Dielectric-breakdown tests of water at 6 MV

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(Received 6 May 2008; published 30 January 2009)

We have conducted dielectric-breakdown tests on water subject to a single unipolar pulse. The peak voltages used for the tests range from 5.8 to 6.8 MV; the effective pulse widths range from 0.60 to 1.1 μs; and the effective areas tested range from 1.8×10^5 to 3.6×10^6 cm^2. The tests were conducted on water-insulated coaxial capacitors. The two electrodes of each capacitor have outer and inner radii of 99 and 56 cm, respectively. Results of the tests are consistent with predictions of the water-dielectric-breakdown relation developed in [Phys. Rev. ST Accel. Beams **9**, 070401 (2006)].

DOI: 10.1103/PhysRevSTAB.12.010402 PACS numbers: 52.80.Wq, 77.22.Jp, 84.60.Ve, 84.70.+p

Large-area water-insulated electrical components are often incorporated in the designs of multiterawatt pulsed-power accelerators, such as the Z [1–10] and ZR [11] machines. Water-insulated components are also proposed for use in future accelerators [12–19]. Optimizing the design of such an accelerator requires a knowledge of the conditions under which its water-insulated components can be operated reliably.

Reference [20] proposes that the characteristic time delay τ_{delay} between the application of a voltage to a water-insulated anode-cathode gap, and the completion of dielectric failure of that gap, can be approximated as follows:

$$\tau_{\mathrm{delay}} = \tau_{\mathrm{stat}} + \tau_{\mathrm{form}}. \tag{1}$$

In this expression τ_{stat} is the statistical component of the delay time; i.e., the characteristic time between the application of the voltage and the appearance of free electrons and ions that initiate the formation of streamers in the water. We define τ_{form} to be the formative component: the time required for the streamers to propagate across the gap and evolve sufficiently to produce complete dielectric failure.

To inhibit electrical breakdown, water-insulated components are usually designed to produce a nominally *uniform electric field* over most of the component's area. We assume that, when the area of a water-insulated system with a uniform field is sufficiently large, the appearance of free electrons and ions necessary to initiate a breakdown occurs *somewhere* in the system very early in the voltage pulse [20]. Under this condition the statistical time delay τ_{stat} can be neglected, and the breakdown delay is dominated by its formative component:

$$\tau_{\mathrm{delay}} \sim \tau_{\mathrm{form}}. \tag{2}$$

In principle, dielectric breakdown dominated by the formative component can be studied with an electrode geometry that consists of a point anode and a planar cathode [20–22]. Although measurements with an infinitely field-enhanced anode point and an infinitely extended flat cathode are not possible, a number of dielectric-breakdown measurements between a *significantly field-enhanced* anode electrode and a *less-enhanced* cathode have been described in the literature.

Using these measurements, Ref. [20] finds that complete dielectric failure is likely to occur in water between a field-enhanced anode and a less-enhanced cathode when

$$E_p \tau_{\mathrm{eff}}^{0.330\pm0.026} = 0.135 \pm 0.009. \tag{3}$$

In this expression $E_p \equiv V_p/d$ is the peak value in time of the spatially averaged electric field between the anode and cathode (in MV/cm, where V_p is the peak voltage difference and d is the minimum distance between the electrodes), and τ_{eff} is the temporal width (in μs) of the voltage pulse at 63% of peak. This relation is based on 25 measurements for which $1 \leq V_p \leq 4.10$ MV, $1.25 \leq d \leq 22$ cm, and $0.011 \leq \tau_{\mathrm{eff}} \leq 0.6$ μs.

To develop a tentative design criterion for a *large-area* water-insulated system with a nominally uniform electric field, Ref. [20] further applies a safety factor to Eq. (3) by reducing the right-hand side by 20%:

$$E_p \tau_{\mathrm{eff}}^{0.330} \leq 0.108 \quad \text{when } A \gtrsim 10^4 \text{ cm}^2, \tag{4}$$

where A is the effective area of the system. Equation (4) assumes that the area of the system is sufficiently large to have a negligible statistical time delay, and hence that the breakdown delay is dominated by the formative component. Both Eqs. (3) and (4) assume that voltage pulses of interest have normalized time histories that are mathematically similar; under this condition, $\tau_{\mathrm{eff}} \propto \tau_{\mathrm{delay}} \sim \tau_{\mathrm{form}}$.

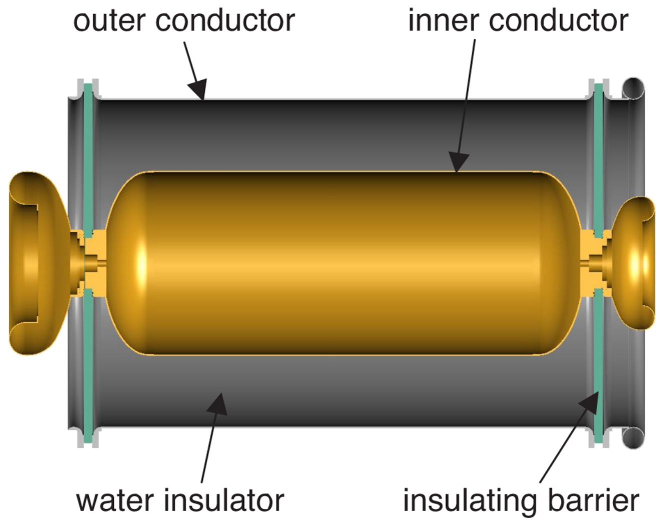

FIG. 1. (Color) Cross-sectional view of a ZR-accelerator intermediate-storage capacitor. The two electrodes have outer and inner radii of 99 and 56 cm, respectively.

In this article, we describe three tests of Eq. (4), which we believe are the first performed under the following simultaneous conditions: (i) peak voltage ≥ 4.10 MV, (ii) AK gap ≥ 22 cm, (iii) effective pulse width ≥ 0.6 μs, and (iv) effective anode area $\geq 10^4$ cm^2. Two of the tests were conducted on the 36-module ZR accelerator; the third was conducted on the Z-20 machine, which is a single ZR module used for component development.

All the tests were performed on one or more water-insulated intermediate-storage capacitors. A cross-sectional view of a single capacitor is presented by Fig. 1. The capacitor includes two coaxial electrodes. The inner radius of the outer electrode is 99 cm; the outer radius of the inner electrode is 56 cm; and the anode-cathode gap is 43 cm. The total effective area of the anode of a single capacitor is 1.8×10^5 cm^2. The electric field at the anode is nominally uniform. The voltage across each capacitor was measured using the D-dot monitor described in Ref. [23].

The tests were conducted over the course of operating the ZR and Z-20 accelerators for various experiments, and were not performed on accelerator shots dedicated specifically to measuring the dielectric strength of water. Given the high voltages involved, large AK gaps, long pulse widths, and large areas, dedicated shots require a substantial investment of resources and hence are not readily conducted. For this reason, we report in this article results of tests that were performed during normal accelerator operation.

Results of the tests, along with those previously described in Ref. [20], are summarized by Table I. Two capacitors were used for the 5.8-MV test; the corresponding voltage pulses are plotted by Fig. 2. One capacitor was used for the 6.8-MV test; 20 were used for each of the five tests conducted at 6.1 MV. For the 6.8- and 6.1-MV tests, the voltage pulse applied to each capacitor was shortened by closing a switch that was connected to the capacitor's inner conductor. Correcting for the coaxial geometry, we find that the peak anode electric fields were 0.103, 0.121, and 0.108 MV/cm for the 5.8-, 6.8-, and 6.1-MV tests, respectively.

The values of $E_p \tau_{\mathrm{eff}}^{0.330}$ for all the tests are listed in Table I, and suggest that the results are consistent with Eq. (4). (The results are also consistent with the predictions of Woodworth and colleagues [26].)

In addition to Eq. (3), other published water-dielectric-breakdown relations are considered; specifically [21,22,27,28]:

$$E_p \tau_{\mathrm{eff}}^{1/3} A^{0.058} = 0.230, \tag{5}$$

$$E_p \tau_{\mathrm{eff}}^{1/3} A^{1/10} = 0.3, \tag{6}$$

TABLE I. Conditions under which dielectric breakdown of water is observed *not* to occur. Each of these five observations was made on a large-area ($A \geq 10^4$ cm^2) water-insulated system with a nominally uniform electric field. The quantity V_p is the peak voltage difference between the anode and cathode, d is the minimum distance between the electrodes, $E_p \equiv V_p/d$, and τ_{eff} is the temporal width of the voltage pulse at 63% of peak. The last column assumes E_p is expressed in MV/cm, and τ_{eff} in μs. The Maxwell-Lab measurements were performed on a capacitor with coaxial electrodes that had outer and inner radii of 60 and 48 cm, respectively [22,24]. The peak field E_p given for the Maxwell measurements is that at the outer conductor (which was the anode), and is corrected for the coaxial geometry. The peak fields of the tests described in the present article are similarly corrected. The observations summarized in the table are consistent with the design criterion given by Eq. (4).

Reference	Number of accelerator shots	A (cm^2)	V_p (MV)	d (cm)	E_p (MV/cm)	τ_{eff} (μs)	$E_p \tau_{\mathrm{eff}}^{0.330}$
Measurements conducted by Maxwell Labs [22,24]	(not available)	5.5×10^4	2.1	12	0.150	0.5	0.119
Ref. [25]	~1500	5.3×10^5	3.6	14	0.257	0.083	0.113
Present article	1	3.6×10^5	5.8	43	0.103	1.1	0.106
Present article	1	1.8×10^5	6.8	43	0.121	0.60	0.102
Present article	5	3.6×10^6	6.1	43	0.108	0.63	0.093

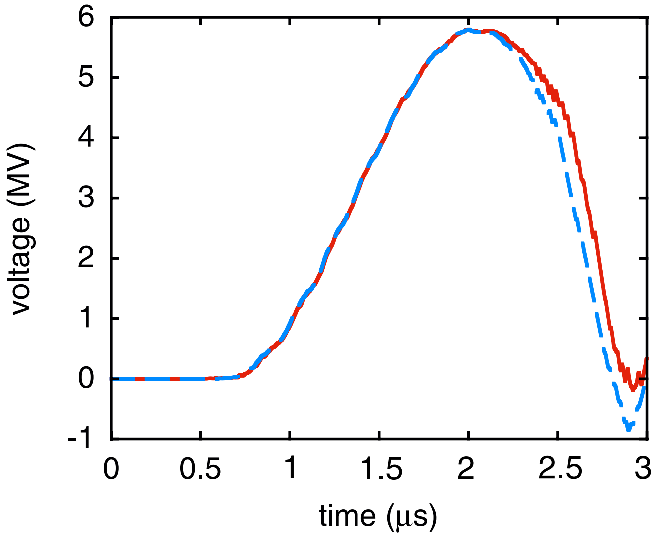

FIG. 2. (Color) Time histories of the voltage applied to the two ZR intermediate-storage capacitors that were used for the 5.8-MV test.

$$E_p \tau_{\rm eff}^{0.4} = 0.11, \tag{7}$$

$$E_p \tau_{\rm eff}^{0.5} = 0.1, \tag{8}$$

$$E_p \tau_{\rm eff}^{0.5} = 0.133. \tag{9}$$

[Equation (5) is obtained from Ref. [27], Eq. (6) from [21,22], Eq. (7) from [28], and Eqs. (8) and (9) from [22]. Equations (5)–(9) are given as Eqs. (1), (2), and (6)–(8), respectively, in Ref. [20].] As discussed in Ref. [22], Eqs. (8) and (9) were proposed as tentative relations, and were only intended to be preliminary. Equations (5), (6), and (8) are evaluated by Smith and colleagues in [29]. Equation (6) and other water-breakdown relations are discussed by Zahn and co-workers in a comprehensive review article on water insulation in pulsed-power systems [30].

Equations (5)–(9), like Eq. (3), estimate conditions under which the probability of water breakdown is ~50%. Applying a 0.8 safety factor to the right-hand sides of Eqs. (5)–(9), one obtains

$$E_p \tau_{\rm eff}^{1/3} A^{0.058} = 0.184, \tag{10}$$

$$E_p \tau_{\rm eff}^{1/3} A^{1/10} = 0.24, \tag{11}$$

$$E_p \tau_{\rm eff}^{0.4} = 0.088, \tag{12}$$

$$E_p \tau_{\rm eff}^{0.5} = 0.08, \tag{13}$$

$$E_p \tau_{\rm eff}^{0.5} = 0.106. \tag{14}$$

Table II compares the predictions of Eqs. (4) and (10)–(14) with the test measurements. The results suggest Eqs. (10)–(13) are more conservative—but less accurate—than Eq. (4). Equation (14) is less conservative than Eq. (4); however, Eq. (9) [from which Eq. (14) is derived] is significantly less consistent than Eq. (3) with other measurements (Ref. [20], Table II).

Finally, it is worth noting that Eqs. (3) and (5)–(9) estimate conditions under which the failure probability is ~50%. At present, it appears that the literature does not describe explicitly how these relations are to be used to estimate, *in general*, a failure *probability* for arbitrary experimental conditions [20–22,27–30]. For this reason we simply use a 0.8 safety factor to obtain Eqs. (4) and (10)–(14). Applying this approach to obtain Eqs. (4) and (12)–(14), one makes the implicit assumption that the water-streamer velocity cannot be much greater than its average value. This might not be too unreasonable, since Table II suggests Eq. (4) is a useful design criterion for a large-area uniform-field system. Nevertheless, it would be of interest to develop a water-dielectric-breakdown expression that estimates the failure probability under a given set of conditions, and to compare the predicted probabilities to measurements.

TABLE II. Comparison of the results summarized by Table I with the predictions of Eqs. (4) and (10)–(14). The second column lists ratios obtained from the equations; columns 3–7 list values of the ratios for the 2.1-, 3.6-, 5.8-, 6.8-, and 6.1-MV tests, respectively. The values listed in the first five rows suggest Eqs. (10)–(13) are more conservative—but less accurate—than Eq. (4). The first and last rows suggest Eq. (14) is less conservative than Eq. (4); however, Eq. (9) [from which Eq. (14) is derived] is significantly less consistent than Eq. (3) with other measurements performed at megavolt voltages (Ref. [20], Table II).

Equation	Ratio	2.1-MV test	3.6-MV test	5.8-MV test	6.8-MV test	6.1-MV test
(4)	$(E_p \tau_{\rm eff}^{0.330})/0.108$	1.10	1.05	0.98	0.94	0.86
(10)	$(E_p \tau_{\rm eff}^{1/3} A^{0.058})/0.184$	1.22	1.31	1.21	1.11	1.21
(11)	$(E_p \tau_{\rm eff}^{1/3} A^{1/10})/0.24$	1.48	1.75	1.59	1.42	1.75
(12)	$(E_p \tau_{\rm eff}^{0.4})/0.088$	1.29	1.08	1.21	1.12	1.02
(13)	$(E_p \tau_{\rm eff}^{0.5})/0.08$	1.33	0.93	1.35	1.17	1.07
(14)	$(E_p \tau_{\rm eff}^{0.5})/0.106$	1.00	0.70	1.02	0.88	0.81

ACKNOWLEDGMENTS

The authors would very much like to thank J. Porter, R. Leeper, and our many other colleagues at Sandia National Laboratories, EG&G, Ktech Corporation, L-3 Communications, and Team Specialty Products for invaluable contributions. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract No. DE-AC04-94AL85000.

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