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ELECTRICAL BREAKDOWN IN WATER IN THE MICROSECOND REGIME

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ABSTRACT

This paper describes the research on electrical breakdown in water currently being pursued at NSWC/DL. The experimental apparatus is described in some detail. Results of over 500 tests are presented. Breakdown events were observed predominantly in the 2-10 microsecond time domain for applied electrical fields in the range 200-500 KV/cm. The wide scatter of the breakdown time which is intrinsic to the phenomena requires a careful examination of the statistics of the data.

Background

Water, because of its high dielectric constant, self-repairability, cheapness and ease of handling is finding increasing use as the intermediate energy store in pulse power devices. Large machines, which are high energy as well as high power devices can be expected to have the water capacitor charged in the multi-microsecond regime. The water must not suffer electrical breakdown during this charging time. These considerations have led the pulsed power group at NSWC/DL to actively pursue research on this topic. The goals of the effort are to provide empirical performance comparisons in order to establish design-trade off rationale, and provide experimental evidence to test various theories of breakdown.

In the regime to be reported on in this paper, the process of electrical breakdown has wide (apparently) statistical variation. To measure these intrinsic variations requires large numbers of tests and good control on all process variables. These considerations have formed the rationale of the experimental approach.

Apparatus

The test apparatus built at NSWC/DL explicitly for water breakdown research consists of three components (refer to Fig.(1)). A water conditioning system, an electrical system, and the test cell.

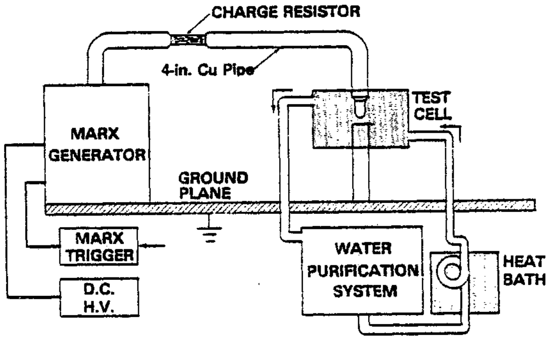

Figure 1. Water Breakdown Experiment

The water conditioning system was designed to provide water which could be well characterized. It consists of (a) a pump of > 4 GPM capacity, (b) a mixed bed deionizer, (c) a deaeration column, (d) a heat bath to maintain temperature and (e) an ultra-violet sterilizer to suppress algae growth. This last item is used only intermittently and may not be necessary. Resistivity probes measure the resistivity of the water at the outlet of the deionizer and at the outlet of the test cell. Temperature is measured by thermistor probes located at the outlet of the heat bath, at the outlet of the test cell and in the deaeration column. The pressure in the deaeration column is maintained by

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14. ABSTRACT

This paper describes the research on electrical breakdown in water currently being pursued at NSWC/DL. The experimental apparatus is described in some detail. Results of over 500 tests are presented. Breakdown events were observed predominantly in the 2-10 microsecond time domain for applied electrical fields in the range 200-500 KV/ em. The wide scatter of the breakdown time which is intrinsic to the phenomena requires a careful examination of the statistics of the data.

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a vacuum pump, protected from water vapor fouling by a trap cooled by an alcohol-dry ice slurry, the pressure is measured by a mercury manometer. The water is conditioned for about 3 hours before testing, and continually during testing. All told, about 40 gallons of treated water are continually circulated. It takes about an hour to bring the resistivity of the water to above 18 MΩ-cm (25°C) from the 2-3 MΩ-cm value the water degrades to overnight. The resistivity obtained in the system is at or near the ultimate value for water and success in obtaining such high values is ascribed to flowing continually above 2.5 GPM and to the fact that with the exception of the test electrodes, the copper coils of the heat bath, and the small area of the stainless steel probes, the water touches no metal or glass. All pipes and valves are hard PVC, the pump has a nitrile impeller and the deaeration column is plexiglas. Deaeration takes longer than deionizing, especially if the test cell has been opened to air. At equilibrium the percent deaeration is computed as

$$\% \text{ Deaeration} = 100 \times \left(1 - \frac{p - P_{H_2O}(T)}{760}\right)$$

where: p = pressure in column, torr

$P_{H_2O}(T)$ = water vapor pressure, torr

The circuit of the electrical system is shown in Figure 2. The voltage source is a 10 stage Marx generator capable of 500 KV maximum, whose erection time is a couple of hundred nsec. The Marx charges the water test cell through a 4000Ω copper sulphate resistor. The voltage also bleeds through a Marx internal resistance of approximately 900Ω. Circuit inductance is unimportant and the voltage across the water is closely given by

$$V(t) = .71\, V_o\, (e^{\omega_1 t} - e^{\omega_2 t})$$

where V_o = Erected Marx Voltage

$-1/\omega_1 = R_m C_m = 20$ µsec

$-1/\omega_2 = R_c(C_w + C_s) = 2.0$ µsec

The voltage is measured by a copper sulphate dividing resistor, the current is measured by a Rogowski coil. The observed voltage and current waveforms agree with computer modeling (which takes into account temperature and gap size effects) to the resolution of the oscilloscope traces. Breakdown time is also measured by counting a 100 MHz clock signal gated by the voltage signal. These all are recorded on a Tektronix Model 7844 Dual Beam Oscilloscope. Figure 3 shows a sample test trace.

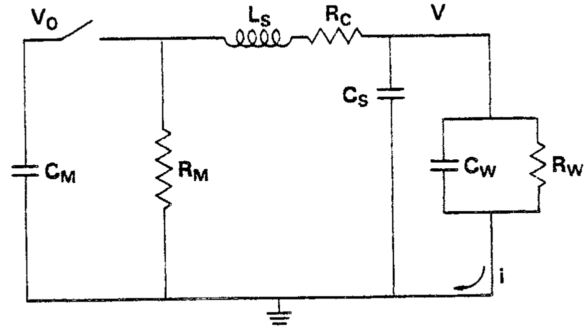

Fig. 2. Electrical Circuit

C_M,	Marx Capacitance	22nF
R_M,	Marx Internal Resistance	900Ω
L_s,	Stray Inductance	4µH
C_s,	Stray Capacitance	.1nF
R_c,	Charge Resistor	4KΩ
C_W,	Water Capacitance	.4-.5nF
R_W,	Water Resistance	>300KΩ

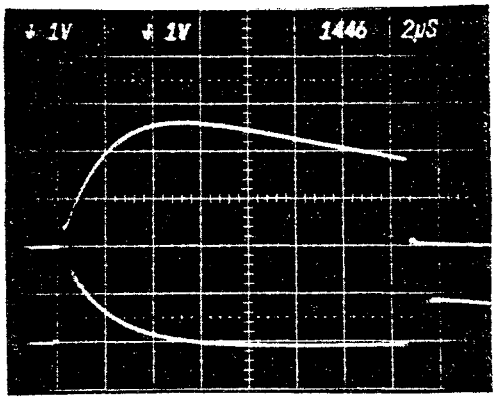

Fig 3. Sample Data Trace
Top Curve V(t), 1 CM = 41.7 KV
Bottom Curve i(t) 1 CM = 20 A
At Breakdown $V(t) \to 0$ and $i(t) \to$
$V_o \exp(-R_m C_m t)/R_c$ since capacitor is shorted.
Starting glitch due to Marx gap transients.

The test cell is a plexiglas box 20"x20"x14" which holds the test electrodes. The electrodes are tough pitch electrolytic copper in a hemisphere (R = 1")-plane configuration. The final surfacing is done by sand blasting with glass beads (Blastolite, size B1-10). This surfacing technique is chosen, not out of any belief that it produces a superior surface, but because it produces a well-characterized, easily restored and reproducible surface. The gap spacing is measured to .001" by a cathetometer before each shot.

Process Variable	Condition
Water Temperature	19 ±2°C
Water Flow Rate	> 2.2 GPM
Water Resistivity	> 18 MΩ-cm
Pressure in Test Cell	1.3 psig
% Deaeration	> 95%
Electrode Material	Electrolytic Cu.
Surfacing	Sandblasted
Stressed Area	300 mm^2
Gap Spacing	2.8-6.4 mm

Table 1. Summary of Experimental Conditions

Results

For any real apparatus the applied field is a function of time, consequently there is a built in dependence of field at breakdown to time of breakdown for any single test. Further, any real apparatus can only span a finite region of the E-t plane. The region investigated in this work is bounded by the curves shown in Figure 4. Also displayed in this figure are the experimentally observed point pairs (E_{MAX}, t_b) where E_{MAX} is the maximum field experienced before breakdown and t_b is the time at which breakdown occurred, measured from onset of voltage. The touchstone of water breakdown field-time experiments is the relation due to Martin[1]:

$$M = E_{MAX}\,(t_b - t_o)^{1/3} = \text{constant}$$

Here, t_o is a time parameter usually defined as the time when the applied field exceeds some given fraction of its maximum value (e.g., 50%, 63%). A linear regression[2] on the relation

$$t_b = t_o + (M/E_{MAX})^3$$

yielded from the data the values

$$M = .562\ (\mathrm{MV/cm})\cdot(\mu\mathrm{sec})^{1/3};\quad t_o = 0.53\ \mu\mathrm{sec}$$

This value of M is close to the value .6 usually quoted for uniformly stressed electrodes. The value t_o corresponds to the time $E(t) = 0.28\ E_{MAX}$. The regression curve is also plotted in Figure 4.

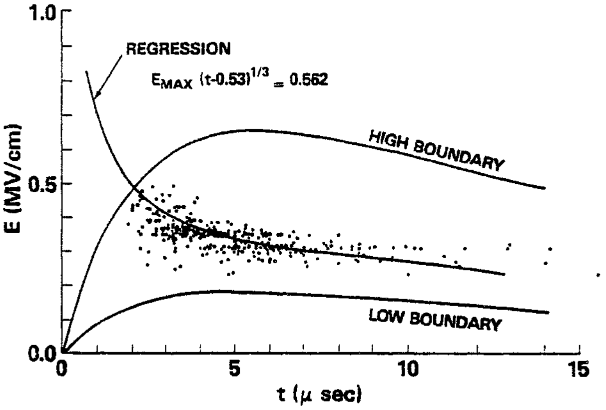

Fig. 4. Breakdown Time vs Maximum Field - Summary of Data. The dots are the experimental points (E_{MAX}, t_b).

To examine the properties of M as a measure of breakdown, the quantities

$$M_i = E_{MAX\,i}\,(t_{b_i} - .53)^{1/3} \qquad i = 1,\ldots,294$$

were computed from the data. The result is displayed as a histogram, Figure 5. The histogram shows the mean and mode are close to the regression value of M.

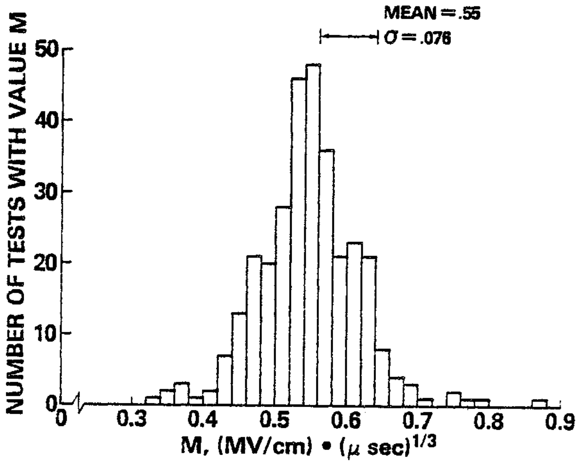

Fig 5. Histogram of Martin's Relation

A criticism of the regression analysis stems from the observation that the standard deviation of t_b is not constant over the population. This is shown in Figure 6. This graph was generated by arranging the data in order of increasing E_{MAX} and computing the means and standard deviations of t_b for all sets of 30 ordered points. Whether this variation in the RMS deviation of t_b with t_b is intrinsic to the phenomena, or due to the particular waveform used in the experiments, or one of the process variables is a point yet to be resolved.

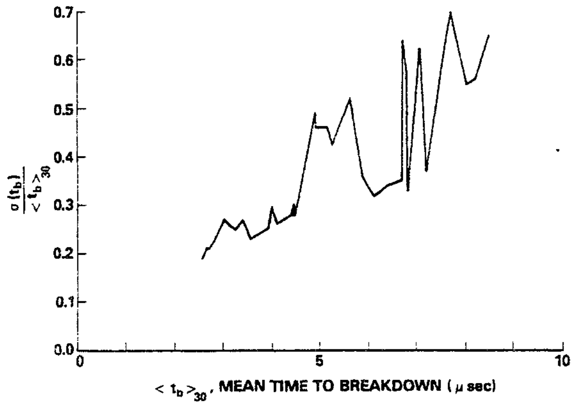

Fig. 6. Variation of Fractional Deviation of Breakdown Time with Mean Time to Breakdown, Running 30 Point Averages.

The same set of electrodes was used for all tests. These electrodes sat in deaerated water for over two months. During this time a thin, uniform patina of oxide developed on the sandblasted copper surfaces. The oxidation rate in the deaerated water was noticeably slower than when the surfaces were exposed to air. Aging (i.e., the change in breakdown character with time, or number of breakdowns suffered) due to two mechanisms could be postulated. One mechanism due to the oxide layer buildup, the other due to pitting and scarring from repeated breakdowns. Aging was studied by arranging all breakdowns in the chronological order in which they occurred and computing the running statistics of M. The results are displayed in Figure 7. There seems to be no clear trend due to aging. This is somewhat surprising for at the conclusion of the tests, the electrodes were highly scarred and pitted. The positive electrode was more severely damaged than the negative. The pits, reminiscent of Moon craters when viewed under the microscope, were of uniform diamter (∿ .17 mm) and uniformly distributed over the stressed area. Breakdowns were visually observed through the cathetometer during testing and showed no tendency to occur in the same place.

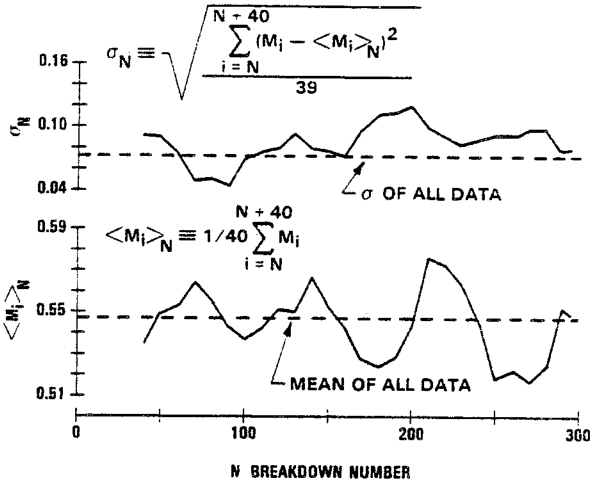

Fig. 7. Aging Study. If aging was strong, it would be expected that these curves would have a monotonic trend up or down.

An apparent threshold effect at about .275 MV/cm was observed, below this value breakdown often did not occur. Figure 8 shows the results of a series of tests used to explore this phenomenon. At these lower field values sets of at least 10 tests with identical waveforms were performed and the probability of breakdown defined as

$$\frac{\text{The no. of tests in a set breaking down}}{\text{Total no. of tests in a set}}$$

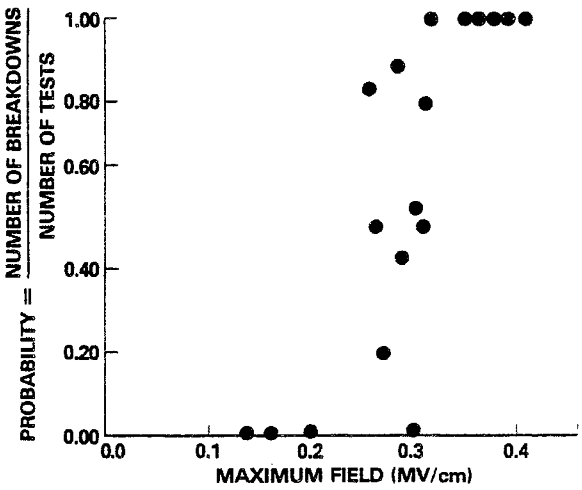

Fig. 8. Threshold Study

It should be made clear that the abcissa of Figure 8 is the maximum field the waveform would have achieved if breakdown didn't take place, which is not necessarily the same as the maximum field achieved. Also the above simple definition of breakdown probability is confounded by the experimental observation that the probability of breakdown on the nth test depends on whether the n-1st test broke down, which is to say each test is not a Bernoulli chance. This effect, which is difficult to quantify, was explored in a qualitative way. It was established that, following application of a high stress, the low stressed test would probably break down. But the application of low stress a second time would not result in break down. This effect is ascribed to transistitory damage, wherein a violent breakdown produces surface conditions which weaken the hold-off strength, while a mild breakdown following repairs the damage.

Summary

It has been the intent of this paper to report the findings to date of the continuing research efforts on electrical breakdown in water being pursued at NSWC/DL. It has been shown that Martin's Relation is a good gross measure of breakdown in the region 2-10 μsec, but that shot to shot variability in time of breakdown is large. Aging seems unimportant and there is evidence for a threshold. Obviously much more work must be done. The effects of temperature, resistivity, electrode material, and surfacing need to be studied. The time regime should be extended to the 20 and 30 μsecond domains.

Acknowledgement

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