Water Breakdown Measurements of Stainless Steel and Aluminum Alloys for Long-Charging Times

A.R McLeod and V.H. Gehman,Jr.

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Abstract:

This paper presents results from research on electrical breakdown in water carried out at the Naval Weapons Surface Center, Dahlgren Virginia. The breakdown performance of two electrode materials; 430 stainless steel, and 6061 Aluminum; is presented. Also reported are results from experiments performed using one electrode of 2024 aluminum, a negative charge injector[1], and one 304 stainless steel electrode, which injects a positive charge[1]. It is theorized that when both electrodes inject charge the electric field very close to the electrode surface is reduced and thus breakdown should occur at a higher average electric field.[1]

This work is performed to provide empirical performance comparisons in order to establish design trade off rational and to provide experimental evidence to test various theories of breakdown.

I. Introduction

This study is done as part of an on-going effort to determine the effect of different electrode materials on the breakdown strength of water and water mixtures.[2,3] For this set of experiments the 10% breakdown threshold, for 81 cm^2 electrodes, with stress times greater than 100 microseconds, in pure water is used as the standard for breakdown strength. The 10% breakdown threshold is defined as the highest average electric field that successfully held off 10 shots of the Marx generator, while at least one breakdown occurred in the next 10 shots at a slightly higher electric field. A minimum stress time of 100 microseconds is used because previous work demonstrated that breakdown strength is not time dependent for stress times greater than 65 microseconds.[4]

The 10% breakdown threshold is measured for bead blasted 6061 aluminum, and bead blasted 430 stainless steel alloy. Also measured is a mixed set of electrodes, one 2024 aluminum and one 304 stainless steel. Since 2024 aluminum is a negative charge injector, and 304 stainless is a positive charge injector, either bipolar charge injection or no charge injection can be selected by changing the polarity of the Marx generator .[1]

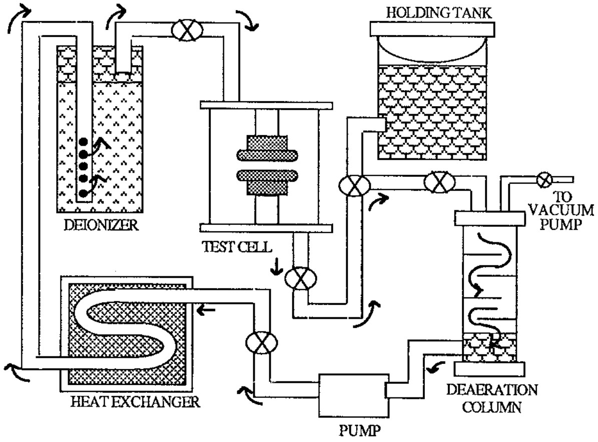
II. Apparatus

The test apparatus is described in detail in previous papers.[4,5] A brief description is given here.It consists of a water conditioning system, an electrical system, and the test cell.

The conditioning system was designed to provide well deareated water with a resistivity above 18 Megohm-cm (25°C). Figure 1 is a flow diagram for the system.

Figure 1.

FLOW DIAGRAM FOR WATER PURIFICATION SYSTEM



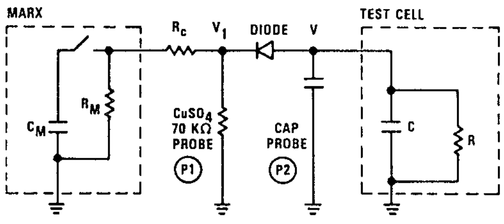
The flow rate is about 2.3 gal/min. During testing the temperature can be maintained within 1°C by occasional addition of dry ice to the heat exchanger. Water conditioning is continued during testing.

The electrical system consists of a ten stage Marx generator capable of 500kV maximum output. The high voltage circuit is shown in Figure 2. When the Marx spark gap fires, the diode conducts charging the test capacitor. When $V(t_s)=V_m(t_s)$ (t_s= 19microseconds) the diode stops conducting since after that time $V(t)>V_m(t)$. Both capacitors then decay with their respective time constants. The $CuSO_4$ resistive divider probe is used to verify peak voltage across the test cell. The capacitive probe signal pick-up is positioned after the high voltage diode and is an accurate measure of the voltage across the test cell. A typical oscilloscope trace is shown in Figure 3.

The test cell is a plexiglas cylinder (ID=0.28m, OD=0.3m) with stainless steel end plates. The planar, circular cross-section parallel electrodes, of area 81 cm^2 (10 cm diameter), rounded at the edges are centered in the middle of the cell. The gap spacing for these tests was 1 ± 0.02cm.

Figure 2.

ELECTRICAL DIAGRAM OF THE LIQUID DIELECTRIC EXPERIMENTAL APPARATUS



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14. ABSTRACT
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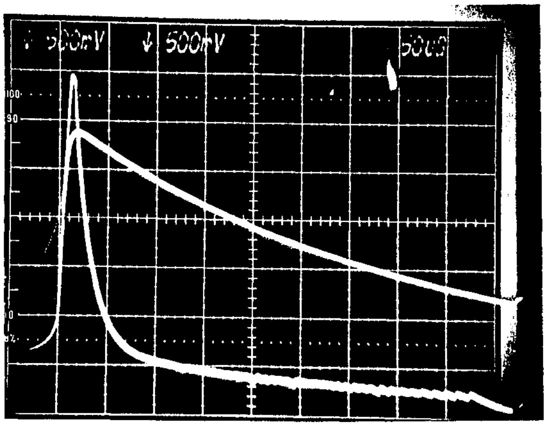
Figure 3. High-voltage test traces with the 430 Stainless steel electrodes. The bottom trace is the $CuSO_4$ probe signal. The top trace is the capacitator probe signal. $\hat{E}_{max}$ = 178 kV/cm; t_{eff} = 175 μs; $\mathcal{T}_{lv}$ = 406 μs; Υ_{hv} = 350 μs; temperature = 6.3°C.



III Test Procedure and Results

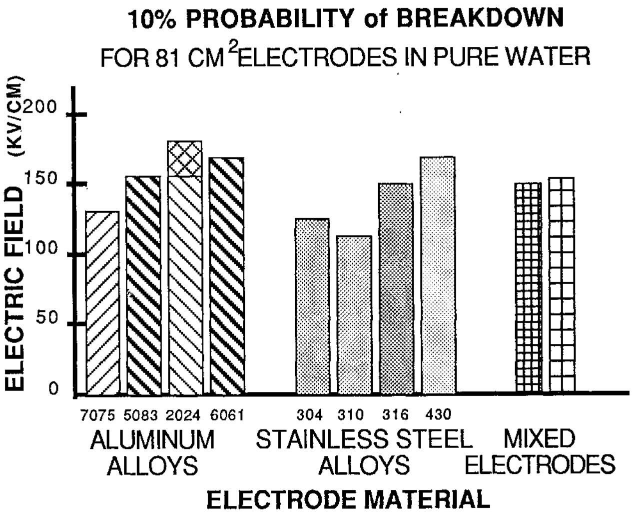
Each electrode set is put in the apparatus and the water is conditioned for two or three days prior to testing. This is done to insure that the water condition is the same from test to test. On the day of the tests water conditioning is performed for two or three hours to raise the resistivity back to near-theoretical purity levels from the 2 - 3 Megohm-cm it degrades to overnight. The temperature is maintained at approximately 6°C.

A test series begins with 10 shots at a setting on the Marx generator far below the breakdown voltage of the electrodes being tested. These early shots serve to condition the electrodes, which has been shown to improve the breakdown strength.[2] If no breakdown occurs the voltage is increased 20kV on the Marx (about 10kV across the test cell) and ten more shots fired. This procedure is repeated until there is a breakdown. The 10% breakdown threshold is defined as the highest electric field to successfully hold off 10 shots, while a slightly higher field broke down at least once out of ten shots.

The 430 bead blasted stainless steel electrodes have a 10% breakdown threshold of 170 kV/cm. This is higher than any stainless steel alloy previously tested at this laboratory. See Figure 4,which includes the results for stainless steel alloys 304, 310, 316 and aluminum alloys 2040, 5083, and 7075, which are measured in the same fashion.

The 10% breakdown threshold for 6061 bead blasted aluminum is also measured as 170kV/cm. This is higher then most other aluminum alloys that have been tested. (Figure 4) Aluminum alloys in the past have shown a change in breakdown strength with time in water.[6]

Figure 4.



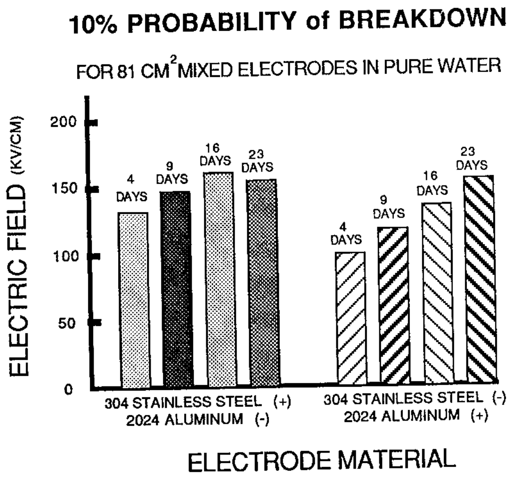
When some metals are subjected to an electric field they will inject charge, either negative, positive, or both. When charge injection occurs the electric field is reduced near the electrode doing the injecting. If both electrodes are ejecting, one positive, one negative, the field at both electrodes should be lower , thus the breakdown strength should be higher than when no charge injection occurs. Bipolar charge injection can be obtained by judicious choice of electrode materials and polarity. One can observe bipolar charge injection or no charge injection by switching the polarity of the Marx. Zahn at MIT has identified 2024 aluminum as a negative charge injector and 304 stainless steel as a positive charge injector.

Initial tests using these alloys showed that bipolar charge injection did improve the breakdown strength of the electrode pair when compared with the no charge injecting case. See Figure 5. For the bipolar charge injecting case the 10% probability of breakdown was 145kV, for non-injecting the breakdown strength was 100kV. A time dependence was observed though and it seems that with exposure to water the contribution of charge injection is not as noticeable. The case of no charge injection increased its breakdown strength to a much greater extent than the case with charge injection. At this time the best 10% breakdown threshold for the charge injecting case is 155kV and 160kV for the non-charge injecting case.

IV. Summary and Discussion

This paper provides support for engineering design decisions for pulsed power lines. It should be noted that by changing the alloy used for the PFL that breakdown strength can be improved by 50% (430 stainless steel rather than 310). Also noted is the fact that the aluminum alloys tend to have a much greater time dependence than steels. The breakdown strength of the aluminum changes with time in water, as well as gives a greater scatter of results.

Figure 5.



Theoretical work is continuing at NSWC and several universities to explain: the value of the electric field where breakdown inception occurs, the effect of electrode alloy on the breakdown strength, the different breakdown behavior of stainless steel and aluminum, and the fundamental nature of charge injection and its role in breakdown. this theoretical work is largely incomplete, but present efforts are concentrating on the electrical double layer at the electrode / liquid interface. In the double layer the dielectric constant, ionic concentration, mobilities, and electric field magnitude are vastly different from the bulk liquid. Consequently, current efforts are attempting to identify the breakdown initiation process(es) in the double layer.

The mixed electrode set tested (2024 aluminum and 304 stainless steel) increased breakdown strength with time in the water. There is no great advantage in using this pair of electrodes, that inject charge, over a set of 6061 aluminum electrodes or 430 stainless steel electrodes. The breakdown strength of the 6061 aluminum and the 430 stainless steel is higher than the mixed set. The explanation for the time-dependent nature of the breakdown behavior of the mixed electrode set is expected to be intricately related to the theoretical modeling of the breakdown initiation process, as described above.

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