Effect of De-aeration on the Electrical Breakdown Characteristics of Water

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Abstract
In the study of electrical breakdown in liquids, attention is typically paid to the contamination of the liquid, and particularly ionic impurities. However, the purity of the sample is also compromised by dissolved gases as well as ionically charged species. To test the effect of de-aeration, water, a highly gas-soluble liquid, was chosen as the test liquid. The delay time to breakdown was measured under the action of a rectangular pulse of 50 kV peak amplitude, 4 ps duration and 250 ns risetime to planar electrodes. The de-aeration apparatus and a test to verify the complete degassing of the water is described. The breakdown properties are strongly affected by the presence of dissolved air: the air saturated water takes significantly longer to breakdown. The experiment suggests that the breakdown strength in some liquids may be raised by careful degassing.

Introduction
The physics of electrical breakdown in liquids is not well understood, and is strongly dependent on the chemical nature of the liquid under study. Water is a good test liquid, because its chemistry is fairly well understood. Water purity is particularly difficult to maintain since its high solubility also makes it easily contaminated. Predominant contaminants are free ions and dissolved minerals and gases.

The quality of the test liquid is a critical control parameter in the study of electrical breakdown, yet liquid purification techniques vary widely. Frequently, liquid insulators are purified for particulate and ionic impurities, but impurities introduced by dissolved gases are ignored. The role that dissolved gases play in the prebreakdown process are of engineering importance as their introduction into a liquid insulator may be unavoidable. It also provides a clue as to the initiation mechanism of electrical breakdown in liquids.

To study the role of dissolved air on liquid insulators, the delay time to breakdown, under action of a rectangular applied voltage, has been measured. The method investigation for obtaining and maintaining degassed, reasonably pure water is described.

Experimental Arrangement
A high voltage pulser was constructed to deliver a single 50 kV, 250 nsec rise time pulse of 4 μs duration to the test chamber. A lumped element E-type pulse forming network discharged through a self breaking pressurized nitrogen switch, and produced a rectangular pulse of 4 μs duration. A liquid resistor, R_LIQ, connected as shown in Figure 1, was used to match the 100 ohm pulse forming network to the test chamber.

Figure 1. The experimental test setup. The water filled test switch is S_1, which is terminated in a short circuit. The gas switch, S_2, is a 100 psi transfer switch from which the time datum is taken.

The test chamber is of coaxial geometry, with an impedance of 52 ohms, and is terminated in a short circuit. The chamber is constructed of polycarbonate resin which surrounds a liquid filled section. The liquid filled section is nearly a liter, and is small compared to the rest of the discharge chamber. The electrodes were constructed of stainless steel in a hemispherical profile, and the test chamber is designed for safe operation at pressures up to 400 atm. The outer conductor is constructed of stainless steel, the inner conductor is nickel plated naval brass, and the dielectric isolating interface is Lexan®. These materials were chosen for their high yield strength and chemical resistance (resistance to leaching) in water.

The onset of breakdown was measured with a current viewing resistor at the short circuit termination of liquid discharge chamber. Delay time to breakdown information was obtained by converting the light output of the self-breaking spark gap into a TTL voltage, which
is used to trigger the oscilloscope. Hence, the oscilloscope is triggered when the high voltage pulse is applied to the cathode, giving an absolute measure of the lag time to breakdown. A representative waveform obtained with this arrangement is shown in Figure 2.

![Figure 2. The current pulse as measured by the current viewing resistor. The delay time to breakdown is the time between the arrival of the pulse at the gap and when the current becomes circuit limited.](image)

The experiment was designed so that a constant voltage pulse was applied to a liquid filled test gap. This occurs whenever the lag time to breakdown exceeds the rise time of the applied pulse. Experiments under similar conditions were performed on the air saturated and the de-aerated samples.

### De-aeration Apparatus

The initial purification used a deionization column configuration, which assured a minimum resistivity of 10 MΩ-cm. Steps were taken in the design to maintain this purity level during the remainder of the purification process. Materials that come into contact with the water were chosen for their chemical inertness. Teflon, being very chemically inert in water, is used wherever possible. Pyrex reservoirs were used as intermediate storage units.

Great care has been taken to eliminate dissolved air in the test water. The purification/de-aeration process is illustrated in Figure 3. The test liquid is placed in the first Reservoir, R₁, and a light vacuum is applied. The vacuum is adjusted so the process is gentle. Ultrasonic waves are applied to the test water in this reservoir to excite the dissolved gas into forming a bubble. The bubble rises to the surface due to the pressure difference induced by the vacuum and is sucked into the roughing pump.

A peristaltic pump, which will not re-introduce air back into the purified water, transports the water between reservoirs. This pump is equipped with an all teflon pump mechanism to maintain the purity of the water. Reservoir #2 feeds a high pressure hydraulic pump. The high pressure pump acts as a verification test for the de-aeration process.

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![Figure 3. The de-aeration column.](image)

At atmospheric pressure, the liquid and the gas which is dissolved in the liquid are in equilibrium. Dissolved gas in a liquid can be thought of as a solution, in which the solute is the gas and the liquid, the solvent. When pressure is applied to the liquid/gas solution, that equilibrium is shifted to favor the liquid. Gas, previously dissolved in the liquid, comes out of solution as bubbles. These bubbles are easily recognized if they travel through a liquid filled viewing chamber. Verification of deaerated liquid can thus be obtained.

### Experimental Results and Discussion

The experiment was performed in which water that was carefully de-aerated and purified is compared to that which was purified but not de-aerated. The latter is considered an equilibrium solution of gaseous air and water, and is referred to as being air saturated. Large number of events were recorded, thus, it should be noted that the test liquid was replenished during the sequence, to insure the integrity of the water.

The results of measuring the delay time to breakdown is illustrated in Figure 4, with the gap length as a parameter. The electric field within the gap is varied by adjusting the distance between the electrodes. Large gap spacings produce low electric fields, with accordingly larger lag times to breakdown and standard deviations. The electric fields at the largest gap lengths correspond to threshold breakdown fields, and the
magnitudes of the delay times in this experiment reflect the probabilistic nature of the breakdown event. The standard deviations of the lag times are statistically significant: the number of trials is in the range of 50 to 100 shots, with the one exception. The 1.15 mm gap establishes such a strong electric field that it converges to an average value with very little deviation with sample size of 25 events. A similar plot for the air saturated water mandated a larger sample size.

The averages for the air saturated water deviate significantly from the degassed sample. Even more striking is the effect on the standard deviations of the samples. The scatter plots as a function of shot number are shown in Figure 6 for both the air saturated and de-aerated sample. The air saturated test water shows an unexpected large standard deviations from the average. For instance, at low electric fields, the lag time to breakdown in degassed water is \( (2.47 \pm 1.6) \mu \)s. The magnitude of the standard deviation reflects the low electric field in the interelectrode gap. For the same experimental parameters, the air saturated water has a delay time to breakdown of \( 4.97 \mu \)s with an incredible standard deviation of \( 7.47 \mu \)s, with a sample size is 100 events.

The effect of degassing the test water is illustrated in Figure 5. The average values of the delay time to breakdown for degassed water can be compared to those for air saturated water, as a function of the interelectrode gap. On average, air saturated water takes a significantly longer time to complete the prebreakdown process. The effect is independent of the gap spacing. Another notable trend in comparing the effects of degassing the liquid is on the standard deviation of the lag times. For the air saturated water, the standard deviation is very large compared to that of de-aerated water.

Figure 6. is a comparison of two scatter plots for the air saturated and de-aerated water samples. The air saturated sample shows a marked increase in jitter, which is amplified at the low electric fields in the gap.
The experimental results consistently show that the de-aerating the water decreases the average lag time to breakdown and stabilizes it by reducing the switch jitter. These results may provide an insight into the initiation mechanism of breakdown phenomena in liquids.

The theory that electrical breakdown in liquids is initiated in a gaseous phase within the liquid is inconsistent with the above observed experimental results. The data suggests that bubble formation in a gaseous phase is not the primary mechanism by which liquids fail electrically. Degassing the liquid results in the absence of nucleation seeds, in the form of dissolved gases, which drastically reduces the possibility that bubbles are produced. In the absence of nucleation sites, that is in the degassed liquid, the lag time was significantly lower than in the air saturated water which is evidence that bubble generation is not a necessary condition of the initiation of electrical breakdown in liquids. It does not preclude the existence of other thermally induced processes which may facilitate the onset of electrical breakdown.

To conclude that prebreakdown phenomena in liquids is not necessarily due to the existence of a gaseous phase does not fully explain the observed experimental data. The question remains: Why are the lag times to breakdown different at all, then? The answer likely lies in the chemical makeup of the dissolved air. Air is composed principally of atomic nitrogen (78.08%) and oxygen (20.95%) by volume with other trace constituents. Nitrogen is a very inert gas, but oxygen is highly electronegative. The formation of the ion O− has an electron affinity of 33 kcal/gm-ion, which is nearly that of sulfur hexafluoride, SF6,2, the electronegative gas of choice for many applications. Other oxygen compounds are also strong electron scavengers: atomic oxygen has an electron affinity of 10 kcal/gm-ion, and ozone, 45 kcal/gm-ion. Furthermore, a dissociation product of the water molecule itself, (OH), is strongly electronegative with an electron affinity of 45 kcal/gm-ion.

The measurements indicate that dissolved air in the water strongly increases the mean lag time and the jitter relative to de-aerated water. This result is consistent with the scenario in which electrons are captured by a strongly electronegative gas dissolved in the water. Moreover, this is consistent with the experimental results of A. Beroual, who used an additive electron scavenger, chlorocyclohexane (CCL4), in pure cyclohexane (CH)[B]. The addition of the electron scavenger indicates that electronic processes are involved in streamer prebreakdown mechanisms.

The large statistical variation in the lag time to breakdown further argues against the formation of prebreakdown bubbles. The availability of a large number of nucleation sites would facilitate the formation of a gaseous channel, minimizing the standard deviation of the lag time to breakdown if a true bubble mechanism were required.

Conclusions
This experiment has investigated the role of dissolved air in the electrical breakdown of liquids by measuring the lag time to breakdown. The presence of dissolved air significantly increases the lag time to breakdown under uniform field conditions. Moreover, de-aerating the water reduces the jitter, that is, the statistical variation, in the time delay of the switch.

It is suggested that the presence of dissolved air in the test water introduces electron scavengers into the test media, which may explain the larger lag times to breakdown reported for the air saturated water.

It is well known that the dissolved air in a liquid acts as a nucleation seeds for phase changes. Thus, the experimental data indicates that the presence of dissolved air (nucleation sites) inhibits the onset of breakdown. This, in turn, implies that electrical breakdown, under these experimental conditions, is not initiated in a gaseous phase.

References