Switching Notes

Note 27

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BREAKDOWN OF UNIFORM FIELD PRESSURIZED SF_6 SPARK GAPS AS A FUNCTION OF CHARGE TIME

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ABSTRACT

A survey of available literature and existing simulators has been made to determine the breakdown field strengths of pulse charged SF_6 spark gaps, in particular when they are rapidly charged, as in peaking circuits.

1. DATA

Switch data are summarized in Table 1. An AWRE note [1] gives data for switches in several pulsers built by J.C. Martin's group: Plato, Web, and Tom, half and full scale. Characteristics are summarized in Table 1.

Reference [1] gives two measures of the charge time: the durations at 63% and 89% of peak. The use of the 89% value follows J.C. Martin's treatment of the breakdown of point plane gaps at pressures of one to a few atmospheres, where the breakdown field is proportional to $t^{-1/6}$.

The rationale for 89% is that breakdown proceeds at a rate proportional to E^6, where E is the electric field. The breakdown constant for square pulses is then given by the equation [1]

$$E^6 \, t = \text{a constant} = k^6 \tag{1}$$

where

$$E \, t^{1/6} = k \tag{2}$$

For arbitrary waveforms,

$$\int E^6(t) \, dt = k^6 \tag{3}$$

The integral can be approximated by using the peak value of E and multiplying by the FWHM of E^6, which is the width of E(t) at the 89% ($0.89^6 = 0.5$) level, here designated t_{89}. The result for non-square waveforms then becomes

$$E \, t_{89}{}^{1/2} \cong k \tag{4}$$

where E now refers to the peak value of E(t).

Since the uniform field gaps have a breakdown strength whose time dependence is again weak and not dissimilar from a 1/6 power law, the use of the duration at the 89% level is more appropriate than that at the 63% level. Thus the data used from [1] is that for t_{89}, and the same definition is applied in analyzing the results for the other switches considered in this note.

For both Plato with $t_{89} \sim 40$ ns and Tom with t_{89} varied from 3.5 to 13 ns, the pressure dependency from 1 to 7 atm. abs. is well described by a variation of breakdown field as $p^{0.7}$, a

Table 1. Switch parameters.

Switch	Gap (V/E_{pk}, cm)	Area (cm^2)	$\sqrt{LC}$ (ns)	t_{89} (ns)	E at 1 atm. (MV/m)	E at Max P (MV/m)	Max P (atm.)
Plato (AWRE)	2.3	~ 1	270	40	14.0	64.0	7.0
Web (AWRE)	1.0	~ 10	100	25	11.0	48.0	4.5
Tom (slow) (AWRE)	1, 2.4	25, 100	103	13	16.5	59.0	7.0
Tom (fast) (AWRE)	1, 2.4	25, 100	28	3.5	21.0	74.0	7.0
ATHAMAS I (HPD)	5	~ 50	100	12.5	----	43.0	5.2
ATHAMAS II (VPD-II) (AFWL)	7	120	120	15	----	38.5	3.5
ATLAS I (Trestle) (AFWL)	7	~ 20	60	7	----	56.0	7.7
ATLAS I (Trestle) (AFWL)	4.5	~ 40	60	7	----	87.5	7.7
TEMPS (PI)	7	~ 100	40	5	----	70.5	5.8
Fast Switching (PI)	0.2	< 0.1	7	0.6-1	----	250.0	16.3

simplification first suggested by Maxwell Labs during the development of Trestle. This result will be assumed in what follows.

Plato is relatively slowly charged, breaking down near the peak of a (1-cos) waveform. The electrode area is small. Its performance may be characterized by a breakdown field (E_o) of 14 MV/m at 1 atm.

Both of the Tom switches were used in peaking mode, firing near the midpoints of the (1-cos) waveform, and the time constant was varied by a factor of about four. The extreme cases are designated "slow" and "fast"; in each of these the two gaps gave similar breakdown fields, characterized by E_o = 16.5 and 21.0 MV/m at t_{89} = 13 and 3.5 ns respectively.

The Web switch appeared to have an essentially linear pressure dependence, at least up to 4 atm., with only 11.0 MV/m at 1 atm. If we calculate $E_o = E/p^{0.7}$ from the 4 atm. results we get 16.7 MV/m at 1 atm. Here we take an average, E_o = 13.9 MV/m.

For ATHAMAS II (VPD-II), the operators of this facility state that an 8.5 cm, 40 psig switch breaks at 2.7 MV. Calculating the field enhancement as 22% for the 50 cm diameter of the positive electrode gives E_o = 16.0. The charge waveform for the peaking capacitor as shown in [2] gives t_{89} = 15 ns.

For ATHAMAS I (HPD), the operators indicate a breakdown voltage of 2.6 MV for a 6 cm gap at 50 psig. Assuming that the field enhancement is 20% (similar to VPD-II), E_o = 16.7 MV/m. The switchout time of the peaking circuit is 150-180 ns, from which $t_{89} \cong 12.5$ ns.

Data has also been supplied for ATLAS I (Trestle). The East Side switch operates at 4.75 MV Marx voltage without enhancement from the sharp edge, which is retracted. The spacing is 6.4 cm at 100 psig. From the electrode shapes and the field distribution calculated by Maxwell for a 12 cm gap, the field on the positive plane electrode is estimated as 56.0 MV/m, assuming the switch voltage to be about 4 MV. This corresponds to an E_o value of 13.5 MV/m. The gap does not break down from this electrode, however, so that this is a lower limit for the positive electrode. Breakdown occurs from the outer radius of the negative cone electrode, where the field is similarly estimated at 87.5 MV/m, giving E_o = 21.1. For the East switch, breakdown occurs at 94 ns and t_{89} is estimated to be 7 ns.

For the West ATLAS I (Trestle) switch, field enhancement on the negative (plane) side of an 11 cm, 100 psig gap is used to regularize breakdown at slightly smaller voltages and times. The field at the edge of the positive cone is again estimated at 56.0 MV/m; since this is a lower limit to the breakdown field and the time is smaller than for the East switch, this adds no additional information.

In TEMPS, the output switch gap is stated to be 7.1 cm at 70 psig for "nominal" 6 MV operation. About 5 MV is probably across the switch, since the prepulse is 1 MV. Because of the electrode shapes, it is mainly one side of the switch that is enhanced (and only sightly). Assuming that this is the negative side, and that on the positive side the field is equal to the average, gives E_o = 20.5 MV/m. [3] states that the peaking capacitance is 0.5 nF, the Marx 2.5 nF, 5.8 μH, and the switchout time 65 ns; from this, $t_{89} \cong 5.0$ ns.

Fast switching experiments by Physics International [4] provides the shortest pulse charge time data at present available. The output switch charge waveform was not measured. For the purposes of this note, the values of t_{89} have been estimated from the circuit values given, and from the ratio of the switch output voltage to the voltage on the charging capacitor. A range of ratios and fields is given in [4], and this corresponds to different switchout times on the charge waveform. Two representative sets of values of time and field are given in Table 1.

2. ANALYSIS OF RESULTS

The data for E_o and t_{89} is summarized in Table 2 and plotted against log-log scales in Figure 1. The almost straight line plot clearly suggests a dependence of the form $E\,t^n$ = a constant. When all positive electrode data are included, the best fit result (correlation coefficient r = 0.989) is

$$E_o = \left[30.7\ t_{89}^{-0.237}\right]\ (\mathrm{MV/m}). \qquad (5)$$

where t is in units of nanoseconds.

It can be argued that the Plato data should be excluded, since the charge time is longer than the range of chief interest here, and at long times the time dependence must weaken. Also, the charge waveform is different. Without Plato the best fit is

$$E_o = \left[31.1\ t_{89}^{-0.252}\right]\ (r = 0.995)\ (\mathrm{MV/m}). \qquad (6)$$

According to this result, the breakdown field at 1 atm. becomes 8.8 MV/m, the dc strength of SF_6, when t_{89} reaches approximately 150 ns. At some shorter time, the time dependence implied by the formula must therefore begin to weaken. This, and the higher correlation coefficient obtained, support using the data without Plato. The rounded result

$$E_o = \left[31\ t_{89}^{-0.25}\right]\ (\mathrm{MV/m}) \qquad (7)$$

or

Table 2. Summary of values of E_o and t_{89}.

(Breakdown field = $E_o\ P^{0.70}$, where P = pressure in atm. abs)

Switch	t_{89} (ns)	E_o (MV/m)
Plato	40	14
Web	25	13.9
Tom (slow)	13	16.5
Tom (fast)	3.5	21
TEMPS	5	20.7
ATHAMAS I (HPD)	12.5	16.7
ATHAMAS II (VPD-II)	15	16.0
ATLAS I (Trestle) (+)	7	> 13.5
ATLAS I (Trestle) (-)	7	21.1
PI Fast Switching Experiments	1.04	30.8
PI Fast Switching Experiments	.655	36.0

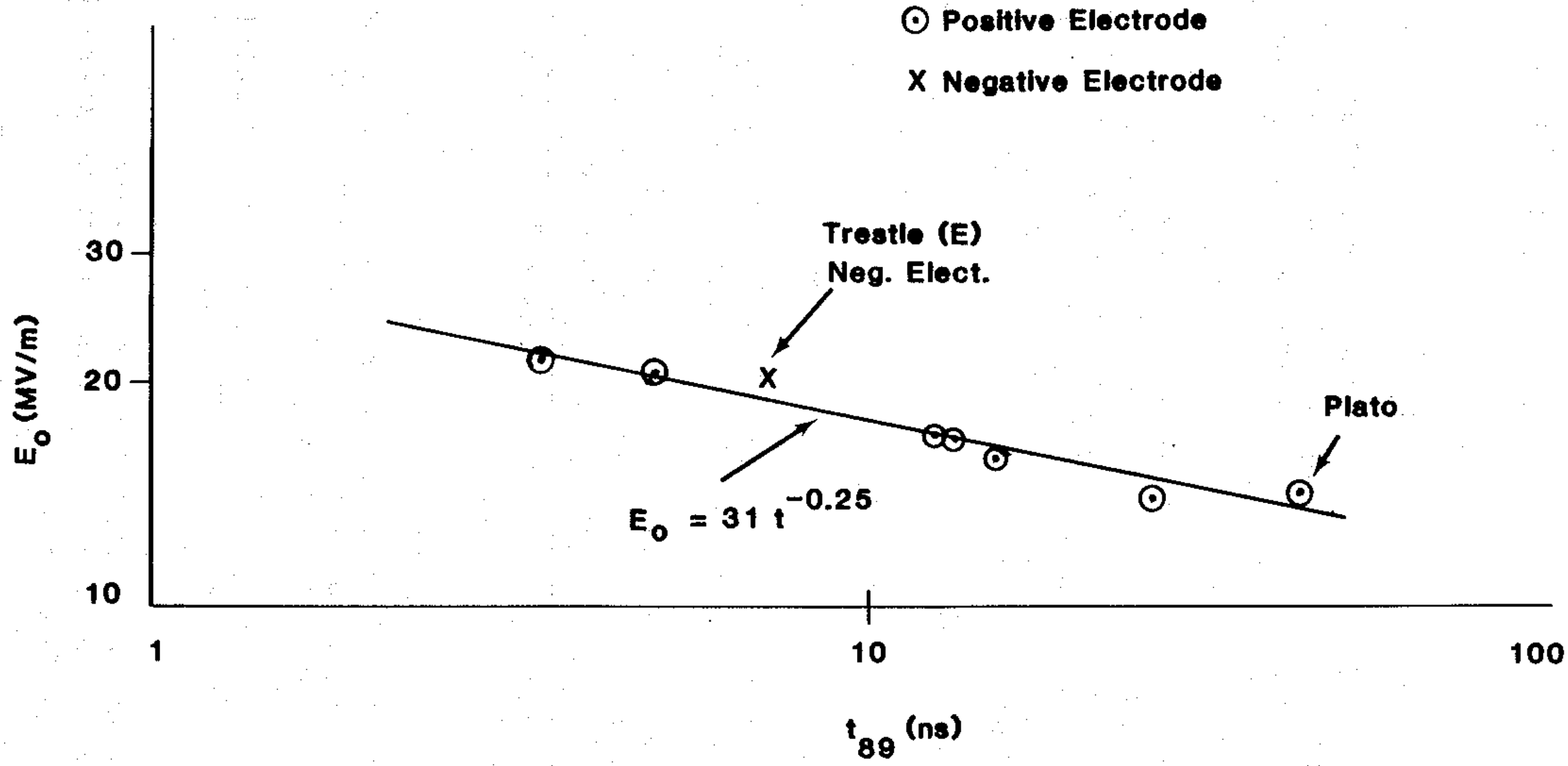

Figure 1. E_o as a function of t_{89}.

$$E_o \, t_{89}^{1/4} = 31 \qquad (8)$$

is proposed. Including pressure dependence, this becomes

$$E \, t^{1/4} = 31 \, p^{0.7}. \qquad (9)$$

The range of validity of this result is roughly t_{89} = 0.5 to 25 ns. For smaller values of t_{89}, the time dependence is unknown. For larger values, the time dependence is known to disappear, and E_o approaches 8.8 MV/m. The $p^{0.7}$ pressure dependence is not checked above 7 atm.

Note that the result for the negative electrode in the ATLAS I (Trestle) East switch is about 11% higher than (9) suggests. This supports, though not very strongly, the assumption that the positive electrode controls. Other evidence to this effect in-cludes a measurement made by the author at AWRE that indicated a ~ 20% polarity effect in this sense for a moderately field-enhanced geometry (no sharp edge) with a few hundred ns charge time; and the fact that for sharp edged electrodes the breakdown field is considerably larger when the edge is negative (a factor of about two greater for p = 5 atm.).

Some additional comments are as follows.

There is no evidence that the breakdown field depends on spacing. The Tom results indicate that it does not.

There is presumably some effect of area, but it does not seem to be large. All the data except Plato is for EMP simulators where the total charge transferred is small and the electrodes are relatively smooth. Very rough electrodes may break at lower fields, especially at higher pressures.

3. REFERENCES

1. J.C. Martin, "High Speed Breakdown of Pressurized Sulphur Hexafluroide and Air in Nearly Uniform Gaps", Switching Note 21, February 1972.

2. "Survey of Existing High Altitude Burst Simulator Technology," PITR-3348-1, Physics International Company, August 1985.

3. H. Aslin and I. Smith, "Pulsed Power for EMP Simulators," IEEE Transactions on Antennas and Propagation, January 1978, pp. 53-59.

4. T. Naff, Physics International Company, Private Communication, 1987.