# IMPULSE ELECTRICAL BREAKDOWN OF HIGH-PURITY WATER

by

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(ABSTRACT)

Experiments have been conducted on the electrical breakdown of high-purity water and water mixtures. The electrical regime of interest has been carefully defined and documented to consist of electrical impulses with approximately microsecond rise time and fall time greater than 65 microseconds, on approximately 81-square-centimeter-area planar electrodes with a dielectric gap of approximately one centimeter. The results of over 25,000 shots by a Marx generator have been distilled into database form in an Excel spreadsheet and analysis performed to try to find patterns or indirect evidence into the nature of the breakdown-initiation process.

An extensive review of all the experiments, which had been conducted over eight years by the Naval Surface Warfare Center and which had been designed to find the largest water-breakdown fields, was conducted with the intention of delineating the physical factors that led to breakdown. A variety of theoretical models of breakdown initiation were compared to the data, until it became clear that many of the breakdowns were dominated by impurities of various sorts. An extensive study of old and new experiments led to a more detailed understanding of the phenomenology of impurity-dominated water breakdown (such as the process of "conditioning" the electrodes and hysteresis) and the proposal of a number of new experiments to further characterize the

intrinsic role of electrode materials on determining high-electric-field dielectric breakdown in water.

**Acknowledgments**

My loving wife, Sharon Todd Gehman, and I met in 1973, became engaged in 1974, and married in 1976. For all that time, she has known of my personal dream to earn a Ph.D. in physics; she has constantly offered her support, encouragement, and prayers. Love like that has no name; words are an insufficient vehicle to offer thanks, but they're all I have. Thank You.

The first of our five children started to arrive in 1977. They have never known a father who wasn't spending much of his spare time pursuing an academic degree. They have been supporting and understanding.

My parents gave me love and a determination to excel to the best of my abilities. My brother Brian has always been the best.

I have had the great fortune to have been surrounded by many good people through out my life: starting with relatives, neighbors and friends in Lancaster, Pennsylvania, then Blacksburg, Virginia, and now Dahlgren and King George, Virginia. Again, thanks to my wife because I married into one of the noblest (and kindest) extended families - the Todd's. If I start naming people more specifically, I'm sure to leave someone out, and I don't want to hurt anybody's feelings. So, just let me say that I'm grateful to all of you.

My choices for professors to lead this research committee could not have been better. Sam Bowen and Royce Zia became personal friends and confidants as well as professional colleagues. They have put up with an unusually long process, because most of my work was carried out part time, but never complained. We faced the challenges of this research together, and I am a better scientist as a result.

While at Virginia Tech, other professors have assisted me including the other members of my committee: C. D. Williams, T. K. Lee, R. Zallen, and A. L. Ritter. Thanks also to all the graduate students who helped the rusty old man pass his prelims, especially Charles Potter, K. C. Ho and Peter Lo. Chris Pirie Thomas was always a source of help and inspiration. Judy Faw, Sherri Turner and the other department secretaries and staff were always kind and helpful.

Kenneth W. Chilton (Kenny) is the technician at the Naval Surface Warfare Center, Dahlgren Division (NSWCDD) who worked side-by-side with me throughout this process. The research could not have been accomplished without him. The early experiments were also assisted by L. W. (Sonny) Hardesty, who gave much valuable assistance. Kenny and Sonny taught me the advanced, applied course in working with high voltage (up to 500 kV), getting valid, repeatable results, and surviving. Drs. David B. Fenneman and Ronald J. Gripshover started the water experiments at NSWCDD, designed the initial apparatus, and have given generously of their time and counsel. Dr. Thomas L. Berger has been a source of advice, skill, and encouragement, as have other members of the Pulsed Power Systems and Technology Group. Stuart L. Moran has been the best Branch Head I could have asked for; he has constantly supported me. Eldridge Rowe and Nevin Rupert are two colleagues who became friends - they offered their own insights to this research and were always willing to be a sounding board for mine. Finally, I'd like to thank the management at NSWCDD for supporting me over the years, including a year of full-time study at Virginia Tech.

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# I. CHAPTER ONE: INTRODUCTION

## A. OVERVIEW OF PULSED POWER

The central idea to all of pulsed power is to take energy from a source, store it for a relatively long time, and switch it into a load (i.e., application) within a much shorter time than the storage time. In this way power amplification is achieved via time compression. There are many interesting future applications that require very high peak power, but moderate-to-high average power, and thus are prime candidates to use pulsed-power technology. Some of the more interesting are : inertial-confinement fusion, pulsed cleanup of biofouling, pulsed plasma reactors to clean up hazardous waste, electromagnetic propulsion, pulsed radar, charged-particle beams, free-electron lasers, high-power microwaves, nuclear-event simulators, active-RF jamming, and acoustical jamming.

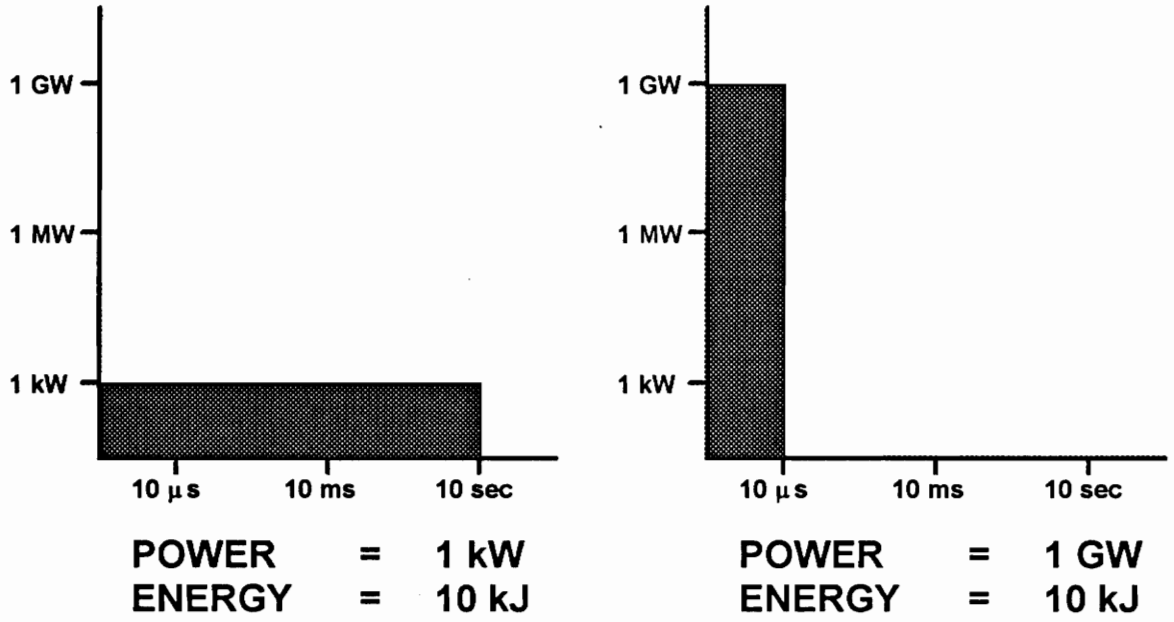
In Figure 1.1, we present a tutorial example whereby a 1-kW power source delivers 10 kJ to an energy store over ten seconds. When the energy is held without loss and then switched perfectly into a load within ten microseconds, a power amplification of $10^6$ is achieved and the 1-kW source is capable of producing a 1-GW pulse. Of course, energy is neither delivered nor stored losslessly and switches do not work perfectly. Research on each aspect of the pulsed-power circuit is active.

In Figure 1.2, we present a simplified pulsed-power circuit in the form of a block diagram. The prime-power block is the constant power source. It charges an energy store over a relatively long period of time and then the energy is

switched out of the energy store at a specific time. Often the energy goes through a pulse-conditioning stage to achieve some desired characteristic, for example to produce a flat-top voltage pulse with fast rise and fall times. Typically, this is achieved with a pulse forming line (PFL) in a real device. Finally, the energy is delivered to the load and the duty cycle of the device may start again.

An important fact to realize is that the energy store and/or the pulse conditioner are usually the largest and heaviest components for high-peak-power machines, and therefore the costliest. Reducing the size and weight of these components is one of the more important tasks required to make pulsed-power machines practical for future applications.

# INTRODUCTION TO PULSED POWER




* SAME ENERGY
* POWER AMPLIFICATION OF $10^6$ ACHIEVED BY TIME COMPRESSION

Figure 1.1: Sketch of pulsed-power concept.

# PULSED POWER TECHNOLOGY BLOCK DIAGRAM

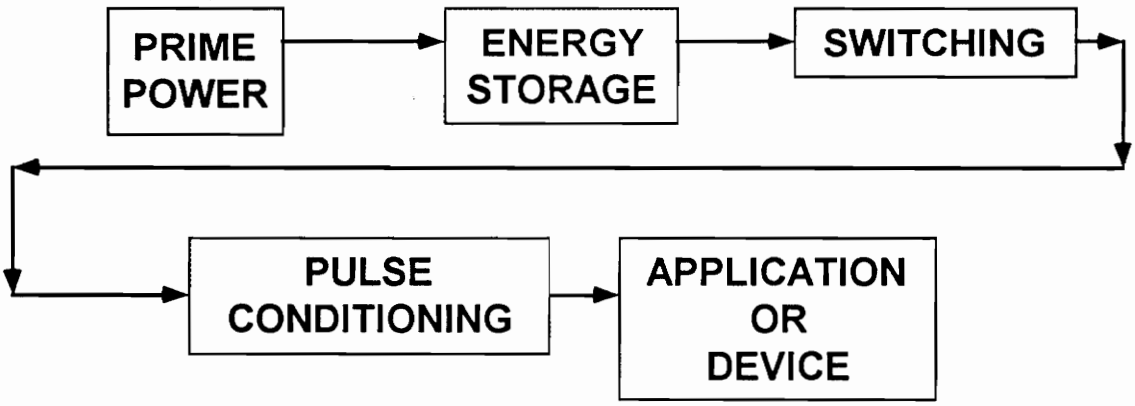



Figure 1.2: Pulsed-power circuit.

## B. WATER AS A DIELECTRIC

Water is a useful dielectric for two parts of the block diagram in Figure 1.2; namely, energy storage and pulse conditioning. In fact, these two functions are often combined into one stage of real pulsed-power devices. Water is useful because it has a high dielectric constant (78 at room temperature) and excellent frequency response. This means that the effective dielectric constant of water does not decrease appreciably for frequencies up to 1 GHz. This is important because more useful energy recovery times for water are in the 10- to 100-ns regime rather than 10 $\mu$s as depicted in Figure 1.1. A high dielectric constant, $\varepsilon$, is important because the energy density is proportional to $\varepsilon$. We wish to keep energy density as high as possible, because that will mean the volume of water needed to store the energy will be minimized. Also, the higher the dielectric constant, the shorter the length of the PFL (length $\propto 1/\sqrt{\varepsilon}$ ). Again, the shorter the PFL, the less mass, volume and cost.

Another valuable characteristic for water as a dielectric liquid is electrical breakdown strength. Energy density varies as the square of the breakdown strength, which considerably affects size, weight, and cost. Within the pulsed-power community, there is a hope that the breakdown strength of water can be significantly improved over the present value. Because of the great impact on energy density, increasing electrical breakdown strength is of the highest priority for water researchers in the pulsed-power community and it is the objective of our thesis.

Water can be purified using commercially available deionizers down to the part-per-billion regime for ionic impurities. Since ordinary water resistivity is controlled by impurity ions, this means that water resistivity can be increased by orders of magnitude by deionization (e.g., 10 kΩ-cm distilled water improved to 18.3 MΩ-cm) If good deaeration is achieved, the intrinsic time constant, $\tau$ (which is equal to the product of dielectric constant times resistivity) can be as large as 650 microseconds at temperatures just above freezing. Since a large $\tau$ leads to slow voltage decay and less energy loss, it is important, in order to achieve minimal loss, for a PFL to be designed with as large a $\tau$ as possible.

Finally, there are other reasons why water is an excellent dielectric liquid. Water is self repairing; after a breakdown it recovers its electrical breakdown strength. Water is certainly non-flammable and non-toxic. Water is cheap, has an acceptable viscosity, and is relatively easy to purify using commercial techniques developed by the semiconductor-manufacturing industry.

The superiority of water is well accepted in the pulse-power community. In fact, almost every large pulsed-power machine, that we know, uses water as a dielectric liquid. Therefore, the focus of this thesis, increasing the breakdown strength of high-purity water, is important to pulsed power and the future applications listed above.

In addition to our empirical investigation of factors that control the breakdown strength of water, we have examined some models for the process. The experimental results which we consider most intriguing are the beneficial effects of filters on breakdown strength and the time dependence of the conditioning process (explained later in Chapter Four). This data is best explained by a population of non-ionic contaminants in a thin stagnant layer of

water next to the electrode surface. In our model, the presence of non-ionic contaminants causes breakdown to occur at a lower value of the electric field than for absolutely pure water. Filters remove contaminants from the bulk water quickly, but only slowly from the stagnant layer. High-voltage shots to the water capacitor breakup the impurities into smaller pieces. We hypothesize that smaller impurities require larger electric field to initiate a breakdown, which means breaking up impurities increases the voltage holdoff of the water capacitor. We further hypothesize that this process is the key to conditioning. The effect of filters on contaminants is that they improve breakdown strength, but only if they are used for some time and constantly. Shutting down overnight allows new contaminants to leach into the water from pipes and other surfaces. As a result, the benefits of conditioning are lost overnight, and a new cycle of filtered flow and conditioning shots are needed before breakdown strength is restored to a high value.

## II. CHAPTER TWO - LITERATURE REVIEW

### A. EARLY SHORT-STRESS-TIME EXPERIMENTS

Experiments on the breakdown strength of water started at the Naval Surface Warfare Center (NSWC) in the latter part of the 1970's and formed the basis for our later work. Then motivation for the Navy to investigate high-purity water as a dielectric liquid arose out of the desire to reduce the volume and weight required for pulsed-power systems that could power any one of several applications (e.g., particle-beam weapons, free-electron lasers, inertial-confinement fusion devices, etc.). The heaviest and largest components of a typical high-peak-power machine was its energy store or its pulsed forming line (PFL). These devices often used water as a dielectric, although energy density must be kept low to avoid breakdown across the water gap. Since energy density increases as the square of the electric field in the water, increasing the breakdown strength was chosen as a logical avenue to pursue increased energy density.

This early work at NSWC built upon experiments carried out by J. C. Martin[1], Ian Smith[2] [3], and P. D. A. Champney[4] at the Atomic Weapons Research Establishment. Their aim was, among other things, to develop better flash x-ray

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[1]J.C. Martin, "Comparison of Breakdown Voltages for Various Liquids Under One Set of Conditions", Note 1, *Pulsed Electrical Power Dielectric Strength Notes*, PEP 5-1, Vol. 1, Notes 1-23, Air Force Weapons Lab TR 73-167, April 1973.
[2]Ian Smith, "Impulse Breakdown of Deionized Water", Note 4, *Pulsed Electrical Power Dielectric Strength Notes*, PEP 5-1, Vol. 1, Notes 1-23, Air Force Weapons Lab TR 73-167, April 1973.
[3]Ian Smith, "Further Breakdown Data Concerning Water", Note 13, *Pulsed Electrical Power Dielectric Strength Notes*, PEP 5-1, Vol. 1, Notes 1-23, Air Force Weapons Lab TR 73-167, April 1973.
[4]P.D.A. Champney, "Impulse Breakdown of Deionized Water with Asymmetric Fields", Note 7, *Pulsed Electrical Power Dielectric Strength Notes*, PEP 5-1, Vol. 1, Notes 1-23, Air Force Weapons Lab TR 73-167, April 1973.

devices. They are the first, as far as we are aware, to measure intrinsic high-voltage properties of water and other materials using modern devices. Other researchers from that period include T. H. Martin[5], who envisioned pulsed power for inertial confinement fusion, A. R. Miller[6] who helped create several large devices, and J. P. VanDevender[7].

During this time a figure-of-merit for the breakdown performance of water came into use. At NSWC, it was given the designation M in honor of J. C. Martin:

$$M = E_{max} * t_{eff}^{1/3} * A^{1/10},$$

where M was Martins number (higher is better), $E_{max}$ was the maximum electric field in the water, $t_{eff}$ was the effective time duration of the electric stress and was defined as the time interval for which the field exceeded 63% $E_{max}$, and finally A was the area of the electrode which experienced 90% or more of the field. For electric field in MV/cm, time in μs, and A in $cm^2$, M was a measure for an electrode system that ranged between 0.3 and 0.6, but mostly remained nearer the 0.3 mark.

Subsequently, D. B. Fenneman and R. J. Gripshover repeated these experiments while meticulously purifying, deionizing, and deaerating the water. Careful documentation of all aspects of their apparatus considerably facilitated our work. This had not always been done in previous work. Their result[8] [9] was

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[5]T. H. Martin, "Pulsed Power For Fusion", *Proceedings International Pulsed Power Conference*, Lubbock, Texas, Nov. 1976, IEEE Catalog No. 76 CH1147-8 Reg. 5.

[6]A.R. Miller, "Low Impedance Capacitors Using Pressurized Water as a Dielectric", *Proceedings of the 5th Symposium on Engineering Problems of Fusion Research*, p. 471, IEEE, New York, 1974.

[7]J. P. VanDevender, "Short Pulse Electrical Breakdown Strength of $H_20$", *Proceedings International Pulsed Power Conference*, Lubbock, Texas, Nov. 1976, IEEE Catalog No. 76CH 1147-8 Reg. 5.

[8]D. B. Fenneman and R. J. Gripshover, "Experiments on Electrical Breakdown in Water in the Microsecond Regime", *IEEE Trans. Plasma Sci.*, vol. PS-8, no. 3, pp. 209-213, Sept. 1980.

impressive, namely, an approximately two-fold increase, consistently, in the Martin's number to consistent performance of 0.58 for steel and brass, 0.55 for copper and 0.41 for aluminum.

The fact that electrode materials had an effect on breakdown performance was considered interesting. It reinforced theories that the electrode-water interface was the key to breakdown behavior. Our first effort in water breakdown was to use ion bombardment of the electrode surface to attempt to affect breakdown[10]. Our hypothesis was the ion bombardment might eliminate micro-whiskers or other small imperfections on the electrode surface that might produce field enhancement. Unfortunately the process didn't improve the Martin's number for either copper or stainless steel electrodes. Possible reasons for the result are: (1) small surface inhomogeneities causing electric-field enhancement are not part of the breakdown mechanism, (2) ion flux was too low or (3) the energy of the ions was too low .

However, as a side issue, we also tested the effect of polished stainless-steel surface versus the accepted surface treatment of bead blasting (i.e., glass peening). While the breakdown strength was slightly worse for polished results, we did notice two other interesting phenomena. First, upon post-test examination, bead-blasted stainless-steel surfaces have breakdown craters arranged in a random fashion, but breakdown craters of polished stainless steel are grouped together in a few clusters. Despite this dramatic difference, the breakdown strength was almost the same. Second, post-test microscopic

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[9]D. B. Fenneman and R. J. Gripshover, "Experiments on Electrical Breakdown in Water in the Microsecond Regime", *Proc. 2nd IEEE Int. Pulsed Power Conf.*, pp. 122-126, June 12-14, 1979.
[10]V. H. Gehman, Jr. and D. B. Fenneman, "Experiments on Water-Capacitor Electrode Conditioning by Ion Bombardment", *1980 Fourteenth Pulsed Power Modulator Symposium*, Orlando, Florida, IEEE 80CH 1573-5, pp. 154-160, June 3-5, 1980.

examination of the polished stainless steel revealed large numbers of twins near the breakdown craters in the grains of the metal. This indicates considerable stress in the region of the electrode near the breakdown crater.

This was some of the last short-stress-time work. Focus shifted to long stress time for two reasons: (1) it was more relevant to a new class of machines proposed for pulsed-power applications, and (2) electric breakdown strength was found to be stress-time independent for time longer than about 65 μs.

## B. LONG-STRESS-TIME EXPERIMENTS

Fenneman and Gripshover also performed experiments with longer charging times. One motivation is that a long charging time could allow a new type of pulsed-power machine to be developed, specifically where a new kind of prime-power source (e.g., compulsator, brushless rotary flux compressor-BRFC, etc.) charges the PFL directly. This would eliminate several stages of previous machines. The key connection was the faster prime power interacting directly with the PFL. If charge times as short as 100 μs could be achieved, then pure water could be charged and then discharged in the standard way over a time period of 10-100 ns. This would result in power amplification on the order of 1,000 to 10,000 times. If the new prime-power sources couldn't achieve as short a time as 100 μs, then more conservative charging times of 1 to 100 ms (which would result in power amplification on the order of 100,000 times) would require a different dielectric than pure water, which is limited to an ultimate intrinsic time constant of about 650 μs. However, ethylene glycol and water mixtures can

accommodate these longer charging times, as NSWC researchers demonstrated in a series of ground-breaking papers[11] [12] [13] [14].

Further, the effect of charge injection on electrical breakdown strength was also investigated. NSWC researchers had discovered charge injection in cooled glycol-water mixtures[13] [14], and the result had been confirmed using Kerr electro-optics at the Massachusetts Institute of Technology (MIT) in collaboration with Markus Zahn, et al.[15] [16]. Zahn discovered the different materials injected either positive or negative excess charge or sometimes both. Positive charges are injected if the electrodes are both made of stainless steel or copper. However, a copper electrode will inject negative charges when combined with a stainless-steel electrode. Aluminum injects negative charge, but brass is a bipolar injector. The injected ions have mobilities that are close to the literature values for the hydronium and hydroxyl ions and that identification became the working assumption. Perhaps the most significant fact about charge injection was that the electric field was lower at a charge-injecting electrode and higher at a non-injecting electrode.

Because charge injection would limit the charging time of a PFL and might affect the breakdown strength by altering the electric field at the electrode

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[11]D. B. Fenneman and R. J. Gripshover, "The Electrical Performance of Water Under Long Duration Stress", *Proc. 1980 Fourteenth Pulsed Power Modulator Symposium*, Orlando, Florida, IEEE 80CH 1573-5, pp. 150-153, June 3-5, 1980

[12]D. B. Fenneman, "Water Capacitors for Pulsed Power Applications", *Proc. Symp. on High-Energy-Density Capacitors and Dielectric Materials*, Washington, D. C., National Academy Press, pp. 156-165, 1981.

[13]D. B. Fenneman and R. J. Gripshover, "High Power Dielectric Properties of Water Mixtures", *Proc. 4th IEEE Pulsed Power Conf.*, pp. 302-307, June 6-8, 1993.

[14]D. B. Fenneman, "Pulsed High-Voltage Dielectric Properties of Ethylene Glycol/Water Mixtures", *J. Appl. Phys.*, Vol. 53, No. 12, pp. 8961-8968, Dec. 1982.

[15]M. Zahn, S. Voldman, and T. Takada, "Charge Injection and Transport in High-Voltage Water Glycol Capacitors", *J. Appl. Phys.*, Vol. 54, No. 1, pp. 315-325, Jan. 1983.

[16]M. Zahn and T. Takada, "High Voltage Electric Field and Space-Charge Distributions in Highly Purified Water", *J. Appl. Phys.*, Vol. 54, No. 9, pp. 4762-4775, Sep. 1983.

surface, we investigated[17] the effect of standard bead-blasted surfaces and differing surface treatments on charge injection for 304 stainless steel, electrolytic tough-pitch copper (CDA 110), 70-30 brass and 7075 aluminum electrodes. In order to conduct our analysis of charge injection (since we didn't have the Kerr electro-optics of MIT), we digitized the voltage waveforms and then modeled them with a computer program to determine the amount and mobility of the injected charge. As expected we found that electropolishing and passivating (EP) the surface of 304 stainless-steel electrodes reduces the amount of charge injection by 2-10 times as compared to bead-blasted (BB) surfaces. We found that the effect wears off over the course of a year but can be reapplied. Furthermore, we confirmed that 304 stainless steel is a unipolar positive injector by examining mixed (EP and BB) electrode sets. Unexpectedly, anodized aluminum did not inject less charge than BB aluminum but did have a 20% greater breakdown strength. We also observed charge injection in the brass electrodes, confirming the MIT results.

With the copper electrodes in this experiment [17] we tried a more exotic process. A cuprous oxide layer was grown on the electrode by annealing in a controlled-gas furnace. We chose cuprous oxide because it was p-type semiconductor and we hypothesized that this coating might reduce the gradient of the electric field from the electrode into the dielectric, which might improve the breakdown strength. Copper oxide did inhibit charge injection as compared to bead-blasted copper. A limited number of breakdown tests showed a slight decrease in breakdown strength for cuprous oxide (about 126 versus 129 kV/cm;

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[17]V. H. Gehman, Jr., D. B. Fenneman, and R. J. Gripshover, "Electrode Surface Effects on Unipolar Charge Injection in Cooled Liquid Dielectric Mixtures", *4th IEEE Pulsed Power Conference*, Albuquerque, New Mexico, June 6-8, 1983.

the next paper would have more dramatic results as we learned about the aging characteristics of copper). Using mixed electrode sets, we found that making the copper oxide electrode the anode yielded about the same charge injection as using two copper oxide electrodes. However, making the copper oxide electrode the cathode gave a charge-injection amount roughly midway between two pure bead-blasted copper electrodes and two cuprous oxide electrodes. This ambiguous result is reminiscent of the MIT result, where Zahn found that copper is usually a unipolar positive injector, except when combined in a mixed electrode set with stainless steel. This puzzling result has never been explained nor are we sure that it is important.

Finally, in this comprehensive paper [17] we found that we could inhibit charge injection which would lead to the desirable result of allowing longer charging times. We expressed this result numerically as a new quantity called action density, which was the energy density of the dielectric liquid multiplied by a normalized, high-voltage-measured intrinsic time constant. In this regard, electropolished and passivated stainless steel was best, anodized aluminum was better than bead-blasted aluminum because of the 20% increase in breakdown strength, and cuprous oxide was better than copper.

Since our results with cuprous oxide appeared promising, we expanded our work on this material and its effect on breakdown strength[18]. Before discussing this work, we report the remarkable discovery that the breakdown strength of copper electrodes will improve if they were simply immersed in glycol and water for an extended period. Thus, fresh copper (immersed only a short time and

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[18]V. H. Gehman, Jr., R.K. Hutcherson, Jr., D. B. Fenneman, and R. J. Gripshover, "Effects of Cuprous Oxide Coated Electrodes on the Breakdown Voltage of Liquid Dielectric Mixtures", *1984 Sixteenth Power Modulator Symposium*, Arlington, Virginia, June 18-20, 1984.

freshly bead blasted) has a breakdown strength of about 135 kV/cm for the 2.5-inch diameter electrodes, while aged copper (immersed over a month) has a breakdown strength of 143 kV/cm. Also surprising was that polished copper had the highest breakdown strength of all (153 kV/cm), which is not what we expected based on polished stainless-steel work described previously.

Returning to cuprous oxide layers, our annealing procedure was difficult because cuprous oxide is not thermodynamically favored until the temperature of the copper was within about 50 C of the melting point. Therefore we had to heat and cool for long periods of time under inert argon gas and react for short times with a partial pressure of oxygen. Our research sources indicated that the resistivity of the cuprous oxide would depend greatly on the preparation conditions and could vary from 100 to $10^{10}$ ohm-centimeters. The measurement of surface resistivity is not straightforward because we have a conducting substrate. We could not confirm that a resistivity in the target range of a 1000 ohm-cm or less was ever achieved. Layers with the desired thickness in the micron range were not obtained, instead thickness varied between 0.002-0.007 **inches**. Consequently, breakdown shots would severely damage the oxide layer. Cuprous oxide did inhibit charge injection but it also had low breakdown strength (96-105 kV/cm). Faced with many sources of uncertainties, e.g., whether charge injection was important to increasing breakdown strength, whether our layers were too thick or resistive, how to test for different explanations, etc., this line of approach was eventually abandoned.

In the same work[18] , another important issue was addressed. For rep-rated machine (with a frequency of operation of many times a second), it may be more relevant to introduce another threshold for defining breakdown. We term the new

value as the 1% breakdown threshold. Specifically, in previous studies, breakdown tests in sets of ten shots at each voltage setting were used and the highest groupings of ten shots without a breakdown were defined as the 10% breakdown threshold. However, for some classes of pulsed-power machines more reliability might be needed. It would be interesting to know the highest value of the electric field that would holdoff 100 shots without breaking down. This we define as the 1% breakdown threshold. The two thresholds were assumed to provide similar results. Sincerny[19] explicitly investigated the inherent performance of pure water under high repetition rate (many Hz) and found a slight, but acceptable, decrease in the breakdown strength. Although our apparatus is not designed to achieve Sincerny's repetition rates, we did repeat experiments at several cycles per minute. We found that in cooled glycol and water, for 2.5-inch diameter copper electrodes: the 1% breakdown threshold is 153 kV/cm which is surprisingly better than the 10% value (143 kV/cm). Since the former set of data were taken with aged electrodes, while the latter were not, our conclusion is that the aging process is more important. In experiments we describe below, the breakdown strength of copper are found to depend on other factors as well as immersion time.

Because we continued to see different breakdown and charge-injection behavior for different electrode materials, in our next effort[20] we measured and compared two alloys of stainless steel (304 vs. 310) and two alloys of aluminum (7075 vs. 5083) in a water (40%)/glycol (60%) mixture. Stainless steel contains

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[19]P. S. Sincerny, "Electrical Breakdown Properties of Water for Repetitively Pulsed Burst Conditions", *Proc. 3rd IEEE Int. Pulsed Power Conf.*, pp. 222-225, June 1-3, 1981.
[20]V. H. Gehman, D. B. Fenneman, and R. J. Gripshover, "Effects of Alloys and Surface Treatments on Electrical Breakdown Strength of Water and Water Mixtures", 5th IEEE Pulsed Power Conference, Arlington, Virginia, June 10-12, 1985.