\text{cm}$, the voltage increase seen at the anode prior to breakdown was larger than the increase in the breakdown voltage seen at the cathode and consequently the differential breakdown strength started a downward trend. The results of the conductivity tests are shown in Figure 82 through Figure 90 and a number of interesting trends should be observed.

Figure 81: Voltage recorded during testing of the 1, 3.5, 11, 20, and 38.5 $\mu\text{S}/\text{cm}$ conductivities on the (a) cathode and (b) anode sides of the gap

Figure 82 through Figure 86 compares the dielectric strengths obtained from copper and stainless steel electrodes for each of the various conductivities and surface roughnesses. When the water conductivity was low, there was a substantial increase in the dielectric strength when copper was used as opposed to when stainless steel was used. As the conductivity of the water was increased, the improvement of copper over stainless steel was decreased and in some cases reversed. In all of the tests, there is a decreasing trend as the surface roughness of the electrodes was increased. The effect of surface roughness on stainless steel electrodes was decreased as water conductivity was increased. In fact it almost appears linear when the water conductivity was 38.5 $\mu\text{S}/\text{cm}$.

In the case of copper, the impact of surface roughness remains evident when tested in all of the different conductivities. The standard deviations of the points appear to decrease as the water conductivity is raised.

Figure 82: Dielectric strength vs. R_A (1 $\mu\text{S}/\text{cm}$ conductivity)

Figure 83: Dielectric strength vs. R_A (3.5 $\mu\text{S}/\text{cm}$ conductivity)

Figure 84: Dielectric strength vs. R_A (11 $\mu\text{S}/\text{cm}$ conductivity)

Figure 85: Dielectric strength vs. R_A (20 $\mu\text{S}/\text{cm}$ conductivity)

Figure 86: Dielectric strength vs. R_A (38.5 $\mu\text{S}/\text{cm}$ conductivity)

Figure 87 and Figure 88 display the results obtained from each of the different surface roughnesses tested on stainless steel and copper electrodes versus the water conductivity. As mentioned already, as the water conductivity is increased from 1 $\mu\text{S}/\text{cm}$ to 11 $\mu\text{S}/\text{cm}$, the increase in the breakdown voltage at the cathode is larger than the increase in the anode voltage, caused by a larger conduction current flow, and the dielectric strength increases. This trend is reversed between 11 $\mu\text{S}/\text{cm}$ and 38.5 $\mu\text{S}/\text{cm}$.

Figure 87: Dielectric strength vs. water conductivity (stainless steel electrodes with various R_A 's)

Figure 88: Dielectric strength vs. water conductivity (copper electrodes with various R_A 's)

Figure 89 and Figure 90 compare the results obtained from each of the different surface roughnesses of stainless steel and copper electrodes tested in each of the water conductivities. As mentioned already, the dependence of surface roughness on stainless steel electrodes decreases as water conductivity increases while it remains present when copper electrodes were tested. The current density emitted from field emission is likely incredibly large for the rougher copper surfaces which may be responsible for this trend in all conductivities while it may be less dramatic for the rougher stainless steel surfaces. Despite the latter trend, it appears from the results that as the water conductivity is increased, the breakdown event is more heavily dominated by processes which occur in the bulk water, rather than events which occur primarily at the electrode / water interface.

Figure 89: Dielectric strength vs. R_A
(stainless steel electrodes tested in various conductivities)

Figure 90: Dielectric strength vs. R_A
(copper electrodes tested in various conductivities)

5.5 Aluminum Etched Surface Tests

The results of the etched aluminum surface tests, in comparison to those obtained from the aluminum surfaces tested earlier are shown in Figure 91.

Figure 91: Etched aluminum surface test results

As shown in the figure, the aluminum surface with a mirror finish still provided the highest dielectric holdoff strength. The most important thing to notice is that the etched aluminum surfaces exhibited a higher dielectric strength than the 80 grit surface finish. The chemically etched surface had the highest standard deviation, though the reason for this is unknown, while the mirror surface had the smallest. On the surfaces which have uniform field enhancement patterns, the charge injected into the dielectric should remain consistent across the electrode surface. This minimizes the number of localized field enhancements thereby lowering the probability of a bubble or electronic mechanism initiating. The more uniform nature of the electric field across the surface could improve the likelihood of shielding occurring in front of the electrode surface. This consequently improves the dielectric strength of the etched surfaces in comparison with the random surface roughness patterns where charge injection is more localized.

5.6 Shadowgraph Imaging

As mentioned in the description of the setup back in Chapter IV, the ICCD camera was gated at various times after pulse application. Figure 92 and Figure 93 display the images that were taken with cathode and anode point configurations. In all of the images, the ICCD camera was gated anywhere from 150 ns to 180 ns. In the caption of each figure, times are listed which correspond to the time difference between when the camera was gated and bulk breakdown occurred.

Figure 92: Cathode point discharge development at time before breakdown (a) reference, (b) 300 ns, (c) 195 ns, (d) 95 ns, (e) 70 ns, and (f) 10 ns

In Figure 92, it should be observed that as the camera is gated closer to bulk breakdown, there is a fuzzy shadow that emerges at the tip of the cathode point. It appears to be a density change in the water which has caused a change in the index of refraction. This is likely a result of charge injection from the cathode and could be the

start of bubble formation. The cloud gets larger until 95 ns before breakdown where an arc appears to have formed. At 10 ns prior to bulk breakdown, the arc has fully bridged the gap.

Figure 93: Anode point discharge development at time before breakdown (a) reference, (b) 305 ns, (c) 283 ns, (d) 275 ns, (e) 270 ns, and (f) 200 ns

In Figure 93, which displays the images taken of the anode point configuration, the shadow seen in the cathode point configuration is absent. This confirms that the shadow is not caused by the Kerr effect. In this configuration, there appears to be arc development as early as 300 ns before bulk breakdown. The arc grows quickly and is quite large as early as 200 ns before full gap closure.

5.7 Post Electrical Breakdown Imaging

After all of the tests were conducted, interferometry and SEM imaging was performed on a few of the locations where breakdown had occurred on stainless steel electrodes. A few of the images that were taken are shown in Figure 94. In each image, it

is clearly shown that a large amount of material was ejected from the electrode surface and a large crater was created. Each of the craters is roughly 25 μm and 30 μm deep. It can also be seen that in some locations, the edge of the crater has lifted the surface of the electrode, thereby creating new microprotrusions in the surface.

Figure 94: Interferometry images of breakdown locations

Figure 95: SEM images of breakdown locations

CHAPTER VI

SUMMARY AND CONCLUSIONS

It has been shown in this dissertation that electrode surface area, roughness, material, and water conductivity all have a profound impact on water's dielectric strength. When high fields are applied to the gap, electrons are injected into the water dielectric medium from the cathode through high field emission, explosive emission, and emission from dielectric inclusions. All of these emission processes are responsible for initiating an electronic or bubble mechanism which eventually leads to the bulk breakdown of the liquid dielectric. It has been shown through simulation that under certain circumstances, conditions can occur which allow for the development of localized electric fields in the water on the order of the applied field. These electric fields are formed as a result of space charge that is emitted into the gap and these electric fields may be responsible for shielding of the electron emitters on the surface. These shielding events may help to increase the dielectric strength of water as surface roughness is decreased and as electrode materials with a lower work function are used.

It has been shown that as the electrode surface area is increased; there is a decrease in the holdoff voltage which is exponentially proportional to the electrode's effective surface area. Additionally it has been shown that as the electrode surface roughness average is increased, from 0.25 μm to 1.96 μm , the dielectric strength of water is decreased, by almost 125 kV/cm. Additionally, the electrode surface area dependence is increased as the electrode surface roughness gets larger. A strong decreasing holdoff trend has been observed with increasing material work function. A decrease of almost

24% has been observed when molybdenum electrodes were used, which have a work function of 4.2 eV, as opposed to when electrodes coated with zinc oxide were used, which have a work function of 5.3 eV. Shielding across the electrode surface is believed to play a more significant role as the electrode work function decreases and this is believed to be cause for the increasing dielectric strength as the work function decreases. The results of the water conductivity tests have revealed an increase in the dielectric strength as the conductivity is increased from 1 $\mu\text{S}/\text{cm}$ to 11 $\mu\text{S}/\text{cm}$ and decreased from 11 $\mu\text{S}/\text{cm}$ and 38.5 $\mu\text{S}/\text{cm}$. The results indicate that as the water conductivity is increased, the impact of electrode surface roughness and material is decreased and processes that occur in the bulk water medium play a more significant role. The results of etching a uniform field enhancement pattern in aluminum indicate that the uniform field enhancement pattern exhibits a slightly higher dielectric strength than provided by a non-uniform field enhancement pattern, obtained through mechanical sanding. Water, with its strong electrical and physical properties, is an ideal candidate for use as an insulator or switching medium in pulsed power machines and the results of this paper suggest that there are in fact ways of making its strength even stronger.

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APPENDIX A

MARX GENERATOR REFURBISHMENT

This section documents the changes made to the Marx generator during the experimentation and also to serve as a manual for future users. Inside the generator, there are three main sections which include the capacitor stack, the charging components, and the charging inductor. These are shown in Figure 96 and Figure 97 below.

Figure 96: Marx generator capacitor stacks

Figure 97: Charging components

On the charging section, there are several components which include two 50 kV power packs, two isolation relays, two charging inductors, a voltage dump, two dump resistors, and two 387 M Ω metering resistors. The left power pack is used to charge two stacks of capacitors with a positive DC polarity. The right power pack is used to charge the other two stacks of capacitors with a negative DC polarity. The isolation relays are used to isolate the power packs from the capacitor stack prior to erection. This is done by switching the charging switch on the Marx control panel to fire prior to erecting the Marx. This is shown in Figure 98.

Figure 98: Marx control panel

The charging inductors serve as an additional isolation mechanism during erection. Each inductor is bolted on to a screw on the plastic box seen between them. Two long

charging cables are then used to conduct the charge from the inductors to each of the capacitor banks. These large cables were added so that either the capacitor bank or the charging station could be lifted out of the oil filled tank for repair without having to drain the 3000 gallons of oil which insulates the Marx. The dump is used to dump the charge from the capacitors and is activated when the charging switch on the Marx control panel is moved into the dump position.

Three changes were made to the charging section after the picture above was taken. First, the vacuum relays used to isolate the power packs from the capacitor stacks during erection were replaced with mechanical dumps. When both dumps are closed, the power packs are connected to the capacitors and charging can occur. When the dump is open, the power packs are isolated. Second two 75 k Ω wire wound resistors were added between the power pack and each of its isolation dumps for additional protection of the power packs. Last, the water resistors used as dump resistors were replaced with two 10 k Ω wire wound resistors.

On the capacitor stack there are two columns of capacitors. Each capacitor package has two capacitors built into it resulting in 4 capacitor stacks. The two front stacks and the two back stacks are each separated by an air filled spark gap. Additionally each opposing stack is charged to an opposing polarity resulting in a differential voltage of twice the charge voltage across each spark gap. An overhead schematic of the manner in which they are charged is shown in Figure 99.

Figure 99: Charging configuration

Each connection is made with a banana plug tied to the charging cable as shown in Figure 100. To swap the output pulse polarity, the charging lines to the capacitor stacks simply need to be swapped.

Figure 100: Connection between charging components and the capacitor stacks

Each capacitor package in a stack has a resistor between them used for charging and isolation when the Marx is erected. Initially, 5 k Ω water resistors were used between each capacitor however they had a tendency to leak over time. It was a desire to remove all of the water resistors so they were replaced with 10 k Ω , 100 W wire wound resistors

manufactured by Ohmite, model number L100J10K. These resistors have overall dimensions of 15 cm by 1.27 cm and were encased in 3.7 cm diameter PVC pipe and potted in epoxy to prevent mechanical destruction. Additionally there are two more stacks of resistors between each capacitor ground to serve as ground isolation during erection. The bottom resistor is connected to the ground of the tank by two long copper braids which are contained in polyvinyl tubing. The lengths of the lines are long enough that the capacitor stack can be lifted out of the tank and then disconnected. Figure 101 and Figure 102 displays what the final result looked like after the resistors had been connected in place.

Figure 101: Capacitor Stack lifted out of the tank

Figure 102: Potted resistor

Though this seemed like a good idea at the time, it only took five shots to find out that it was not. Figure 103 shows what some of the potted wire wound resistors looked like after the five shots were taken.

Figure 103: Remains of a destructed electrode

From the image it can be seen that nothing of the resistor remains except the connection terminals and the epoxy that once went through the resistor's hollow center. Since, it was obvious that these resistors would not work two options remained. Either put back the water resistors that were initially there or replace the resistive charging and isolation with a single charging resistor and inductive isolation. Since it was not really known how the ladder would respond, the water resistors were replaced but this time they

were rebuilt so that each resistor has 10 k Ω of resistance and new polyvinyl tubing was used. Additionally each hose clamp was tightened as much as possible so as to hopefully prevent any water from leaking out. Tubing on the upper most resistors was left higher than the oil level so that the water level can always be monitored.

All of the wiring inside the control panel and the Marx was also redone. Two cables, which each contain 8 colored wires inside, were used to connect the control panel to the components within the Marx. These cables have been labeled Line 1 and Line 2. Line 1 was used to wire up the positive side of the charging section and Line 2 was used to wire up the negative side of the charging section. Table 20 and Table 21 list the color within each line and what connections it makes to the Marx. Figure 104 displays a wiring schematic.

Table 20: Positive Side Wiring Description

Line 1	Connection
Brown/Red	AC Line to Positive Power Pack
Yellow/Green	AC Line to Positive Power Pack
Orange	Voltage of the Positive Power Pack
Blue	Current of the Positive Power Pack
White	AC Line to Isolation Dumps
Bare Wire	Ground of the Tank

Table 21: Negative Side Wiring Description

Line 2	Connection
Brown/Red	AC Line to Negative Power Pack
Yellow/Green	AC Line to Negative Power Pack
Orange	Voltage of the Negative Power Pack
Blue	Current of the Negative Power Pack
White	AC Line to Voltage Dump
Black	Common AC Line of the Isolation and Voltage Dumps
Bare Wire	Ground of the Tank

Figure 104: Wiring diagram of the Marx control panel and charging components

APPENDIX B

SURFACE MODELING USING TURBOCAD

The following list of steps should be used to generate 3-D solid models in Turbocad v.11 using 3-D surface points:

1. Collect the data in either tab, comma or space delimited format and save the data with a *.txt file convention.
2. Using the TurboCad's accompanying Import Points program, open the *.txt file that contains the data and:
 - a. The program will prompt for the type of value delimitation, so select the appropriate one and select "next".
 - b. At this point the points will be imported and displayed in a table format. If the points look correct then click "finish".
 - c. Next the data will again be displayed in a larger table format and what appears to be a 1-D image of the points will be displayed in the upper right hand corner
 - d. The last step within this program is to export the points to a *.dxf format. This is done by clicking on the "create geometry" menu bar followed by "write dxf" and finish by selecting "points". A file save dialog box will open. Type in the desired file location / file name and select save.
 - e. Close the import points program
3. Open TurboCad
4. Select the "insert" menu followed by "file". A file dialog box will open. Select the *.dxf file that was created using the Import Points program and click "open".
5. The data will appear as a scatter plot of points.
6. Select all the points and then click on the "surface modeling" menu and select "create triangles". This will triangulate the surface. This process takes a couple of minutes depending upon the number of points and it is best to minimize the application while the triangulation is being performed.
7. Once the triangulation is done, the points can either be deleted or applied to another layer whose visibility should be turned off.
8. Next, select the triangles and then click again on the "surface modeling" menu. This time click the "select triangles" option. This will again take a couple of minutes. It is somewhat confusing to realize when this process is done.
9. The next step is again to click on the "surface modeling" menu and this time click on "create solid". If step 8 is not completed this step will not be available for clicking so when it becomes available that is when you know step 8 is complete. When it is complete and "create solid" is available and clicked, a dialog box will come up asking what layer to put the solid on and what the upper and lower "z" ranges should be. Select automatic and click ok. This step will take the longest amount of time, as long as an hour or two in some circumstances.
10. Once step 9 is done, delete the triangles or put them on another invisible layer.

11. The final step is to select the solid and right click the mouse. Select “properties” and then click on “3-D” which appears as a property in the left hand column. Two options, “surface” or “solid” will be visible and “surface” will be selected. Click on “solid”. The computer may appear to have locked up when you do this. Simply wait a minute. The computer will become responsive and click it again. Then click “ok”. This process will again take a few moments.
12. At this point a solid model has been created. One error that occurred frequently is that at the conclusion of all these steps the solid would have defects. The easiest way to determine if the solid was generated is to look at a front and side wire-frame view. There should be vertical lines connecting the corners. If there are any additional lines connecting the upper portion of the solid to the lower portion then the model is defective and will not import into Maxwell later. If only 4 lines connecting the top and bottom in the corners are visible then the solid is fine.
13. The last step, if the file is to be made available for importing into Maxwell, is to save the solid in an *.sat file format. Click “file” then “save”. The save dialog box will open. Select the file location and type the desired file name. Prior to saving click on setup. Make sure the sat file format chosen is compatible with the version of Maxwell being used. In my tests, I selected version 5 or 6 to ensure success.