Theoretical Notes

Note 312

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Comments on Soil Breakdown

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ABSTRACT

The breakdown date for atmospheric air and liquids are critically reviewed in order to provide guidance and test planning of soil breakdown study.

1. General Objectives

The main objective is assumed to be to help plan and interpret an experiment on the buried resistive link. Understanding of other potential breakdowns between buried objects on the MX site is also of interest.

2. Background

A summary of the "engineering" approach to the bulk breakdown of dielectrics may be useful in deciding how to characterise the breakdown of soil. Atmospheric air, which will be the "weakest link" dielectric in soil, and perhaps liquids, are the most relevant dielectrics.

2.1 Air Breakdown

Uniform field air gaps have a breakdown field given by

$$F = 24.5 + 6.7\, d^{-1/2} \quad (\text{kV/cm})$$ [1]

at atmospheric pressure; d is the spacing in cm. Thus 25-30 kV/cm is typical of microscopic gaps. However, under short pulses ($\lesssim 10\ \mu$sec) breakdown may not occur at these fields because no electrons happen to be present to start an avalanche; at high fields, electrons will be extracted from the negative electrode and breakdown will follow--at 60-100 kV/cm depending on electrode condition and area.

Ionizing radiation can supply electrons and keep the breakdown strength near the d.c. value. However, for short times higher fields are withstood even with irradiation; J.C. Martin has suggested $F \propto t^{-1/6}$ when the pulse duration t is less than about 100 nsec.[2,3]

In highly enhanced gaps the field at one or both electrodes, being much higher than the average field, initiates breakdown locally, early in a pulse. The eventual closure of atmospheric air gaps with one field enchanced electrode (point-plane or edge-plane gaps) has been characterized by J.C. Martin[4] in the equation

$$Ft^{1/6}d^{1/6} = 24$$

where t is the pulse duration in μsec. This holds for gaps up to 5 m in length and pulse durations up to about 100 μsec. For gaps of order 1m and times of order 100 μsec, the breakdown field is only of order 5 kV/cm. It matters little in air whether the point or edge is postive or negative, but in other gases this is not true; in SF_6, for example, a positive point or edge breaks down much more readily than a negative point or edge.

During the breakdown of a point-plane gap, streamers are progressing from the point. The time dependence of the motion prior to closure has not been investigated, though J. C. Martin has interpreted the point plane result to suggest a particular time dependence which he found to be in agreement with photographs of incomplete streamers from the ARES transmission line.[5]

Air/dielectric interfaces in uniform fields may track at somewhat lower fields than the free air would withstand, because of field distortions produced by dielectric polarization or by surface charges. Usually the strength reduction is no more than tens of percent, but a poorly designed interface may approach the point plane result.

Once the breakdown occurs, it causes the voltage applied by the driving circuit to fall in a time of about

$5\rho^{1/2}/F_M^{4/3}Z^{1/3}$ (nsec)[6]

where Z is the driving impedance in ohms, the initial density in g/cm^3 and F_M is the field in MV/cm. For air with $F \sim 25$ kV/cm, $Z \sim 10$-100 ohms, $\rho \sim 10^{-3}$, this is of order 10 µsec. This "resistive phase" is associated with the initial hydrodynamic expansion and heating of the ionized channel, whose conductivity does not grow much after it reaches a few electron volts. It may be preceded by a period of much higher resistance, but this is usually neglected. In times of order 100 nsec or more the spark resistance can be neglected compared with the driving impedance, and is usually significant only in determining the energy deposited. In the 100-1000 µsec range, the voltage drop is of order 50 V/cm and 50V at each electrode, not greatly dependent on current; in the microsecond range it has not been measured to my knowledge.*

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* But see Addendum.

It should be added that many long-lived ($\sim$ 1 µsec) high impedance streamers were photographed to close from the high voltage transmission line of the AFWL Siege Development Facility to ground. This has not been related to other work. The more common observation in a multimegavolt simulator is that a $\sim$ 1 m arc rapidly shorts out a 50-100 kA driving circuit, i.e. it develops less than 0.1 ohms/cm and less than 1000 V/cm, at least by the time that the inductive phase is over (time constant 100 nsec)

2.2 Liquid Breakdown

In uniform fields or somewhat enhanced gaps, breakdown is usually represented by an equation of the form

$$Ft^{1/3}A^{M} = k$$

For water,[7] for example, $k \sim 250$ for the positive electrode, and $k \sim 500$ for the negative electrode,[8] which is stronger. This applies for times ≤ 1 µsec; for times 1 µsec, the time dependence becomes gradually weaker. The term A^M, where A is the electrode area in cm^2, and M = 0.05-0.1 represents the statistical fact that larger areas are likely to have a weaker spot. This effect is not considered important in low pressure gases, but is likely to be even more important in an inhomogeneous and variable medium like soil. The stressed volume, rather than area, may be the important variable in soil (as it is for homogeneous solids, where M $\sim$ 0.1)

Point plane gaps in liquids break down by streamer propagation. Streamer velocities depend in a complicated way on voltage and field, though average closure velocities can be described by empirical equations such as

$$u = 10Vt^{-1/2} \text{ (V in MV)}^{9}$$

for water. As with air, the motion of the streamer at times less than the breakdown time t has not been studied.

Liquids of density one have resistive phases that are approximately consistent with the formula previously given. In water, a significant residual voltage drop along the channel has been inferred after the resistive phase is over. This decays comparatively slowly. In high current circuits it is hard to measure because of inductive drop, and it has been represented in more than one way.[10,11,12] J.C. Martin[1] suggests a voltage drop given by $5t^{1/2}$(kV/cm), roughly independent of current in the $10^5 - 10^6$ A range. However, the effect is apparently medium dependent, since much smaller gradients occur in oil.[13] As distinct from the initial resistive phase, this late-time voltage drop is suggested to be due to slow convective expansion and radiative cooling of the channel.

3. Small Scale Test Results

The small scale tests ($0.5 < d < 3$ cm, $A \sim 100\text{cm}^2$) reported by Jaycor (Report 200-81-201/2148) show mean fields at breakdown of about 20-30 kV/cm under voltage pulses with an effective duration of about 0.1 μsec. This approximates the expected breakdown strength of air. The fields in the air gaps in the soil are locally enhanced by the irregular permittivity and conductivity, and this and the dirty conditions should ensure initiating electrons. A weak time dependence is present, of order $t^{1/6} - t^{1/4}$ according to Fig 24, but becomes weaker for durations greater than about 0.2 μsec; this also resembles the behavior of air.

The formation of discrete breakdown channels is shown by the damage to the soil. It is confirmed by the shot-to-shot variation of breakdown; this would not be expected if the soil were reacting in bulk. The variations are large enough to suggest that statistical size effects will be signficant when scaling is considered.

The resistive phase characteristic of the initial voltage fall (Fig 3) is about 20 nsec under a breakdown field of 20kV/cm. For a 50 ohm driving circuit, a value of 10 nsec would be expected for air; if the medium density is taken to be unity, the resistive phase would calculate to be ~300 μsec. Thus the resistive phase is much more characteristic of air than of a high density medium, but is somewhat long; this may be because the soil cools the channel and prevents its expansion, or because the breakdown path length around soil grains is greater than the minimum gap, which reduces the effective field driving the channel.

A feature that might not be expected for air is the large voltage drop that is present and decays slowly after the initial resistive phase. In Fig 3 (0.5 cm sample) voltage drops of 2-3 kV/cm remain for 0.1 μsec on a breakdown channel carrying 150 -200 A, decaying to about 1 kV/cm after 0.3 μsec. In Fig 14 (2cm sample), a drop of 10 kV/cm immediately after breakdown decays to 5 kV/cm after 0.5 μsec. Since in both cases the soil has 4.5% water, the breakdown field is 20 kV/cm and the current ~100A, the reason for the different voltage drops per cm is unclear; but the important point is that this kind of residual gap voltage is not normally anticipated at all.

There are two possible interpretations of the residual voltage drops observed in soil. First, the cooling of the channel by the high density soil produces a lossy voltage drop comparable to that observed in water; the residual fields are rather less than those in water, perhaps because the current is much less or perhaps because of the air voids. Second, the voltage drop is characteristic of air, but has not previously been observed because fast breakdowns are usually driven by much larger currents, which produce an inductive drop that masks the resistive drop for hundreds of nanoseconds.

The interface tests made by Jaycor showed that the reduction of breakdown strength was significant but modest, again in keeping with experience in air. This is confirmed by the fact that in the ~100 cm^2 tests of bulk soil an interface at the soil container was safely subjected to a field about half that in the bulk soil.

4. Implications for Buried Cable Test

The small scale test results imply that the buried cable will start to break down radially on the leading edge of the voltage pulse generated by the SREMP. If the applied field is modelled by 2MV at a distance of 1000 m, the field on a 1 cm radius wire is 174 kV/cm.

The chief uncertainty is how far the breakdown will propagate. Even if we assume the soil behaves just like air we can only obtain limited information. Using the air point-plane result, under an effective pulse duration of 100 μsec the cable would spark to a 2MV electrode at distances up to about 5m; in the absence of any electrode nearby at a fixed voltage, the propagation distance will certainly be less than 5 m, and may of course be very much less.

It is likely that both in air and in soil the streamers propagate rapidly at first from the field enhanced region then slow down as the gross field on the region of the streamer front decreases. In designing an experiment using a relatively close electrode to produce the initiating field, it is necessary to decide how far the electrode must be placed in order that the maximum streamer propagation distance does not make the field distribution non-representative; if the electrode is too close, the gross field on the extended streamer tips will exceed that in the real case and the streamer will progress too far or break down all the way to the high voltage electrode.

As an example of this, if the cable is surrounded by a 1 m radius electrode, 800 kV is require to produce the 174 kV on a 1 cm radius cable; complete breakdown between the cable and the electrode is predicted to occur in about 7 usec, according to the point plane result.

The small scale tests suggest that soil breakdowns are more resistive than air breakdowns, which is a positive outcome. However, since longitudinal conduction in transverse air streamers cannot be assessed from previous work, it is not quantitatively useful. It does suggest that air breakdown above the ground might be important, since resistance might be lower there.

The tests indicate that the plastic cable interface will not be a weak link.

The tests also suggest that irradiation is not needed to initiate breakdown within the soil; however, the presence of ionising radiation from the bomb should be borne in mind; its effect could be checked on a small scale test.

5. Objectives of 1 m Tests

The most important information needed is the streamer conduction distances vs. time, before breakdown. This is needed to help assess both the real cable and the planned test. As discussed above, it is likely that in a highly enhanced gap the streamers grow rapidly out to a radius at which the gross field has fallen to some value (perhaps much less than the initial breakdown level), then grow more slowly, or stop. This can be verified, and approximate models constructed for streamer velocity and maximum extent, by measuring current versus time in coaxial configurations where the soil conductivity is known; the conductivity needs to be checked at high fields.

In order to help the scaling of results, data on the complete breakdown of edge plane (coaxial) and point plane gaps should be taken from a few hundred kV to the maximum set by flashover round the experiment, or by the Marx. These tests are essentially the tests already proposed with 1 cm and 10 cm electrodes.

It is also desirable to check the length scaling of uniform field breakdown, using 10-20 cm gaps with ~20 cm radius electrodes. This is because statistical size effects may make the breakdown fields lower than in the small scale tests; and also because electrode effects appear to have complicated the interpretation of smaller gap data. The conductivity of soil at high fields can also be obtained from these tests and compared with the value at low fields.

So far, all the tests discussed can be done with a high impedance (~ 100 ohm) source, which will minimize damage and speed data collection. Data on the resistance of channels verus time and current is also desirable for an understanding of breakdown in general and how it relates to previous knowledge. However, it will be hard to apply this data to the problem of longitudinal condition through a transversely broken soil region. The data will also be harder to collect, because of the damage caused to the soil. Thus the arc resistance should perhaps be of lower priority.

Adequate resistance data can be obtained using the 240 kV generator alone (avoiding possible synchronization problems), using ~10 cm gaps--indeed, it could be got still more readily by driving the small scale test samples with higher current, longer pulse sources. The difficulty will be to subtract inductive voltages.

Finally, I would expect that measurements of channel resistance will show that the voltage drop on the channels increases only weakly with current, so that the channel resistance becomes at high currents quite negligible compared with that of the circuit; and that it falls even more through the microsecond time range. Thus the resistance data is relevant mainly to energy deposition or damage predictions.

6. Buried Cable Test

As discussed at Dikewood on 17 March 81, the proposed experiment in which a length of cable buried in soil is driven simultaneously with transverse electric field and longitudinal current appears soundly based and should provide realistic information on the real case. Conditions that must be met are:

(1) The tranverse streamer propagation distance must be controlled and monitored. It must also roughly match that expected in the real case; this distance can be estimated from separate experiments with a transverse field source alone. The main requirement here is that the radius of the test electrodes be adequate. The radius will determine the

minimum useable length, and the radius and length together determine the source energy needed.

(2) The longitudinal current source must have high enough voltage and impedance to maintain the design current against possible increases in cable resistance, if the cable design will produce such increases (e.g. if metal resistors are used) The longitudinal current can be made less than that anticipated in the real cable, to reduce source energy, but its effect on the cable resistivity as a function of time must be roughly correct.

ADDENDUM

In "Pulse Generators", 1964, Published by Boston Technical Publishers Inc, under the MIT Radiation Lab. Series and edited by G.N. Glasoe and J.V. Lebacqz, there are measurements of the voltage drops in the 0.3 - 5 μsec range on sparkes carrying 50-100A, in H_2 and Ar. These suggest about 150-100 V/cm from 0.4-5 μsec, with somewhat higher drops for the first four hundred nanoseconds.

References

Note: Many of the AWRE Notes referenced below are incoporated in the AFWL Note Series related to EMP. In some instances below, the AFWL note reference is given in parentheses.

1. DC Breakdown Voltage of Non-Uniform Gaps in Air, J.C. Martin SSWA/JCM/706/67 June 1970 (AFWL Dielectric Strength Note 16)

2. High Speed Pulse Breakdown of Pressurized Uniform Field Gaps, J.C. Martin SSWA/JCM/708/107 Aug 1970.

3. High Speed Breakdown of Pressurized SF and Air in Nearly Uniform Gaps, J.C. Martin SSWA/JCM^6/732/380 (AFWL Switching Note 21)

4. Pressure Dependency of the Pulse Reduction of Gases, J.C. Martin SSWA/JCM/7679/71 (AFWL Dielectric Strength Note 15)

5. "Corona on the ARES Transmission Line" J.C. Martin, SSWA/JCM/704/33

6. "Duration of the Resistive Phase of Spark Channels", J.C. Martin, SSWA/JCM/1065/25, October 1965 (AFWL Switching Note 9)

7. "Impulse Breakdown of Deionized Water" I.D. Smith, SSWA/JCM/6511/8 (AFWL Dielectic Strength Note 4) and "Further Breakdown Data Concerning Water" (AFWL Dielectric Strength Note 13) I.D. Smith SSWA

8. P.D'A Champney. Impulse Breakdown of Water with Asymmetric Fields, SSWA/PDAC/6610/103, October 1966 (AFWL Dielectric Strength Note 7)

9. "A Possible High Voltage Water Streamer Relation" J.C. Martin, Unpulished.

10. "Expansion of a Spark Channel in a Liquid", YU V Skvortsov et al, Zh, Tekh Fiz. 30 No. 10 p. 1165.

11. "Some Thoughts on the Resistive Phase of Water Spark Channels", J.C. Martin, Unpublished.

12. "Inductance and Resistance Characteristic of Single-site Untriggered Water Switches", P.W. Spence et al, 2nd IEEE International Pulsed Power Conference, 1979, Lubbuck TX.

13. "Study of Arc Characteristics in High Velocity Oil Stream." V.A. Datsenko, V.L. Korol'kov and A.E. Nesterenko, Elektrotekhnika, Vol. 48, No. 10, pp. 44-46, 1977.