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A Model that Predicts Pulse Charged Gas Switching Breakdown Phenomena

(PULSE CHARGED GAS BREAKDOWN)

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I. Introduction

Multi-terawatt accelerators utilize large numbers of gas switches and the accelerator performance is directly related to gas switch performance. For instance, PBFA-I[1] has 576 Marx gaps and thirty-six 2.7 MV pulse charged electrically triggered gaps. PBFA-II will have 1080 Marx gaps and thirty-six 5.5 MV pulse-charged laser triggered gaps.[2] Understanding of gap breakdown mechanisms provides confidence in switch designs and their operational characteristics. No overall model of pulse charged gas switching was found in the literature. In fact, conflicting data and conclusions were often uncovered. Until now, the basic data generated by the pulsed-power community from pulse charged gaps has not been considered in developing models of gas breakdown processes.

This paper uses the pulsed power switching data to develop a new model of gas switching. The extended model explains such diverse phenomena as prefire probabilities, breakdown voltages, triggered switching delays, triggered breakdown mechanisms, and effects of electrode surface finish on gap breakdown in pulse-charged switches.

The concept of a streamer initiating at some predictable field in a pulse charged switch and then propagating across the gap is reasonable and was previously proposed at the Atomic Weapons Research Establishment (AWRE).[3] However, the prediction of the initiation field and the positive

streamer propagation characteristics when calculated are inconsistent with the gap breakdown data.

In this paper an alternate model is proposed: A negative streamer begins when the electric field on either electrode reaches the dc breakdown field. the streamer propagates at a velocity given by the AWRE negative streamer data. The model is related to dc models in other ways. The distribution of voltages at breakdown under dc conditions is translated into the distribution under pulsed conditions through the streamer propagation time. The model works equally well when the streamer is intentionally initiated by triggering; subsequent streamer propagation predicts the time and voltage of breakdown.

The alternate model proposes that the negative streamer closure (not the positive) initiates the current rise of the gap. A considerable quantity of experimental data supports this proposal: First, the close correlation between theory and data presented here. Second, the holographic data from Sandia showing a backstrike developing in SF_6 inside a preformed channel that carried no initial current.[4] Third, the AWRE streamer data for air that showed no breakdown difference between positive or negative streamers since their experiment measured current to determine breakdown.[5] Fourth, the Soviet data in air where the positive and the negative streamers were photographed, showing the fast positive streamer with a negative streamer backstrike traveling at the velocity predicted by AWRE.[6] In all of these experiments, the current in the gap started when the negative streamer closed the electrodes. This data shows the dominance of the negative streamer.

The model was first developed for SF_6 breakdown, then extended to air breakdown by using data from the Soviet literature.[6]

A "streamer bunching phenomena" was discovered and shows that the variation in the voltage at breakdown for pulse-charged gaps is less than it is in dc gaps. Next, valid estimates for gas gap prefire probabilities for both dc and pulse charged gaps (a central issue in building large accelerators) are provided. A trigatron is a particular type of triggered gas switch. The realization that triggered gap breakdown is similar to self-breakdown allows prediction of trigatron characteristics. Trigger gap geometry, trigger delays, and trigger polarity effects are estimated.

The general characteristics of pulse-charged gaps will first be described in Section II. The data and equations will be presented to show correlation and boundaries of the operating regions.

II. A Map of Gas Switch Phenomena Based on the Model

Figure 1, shows the electric field on the electrode as a function of pressure for different stages of gas breakdown. For a given experiment, the gas pressure is constant while the pulsed voltage is applied between the switch electrodes. The figure is typical of gas gaps where the streamer-transient time accounts for a reasonable (approximately 20%) portion of the gap's voltage hold off capability. In actual time, the voltage will typically reach peak within 1 to 2 μs for SF_6. The phenomena can be divided into four phases. These phases are represented by regions on the E vs. P plot in Fig. 1 and constitute a model of the phenomena in pulse-charged and triggered gaps.

A. Lower pressure gap operation

First, the switching process will be described for a gas switch operating at relatively low pressures (below 2 atmospheres). The voltage increases from zero at time t = 0. Streamers cannot be initiated until the electric field on the electrode, E_o, is reached. E_o is the breakdown field strength of an infinitely large electrode at the same gas pressure.[7] Region 1, in Fig. 1, is therefore the parameter space where no streamers should exist unless an external trigger is applied.

The next phase is bounded by dc gas breakdown. This straight line,in Fig. 1, represents the intrinsic gas breakdown that can be derived from basic parameters of the gas and the gap electrode field enhancement factor. For SF_6 the value is approximately 89 kV/cm-atm.[8,9] Streamers are assumed to leave from the electrode by the time this field is present if a small quantity of ionized particles is available (or a rough surface exists).

In principle, if no ionized particles are available and if the electrodes are smooth with small area, then streamers can leave at fields above the dc gas breakdown. In practice with large-area rough electrodes, the dc breakdown line is seldom exceeded more than a few percent.[7]

The region between the E_o and dc breakdown boundaries describes where streamers are initiated, and is shown at the "range of streamer release" in Fig. 1. The voltage range within Region II for streamer initiation in a particular gap depends on electrode area, surface finish, and gas pressure. For instance, a single gap with relatively small electrodes will start streamers over a relatively narrow range near the dc gas breakdown line. Alternatively, a large-area rough electrode will have a broader distribution located closer to the E_o curve. These distribution functions are known and can be expressed with a Wiebull format.[7]

The "streamer-release range" includes the portion of Region II where streamers are initiated and are traveling across the gap. The upper limit to Region II is formed by the line labeled "typical pulse-charged large-switch self-break." This line represents the typical pulse-charged breakdown voltage that is recorded during an experiment. This line is assumed to be determined by the final closure of the negative streamer from the cathode in the proposed model.

Negative and positive streamers have very different velocities. The positive streamer can close to the cathode about twenty times faster than the negative streamer velocity but produces a low conductivity cloud-like plasma.[6] Next, the negative streamer backstrikes through the positive streamer cloud at much less velocity. A true negative streamer without a positive streamer cloud appears to be an unlikely event in most pulse-charged gaps. Even if the negative streamer is launched first, it can be overtaken by the rapidly traveling positive streamer.

Very little gap current flows until the negative streamer crosses the gap. The current rise after the negative streamer closes defines breakdown and is generally fast (a few nanoseconds) and is limited by the AWRE resistive risetime formula providing inductive effects are small.[3]

At lower pressures, the negative streamer arrives and the gap breaks down when the electric field is greater than the dc breakdown line. This low pressure characteristic occurs because the streamers do not leave the electrodes until fields close to dc breakdown are reached and because the streamer velocity is slow at low pressures.

Region III in Fig. 1, can only be reached by an abnormally delayed streamer initiation. This delay was achieved by Ramirez[10] who took great care in preparing the electrode surfaces for a single gap and used a fast rising (~ 1 μsec) voltage pulse. Operating in this region was difficult, the scatter in the breakdown field was large, as expected from the proposed switching model. A small amount of UV radiation on the electrodes, electrode damage, or high gas pressure precludes operating in this region because these effects initiate the streamers at or below the dc gas breakdown line.[7]

B. Higher pressure gap operation

In a gap operating at high pressure (greater than about 3 atm), the average field for streamer initiation generally occurs closer to the E_o line in Fig. 1. The pulse-charged, large-switch, self-breakdown curve "rolls over" because the streamers are now initiated at almost the same voltage which is independent of gas pressure. Additionally, the distribution of voltages, at which the streamer initiates, increases with pressure.

As the gas pressure is increased to several atmospheres and greater, the average field for streamer release no longer increases linearly with increasing gas pressure. Since the gas avalanche length is inversly proportional to the gas pressure, the avalanche length becomes comparable to the electrode surface perturbations, and the electrode surfaces appear "electrically" rough. Thus, a gap that is well behaved and linear at lower pressures develops into an ill-behaved large-spread gap at high pressures.

C. Gap triggering characteristics

For this model, a triggered gap is treated as a self-breakdown gap after the streamer is initiated by the user. Consequently, the only absolutely safe electric field for triggering lies below E_o in Region 1. If a gap is triggered above this range, a streamer may already be present.

In practice, the probability of a streamer already being in the gap at fields slightly above E_o may not be great enough to appreciably affect accelerator operation even on large systems. Delaying the triggering into the region slightly above E_o has some desirable advantages. The delay between the trigger initiation and gap breakdown becomes less and jitter is decreased. However, when operating at fields above E_o, careful analysis of the data is necessary to assure that the gap is being triggered and that the prefire rate is acceptable for the particular application. This model has placed an important feature of a pulse-charged gap in perspective, the trade-off between prefires (streamers leaving before trigger application) and jitter (the variation in the time of gap breakdown).

To date, the triggering mechanism in trigatron gaps has been obscure. The proposed explanations include UV illumination from the trigger pin, or a fast plasma driven into the gap by magnetic fields. In the model presented in this paper, the trigger simply initiates the first streamer with a trigger voltage instead of waiting for gap statistics to initiate self-breakdown. The subsequent process is very similar to that of the self-breakdown gap, except that the triggered traveling-streamer is also driven (aided or retarded) by the trigger voltage.

Support for this hypothesis is found in data where the gap between the trigger pin and its surrounding electrode closed to ground before the main gap broke down.[6] According to this model, the shorting of the trigger pin should reduce the voltage driving the streamer and increase the delay to breakdown. In the other explanations, providing current to the trigger discharge should enhance the proposed mechanisms and reduce breakdown times. The data clearly shows that when the trigger voltage shorted early, the gap delay increased.

D. Repetitive gap operation

If a gap is repetitively operated in a region of Fig. 1 where the electrode's surface roughness affects the dc breakdown (well into the flat E_0 region), then the electrode surfaces can condition (look electrically smoother) and the distribution function for streamer initiation shifts toward the dc gas breakdown line as repetitive shots condition the electrodes. The electrical discharges then successively destroy the more highly field-enhanced points. The upward conditioning happens when the gap discharge current is large enough to destroy electrode roughness, but not large enough to cause electrode damage. Nitta has analyzed data using a 25 shot conditioning phase and presents data in the Weibull format to describe the process.[7]

This conditioning process can allow gaps to self break in the final region - Region IV of Fig. 1. The streamers are simply released later in the voltage charge cycle. The final gap closure voltage is therefore higher when gap breakdown finally occurs. Large areas or roughened electrode surfaces will increase the number of shots required to reach this conditioned mode. When operating in this mode, the average self-breakdown voltage will increase and the distribution will narrow as the number of pulses increases when compared to a "single shot" distribution.

This model predicts that the breakdown voltage of repetitive trigatron gaps will not increase with the number of shots if it is always triggered at the same time and voltage on the charging wave form. This useful outcome occurs since the initiation of the streamer is determined by the trigger voltage while the streamer transient time is determined by the gap and trigger voltages. The percent of self-breakdown voltage at which a pulsed charged gap is operated becomes meaningless in this model's context (a popular method of scaling switching results). The model explains why, in several cases, this scaling method has failed on Sandia trigatrons.

E. Overall gap map

Taking a look at pulsed gap operation from the standpoint of varying gap pressure is interesting. The interaction between the dc breakdown and streamer characteristics becomes clearer. The gap characteristics have been explained at low and high pressures and at low and high fields through the dependence of streamer initiation and propagation time on gap pressure and electrode effects. In addition, a minimum delay point (and probably minimum jitter) has been found and explained at the "roll over" point of the pulse-charged, large-switch, self-break breakdown curve. The "roll over" point occurs where the self-break electric field becomes only weakly dependent on gas pressure.

At lower pressures, the streamer initiation point scales rather linearly with small spread as the pressure is increased. This phenomena was attributed to the streamer initiating near the calculated value of dc gas breakdown. J. C. Martin and his colleagues at the Atomic Weapon Research Establishment (AWRE) have studied breakdown and have obtained empirical relations between the various variables. Data on the breakdown of pulsed gaps with a single highly field-enhanced electrode have been reduced to a formula for streamer transit in SF_6.[5]

$$F\, t_{eff}^{1/6}\, d^{1/6} = Kp^{n} \qquad (1)$$

Where F equals the gap voltage at breakdown divided by the electrode spacing (d), t_{eff} is the time the voltage exceeds .89 of the breakdown voltage, P is the absolute pressure in atmospheres, K is a constant depending on polarity and type of gas and n is .4 for SF_6.

t_{eff} is proportional to the time a streamer takes to close the gap. Next, solving for t_{eff} gives

$$t_{eff} = \frac{K^6}{F^6\, d}\, p^{.4} = K_1\, \frac{p^{.4}}{F^6} \qquad (2)$$

At low pressures, the breakdown field increases with pressure, so

$$F \approx p \qquad (3)$$

and, substituting into Equation 2 yields

$$T_{eff\ low\ pressure} \approx \frac{p^{.4}}{p^6} = \frac{1}{p^{5.6}} \qquad (4)$$

Therefore, the streamers take longer to close the gap at low pressures and times shorten dramatically as the pressure is increased. The overall effect is a pulsed breakdown curve with a pronounced "front bump" at low pressures. This region is shown as the portion of Region II above the dc gas breakdown line.

At higher pressures the situation is considerably different. Since the streamer initiation point becomes almost independent of pressure (approaching the E_o curve), we find

$$F \sim \text{constant} \quad (5)$$

and the higher pressure t_{eff} becomes

$$t_{eff\ \text{high pressure}} \approx p^{.4}$$

or at higher pressures the streamer time lengthens proportional to $p^{.4}$.

Since the time decreases by $1/p^{5.6}$ at lower pressures, and the time increases as $p^{.4}$ at high pressure, then there is a minimum streamer time (or triggering time) for a spark gap. This minimum time is at the "rollover" point which in turn is a function of gas pressure, electrode surface area, and surface roughness.

The model described in Section II will be compared to various applications in Section III and compared quantitatively to existing data.

III. Methods of Calculation and Supporting Data

The SF_6 dc breakdown criteria I have found the most useful are those obtained from T. Nitta,[7] which I used along with the streamer propagation criteria proposed by J. C. Martin.[5] These two sources provided the initial mathematical description for the model. Nitta's data was obtained by using rather low dc voltages, while Martin's relations for streamer propagation covered a limited gap voltage and pressure range and did not allow for streamers starting at initially different times. The synthesis of Nitta's and Martin's works provided the quantitative framework for this proposed model for gas switching. The Soviet data, for air, provided guidance and further verification for the model.

A. DC breakdown analysis

Nitta suggested three different probability distributions for switch breakdown. All of these are used for this switch model and can be thought of as three separate hypothetical switches connected in parallel. Together they provide the externally observed characteristics of a single real switch. I have designated the first hypothetical switch as the "good" gap breakdown (GGBD) switch; the second as the "poor" gap breakdown (PGBD) switch; and the third as the "conditioned" gap breakdown (CGBD) switch. The overall switch probability of breakdown is a function of all three of these parameters. Each of these hypothetical switches will now be described.

1. Good gap breakdown

The "good" gap breakdown (GGBD) is the probability distribution that describes the dc breakdown of a well-polished, UV-illuminated gap. It has a dc voltage breakdown that is linear with pressure and, consequently, has low spread in breakdown time and voltage. This is the dc gas breakdown line shown in Fig. 1. The corresponding equation for SF_6 can be obtained from a handbook.[8]

$$V_{BD} = 88.4 \ P \ d/FEF \tag{6}$$

where P is the gas pressure in bars, d is the gap spacing in cm, and FEF is the electrode field enhancement factor, the ratio of the electrode's field to the mean gap field.

Equation 6 is the voltage with 50% probability of good gap breakdown. The distribution of breakdown is provided by modifying the perfect-gap equation by a breakdown distribution that is only a function of voltage. Using the data from Nitta, I calculated the Weibull equation:

$$F_1(E) = 1 - \exp\left[- 1.77 \times 10^{-44} \ (E/P)^{22.2}\right] \tag{7}$$

where $F_1(E)$ is the cumulative probability that the "good" gap will break at a given dc (or 60 Hz) voltage with a negative electrode field of E kV/cm and a pressure of P bars of SF_6. Equation 7, therefore, is Eq. 6 with a narrow breakdown spread added and the 88.4 constant modified by about four percent to fit the data.

2. Poor gap breakdown

The "poor" gap breakdown (PGBD) describes the second -- and probably most important -- hypothetical switch model. PGBD describes a large area, rough electrode gap. This distribution determines the large, high-voltage, high-pressure gap phenomena encountered on most pulsed power accelerators. The PGBD distribution is a function of gap area, gap pressure, and surface roughness. Fortunately, these effects are partially separable and somewhat independent. The PGBD predicts the "rollover pressure", that is, the gas pressure at which the gap breakdown voltage no longer increases linearly. Nitta proposed that his data is best described in the Weibull format by using the E_o. A graph of E_o is presented by Nitta in the reference.[7] E_o was easily approximated with portions of five straight lines.

Nitta's relation for PGBD is

$$F_2(E) = 1 - \exp\left[-7.2435 \times 10^{-16}\, A(\mathrm{cm}^2)\, (E-E_o)^{6.3}\right] \qquad (8)$$

where $F_2(E)$ is the cumulative probability of an unconditioned electrode gap breakdown; A is the effective gap area in cm^2 (the electrode area that is stressed within 90% of the maximum elastic field E on the negative electrode. The above distribution, $F_2(E)$, was obtained from the first 25 firings of gaps with areas between 500 cm^2 and 3000 cm^2 (an area that approximates the original PBFA I switches). The area term effect expressed in the Weibull format is derived by considering that one gap fired N times should have the same breakdown distribution as one gap fired one time with N times the area.

3. Conditioned gap breakdown

The "conditioned" gap breakdown (CGBD), described as the third hypothetical switch model, is the breakdown for a relatively small area, rep-rated switch after about 25 shots. The equation for this distribution, derived from the Nitta data, has a similar area term and a steeper slope than the $F_2(E)$ distribution.

$$F_3(E) = 1 - \exp\left[-4.687 \times 10^{-38} A(cm^2) (E-E_o)^{14.7}\right] \quad (9)$$

In the proposed model, I assume that these three hypothetical gaps connected in parallel will represent the actual cumulative probability of dc breakdown for a real single gap.

Two important large gas gap characteristics are now predictable. First, the prefire probability can now be calculated. The prefire probability is mainly determined by the poor gap streamer initiation probability (PGBD) and E_o and determine the "rollover" point where switch voltage becomes relatively independent of pressure in large accelerators with multiple switches. The rollover voltage and minimum triggering delay can then be calculated once the initiation model is combined with the streamer propagation model.

B. Streamer propagation formula

1. AWRE gas streamer formulas

J. C. Martin's group at the Atomic Weapons Research Establishment (AWRE) provided gas streamer data in 1967.[3] The AWRE parameter range was 15, 25, and 35 psia with pulsed voltages up to one megavolt and pulse times of .1 to 1 μsec.

A more compact summary was later given by AWRE[5] in Nanosecond Pulse Techniques. This formulation was for very divergent fields and included an added pressure dependent term. The equation was:

$$F_{\pm,}(d\ t_{eff})^{1/6} = K_{\pm,}\,p^{n} \qquad (10)$$

where the variables are as defined previously and p is in atmospheres. The constant values were given for three gasses as:

	Air	Freon	SF_6
K_+	22	36	44
K_-	22	60	72
n	0.6	0.4	0.4

TABLE 1

The exponent of the pressure applies from one to five atmospheres.

2. The streamer formula modification

The AWRE formulas must be modified before they can be used in this model. An understanding of these formulas and experiments will assist in deriving the modification. The original formulas differentiate only between streamers traveling under two different voltage waveforms. Those initiating at T = 0 and driven by a ramp voltage and those initiating at T = 0 and driven by a constant voltage. In the first case, the t_{eff} is defined as the time the voltage is greater than .89 of the breakdown voltage and in the second case the t_{eff} is the duration of the applied pulse (the total pulse time).[3] The AWRE experiment applied the voltage between the appropriate sharp point (cathode or anode) and a ground plane. The streamer was assumed to start immediately from the sharp point (the sharper, the better) and then propagate across the gap. Breakdown was detected by observing the rapid current increase in the external circuit. The time t and peak field F were obtained from oscilloscope data. Since the applied field affects the streamer closure time by approximately $1/F^6$, AWRE reasoned that only voltages (fields) near peak value were important; subsequently, they used peak fields to analyze their data.

The proposed switching model requires streamers to start when an appreciable initial voltage (dc breakdown) already exists between the electrodes and to predict streamer transit times as the voltage continues to increase. Figure 2, a voltage-time diagram, will explain modifications made to permit use of the previous AWRE data. Assume that the gap voltage increases in a linear manner from $V = 0$ and $t = 0$ to a level of $V = V_o$ and $t = T_o$ where "dc" breakdown occurs (the negative streamer is launched). The streamer next travels across the gap while the gap voltage increases above V_o. The streamer arrives at the other electrode at a later voltage of $V_o + \Delta V$ and time of $T_o + \Delta T$. Notice that these quantities are all linearly related when dV/dt is a constant; or

$$\frac{V_o}{T_o} = \frac{V_o + \Delta V}{T_o + \Delta T} = \frac{\Delta V}{\Delta T} \qquad (11)$$

The AWRE data can predict streamer transit times of either a ramp or a constant voltage. Fortunately, these two extremes can bracket the actual pulse charge conditions. The first model extreme, the shortest streamer travel time, is the rectangular (constant) voltage pulse between T_o and $T_o + \Delta T1$. T_{eff} for this case is $\Delta T1$ and the appropriate gap breakdown voltage is $V_o + \Delta V1$.

The second model extreme, the longest streamer travel time, is the voltage starting at $V = 0$ and T_o and increasing linearly to $V_o + \Delta V2$ at $T_o + \Delta T2$. The T_{eff} for this streamer is $.11\ \Delta T2$.

The actual voltage applied to the streamer lies between these two extremes. The actual streamer voltage starts at V_o at T_o then increases linearly until breakdown. Since we know the two extremes of breakdown voltages, $V_o + \Delta V1$ and $V_o + \Delta V2$, the actual gap breakdown lies inbetween these two.

An analysis to determine which extreme best predicts the actual streamer shows the ramp approximation is best for $T_o < .89\ T_{BD}$ while the constant voltage is best for $T_o > .89\ T_{BD}$. Next I found the two extremes converge to identical breakdown voltages as T_o approaches T_{BD}. The ramp voltage was then shown to be the more accurate approximation over the widest range of streamer release times.

A calculation was made to determine the maximum error of the voltage range assumption. The maximum error occurs when $T_o = .89\ T_{BD}$. At this time the constant voltage is accurate while the ramp voltage approximation has the largest error. The gap breakdown voltage using the ramp voltage was within 10% of that predicted by the constant voltage. The ramped voltage accuracy then improves as the streamer release point departs from $.89\ T_{BD}$.

As shown, the proposed linear rising voltage predicts the actual gap breakdown accurately. However, since the streamer travel time is a function of $1/V^6$, the gap voltage at closure time varies relatively little with substantial variations of streamer formulations.

C. <u>The computer model is described</u>

Solution of the implicit streamer equation requires a computer. A Fortran program was written which is shown along with a printout as Figs. 3 and 4. The switch designators used in this program are the ones used previously. Other parameters are T_o (actually only a poor estimate of T_o is needed), the voltage risetime; the gap length d; the negative electrode FEF; the active gap area A in cm^2; and the starting gap pressure p in psia. The computer program provides switch breakdown voltages and prefire probabilities for pressures between the starting gap pressure up to 120 psia in 10 psia increments.

The computer prints the following parameters: V(kV), P(PGBD), P(CGBD), P(GGBD), P(1TOT), P(2TOT), T(ns), ACT BDV, and ACT Field. The V(kV) is the voltage across the gap when the streamer leaves. The P(PGBD), P(CGBD), and P(GGBD) are the probability of three previously defined hypothetical switches initiating the streamer at V(kV). P(1TOT) is the cumulative probability of the good gap and poor gap 1-(1-P(PGBD)) (1-P(PGBD)), while P(2TOT) is the cumulative probability of breakdown of the good gap and the conditioned gap 1-(1-P(GGBD)) (1-P(GGBD)). ΔT (ns) is the actual streamer transit time (ΔT2) previously defined. The ACT BDV and ACT Field are the values of the gap voltage and cathode field at time of negative streamer closure (gap breakdown).

The mean field for initiating a streamer at a given pressure corresponds to the 0.5 probability of a streamer leaving. For larger accelerators, breakdown voltages corresponding to a low-probability of streamer initiation can be readily obtained from the printout. For instance, the probability of

0.2 and 0.9 or 1/36 and 1 are important prediction points for the 36-switch PBFA I or PBFA II.

Note that the average breakdown of a single switch must be modified (by using the appropriate number of switches in an assembly to define the area term) to obtain the average breakdown of the assembly. Otherwise stated, the more switches one has, the lower the average breakdown of the group.

IV. Some comparisons between the calculations and data

A. Sandia data comparison

The first data set is from a Sandia report being written by W. B. S. Moore.[4] Tests were conducted on switches with gap spacings of 9.2 cm and 11.2 cm. Electrical field plots of the switch for both gap spacings were done using the JASON computer code. A fine mesh was used to provide good FEF resolution. Table 2 shows the data summary along with calculated values in parenthesis for the switching model.

Initial Data and Calculations

Gap (cm)	Cathode kV/cm	Anode kV/cm	Cathode FEF	Anode FEF	V_{BD} (MV)	σ_{AV} %	P(80%)
9.2			1.31	1.48			

act	356	403			2.56±0.14	5.4	$1x10^{-4}$
calc	(356)	(412)			(2.50±.124)	(5.0)	($6x10^{-4}$)
11.17			1.44	1.59			
act	369	397			2.92±0.08	3.4	$2x10^{-9}$
calc	(376)	(416)			(2.80±.162)	(5.8)	($3x10^{-4}$)

TABLE 2

The V_{BD} (voltage at switch breakdown), σ_{AV} (one sigma deviation at breakdown), and P (80%) (probability of switch prefire at 80% of self-break voltage across the gap) were obtained with an SF_6 switch gas pressure of 60 psia.

Table 2 shows that the calculated model values are within 2.4% and 4.3% of the actual switch breakdown voltages and; further, the model predicts similar switch spread and prefire probabilities. The model spread values in the table are the combined probabilities of the P<PGBD> AND P<GGBD>. The calculations predict a streamer transit time of 17 ns for the 9.2 cm gap and 23 ns for the 11.2 cm gap at self-breakdown. Figures 5 and 6 show a complete comparison of the data and model predictions over a pressure range for the same switches. In Figure 5 (the 9.2 cm gap) and Fig. 6 (the 11.2 cm gap), the model provides average breakdown voltage and spreads that approximate test data rather well. The model predictions at 70 and 80 psia are a little low but close (~ 10%) and the distribution (width) of the data is very good. The switch model thus approximated actual switch breakdowns and data spreads with reasonable results, although over a rather limited pressure and voltage risetime range. In the next section, the model parameter range will be extended by further modification of the AWRE formula.

B. Comparison with further AWRE data

AWRE has previously designed and tested a rail gap (opposite facing, parallel cylindrical electrodes) for use on an Electromagnetic Pulse Generator.[11] They constructed a 1/2 linear scale model of a switch named Tom and called it 1/2 Tom. Breakdown data was presented on both switches in the report. A wide range of gas pressures was used on the gaps. In addition, the gaps were pulsed by two different risetime voltages -- 45 ns and 175 ns. Either risetime is considerably faster than the above Sandia switch risetimes. Since the two AWRE gaps are scaled in size, the field enhancement factors are about the same even though the distances are a factor of two different. AWRE presented the data as a varying function of $Ft_{eff}^{1/6}$ and gas pressure.

The AWRE test summary is shown in Table 3.

AWRE Experiment Summary

Test Unit	LC(ns)	THM T_o(ns)	Area (cm^2)	FEF	d(cm)
1/2 Scale					
Tom--Slow	103	175	25	1.2	1.25
Fast	28	45	25	1.2	1.25
Full Scale					
Tom--Slow	103	175	100	1.26	3.05
Fast	28	45	100	1.26	3.05

TABLE 3

Figure 7 compares the model calculation with the AWRE data for the Tom 1/2 and full-scale gaps for both the fast and slow pulses. In general, the agreement is fair. The calculated curves have similar slopes and values. As expected, agreement is best for the 100 ns risetime and low pressure where the original streamer data was taken. The gap distance and voltage predicted by the streamer formula appear to scale correctly between the 1/2 and full-scale Tom gaps. This data shows that the dc streamer initiation hypothesis is probably correct over a wide range of parameters. However, a pressure dependent modification to the streamer transient time formula could be done to better describe the data at higher pressures.

C. A modified streamer formula extends the model range

The new suggested modified streamer formula, obtained after a few tries is

$$\Delta T = \left(\frac{114\ d^{5/6}\ p^{.56}}{V} \right)^6 \qquad (12)$$

where this ΔT is the total streamer transient time after streamer initiation by the dc breakdown criterion. The formula is similar to the original except that the pressure term exponential is greater. New model calculations are compared with the AWRE data with the results shown in Fig. 8. The curve fits are excellent and the absolute values are much closer. The modified formula still closely approximates the original formula at lower pressures where the original streamer velocity data was taken.

Also, in Fig. 8, the calculated streamer transit times in nanoseconds are placed adjacent to the calculated model points. The calculated voltage for starting streamers for the 1/2 scale gap are also shown. The streamer transient time accounts for up to 50% of the gap's breakdown voltage. The predicted trend for a minimum streamer travel time at rollover is now noticeable.

Finally, the new streamer formula predictions were compared with the previous Sandia data and the difference was less than the scatter in the data.

D. Model calculation of trigatron characteristics

As previously stated, a triggered trigatron gap is a pulse-charged gap which is forced into initiating a streamer. If a streamer appears when the triggered gap is initiated (similar to dc breakdown), then the delay to gap breakdown can be calculated by this model. Note that the trigger voltage must be added to the gap voltage to calculate the streamer transient times. This fact simply explains much of the data regarding trigatron gap-trigger polarity. One expects that a trigger polarity that adds to the gap voltage is desirable (such as a positive trigger pulse on the positive electrode). It also explains why the highest possible trigger voltages should be used for low-jitter trigatrons.

The MITE-PBFA-I triggering delay data were collected and model streamer calculations were made. The Sandia 11.2 cm triggered gap (the same used for Fig. 6) data was obtained at a pressure of 60 psia. Actual and calculated delay times for this triggered gap are shown as Fig. 9. The agreement between the model prediction and actual trigger delays is good.

V. Streamer Bunching, an Important Phenomena

The model, subsequent data, and computer calculations indicate that another important phenomena is occurring in pulse-charge gas switching. The phenomena, named streamer bunching, will be described. If two streamers leave from similar electrodes in similar gaps at slightly different times, then they will arrive at the other electrode in the same sequence. However, the difference in arrival times will be smaller than the difference in their departure times. Streamer bunching occurs in a pulse-charged system if the voltage increases during streamer transit because the later departing streamer will travel faster in a slightly higher average field. Thus, the later departing streamer actually "gains" on the early departing streamer. This "streamer bunching" phenomena is appreciable for SF_6 since the time to closure is proportional to the inverse voltage to the 6th power. The phenomena explains the added channels in multichannel gas gaps and explains the decreased spread in self-breakdown voltages of pulse-charged gaps when compared to the gap's dc characteristics.

The bunching phenomena can now be calculated from the modified streamer formula to derive a bunching factor (BF). The BF is a function of the streamer starting time (T_o) and the streamer travel time (ΔT).

$$(\Delta T)^{1/6} = (T_{BD} - T_o)^{1/6} = \left(\frac{114 P^{.56} d^{5/6}}{V} \right) \qquad (13)$$

Again referring to Fig. 2, let the voltage across the switch at breakdown be

$$V = (V_o/T_o)(T_o + \Delta t) \qquad (14)$$

where V_o is the nominal streamer initiation voltage at time T_o and Δt is the streamer transient time. Substituting into Eq. 13 and rearranging, we find

$$\Delta t^{1/6}(V_o/T_o)\ (T_o + \Delta t) = 114\ P^{.56}\ d^{5/6} \tag{15}$$

We wish to find the $d\Delta t$ (jitter in streamer closure) as a function of dT_o (jitter in streamer initiation) while holding P, d, and the ratio of V_o/T_o constant. Rearranging, and differentiating yields

$$d\Delta t/dT_o = -6/(7 + T_o/\Delta t) \tag{16}$$

The nominal streamer arrival time (T_{nom}) is $T_o + \Delta t$. The actual streamer arrival time is

$$T_{act} = T_o + dT_o + \Delta t + d\Delta t \tag{17}$$

or

$$\frac{T_{act} - T_{nom}}{dT_o} = 1 + \frac{d\Delta t}{dT_o} = \frac{\text{arrival jitter}}{\text{initiation jitter}} = BF \tag{18}$$

substituting Eq. 17 we have

$$BF = \frac{1 + \frac{\Delta t}{T_o}}{1 + 7\,\frac{\Delta t}{T_o}} \tag{19}$$

The expected BF for a ramped voltage with various ratios of streamer crossing time to streamer initiation time ($\Delta t/T_o$) are given in Table 4.

$\Delta t/T_o$	BF
0.	1.0
.1	.647
.2	.500
.3	.419
.4	.368
.5	.333
.8	.273
1.	.25
5.	.167
∞	.143

TABLE 4

These calculated bunching factors show that streamer bunching is appreciable even for relatively small ratios of $\Delta t/T_o$. A very large bunching factor is readily provided by a highly field-enhanced switch where T_o is almost zero as in the AWRE experiments.

VI. Other Gasses - Air Trigatron Demonstrates the Backstrike Hypothesis

The initial data base was limited to SF_6 gas. A relatively complete comparison of the model with data has been given. During a search to find further data to substantiate the backstrike hypothesis, a Soviet article was found which verifies that a backstrike occurs in a dc air-insulated trigatron.[6]

As opposed to the AWRE observation that positive and negative streamers travel at the same velocity in air, the Soviets observed two stages to the air breakdown process. The first phase (when the gap was triggered) consisted of a very rapid, diffuse glow coming from the positive trigger pin which rapidly closed the gap with a velocity of 2×10^8 to 2×10^9 cm/sec. The trigger pin current was very low during this phase (less than 100 A). This initial ionization was later superseded by another process that developed into the main discharge. The second process was characterized by the development of a bright branch, the leader, which advances toward the triggered electrode. The Soviets observed that the leader never makes an appearance without the first ionization phase. When the leader closes, then breakdown occurs with resulting large currents. This Soviet description seems to provide the link between the leader, negative streamer backstrike, and current rise.

My calculations show that the Soviet leader velocity corresponds to that predicted by the AWRE, while the diffuse glow from the positive trigger pin was about 20 times faster and corresponds to the expected positive streamer velocity.

VII. Summary

The modified negative streamer formula, when used with the dc breakdown data from Nitta, predicts the actual gap breakdown voltage of SF_6 (and probably other gasses) pulse-charged gaps rather well. This model was successfully extended to predict trigatron triggering characteristics. The streamer velocity and bunching characteristics were shown to be necessary for understanding and analyzing pulse-charged gaps.

The pulse-charged switching effects of surface roughness, gas pressure, and field enhancement factors on the prefire rate are now predictable from dc data and streamer velocity data, and agree with the observed data in untriggered or triggered, pulse-charged, gas gaps.

It is hoped that this model will be used to direct and outline useful areas in switching research. The grouping of switch action into low voltage, larger area dc breakdown and high voltage streamer propagation represents a major simplification in understanding pulse-charged gaps.

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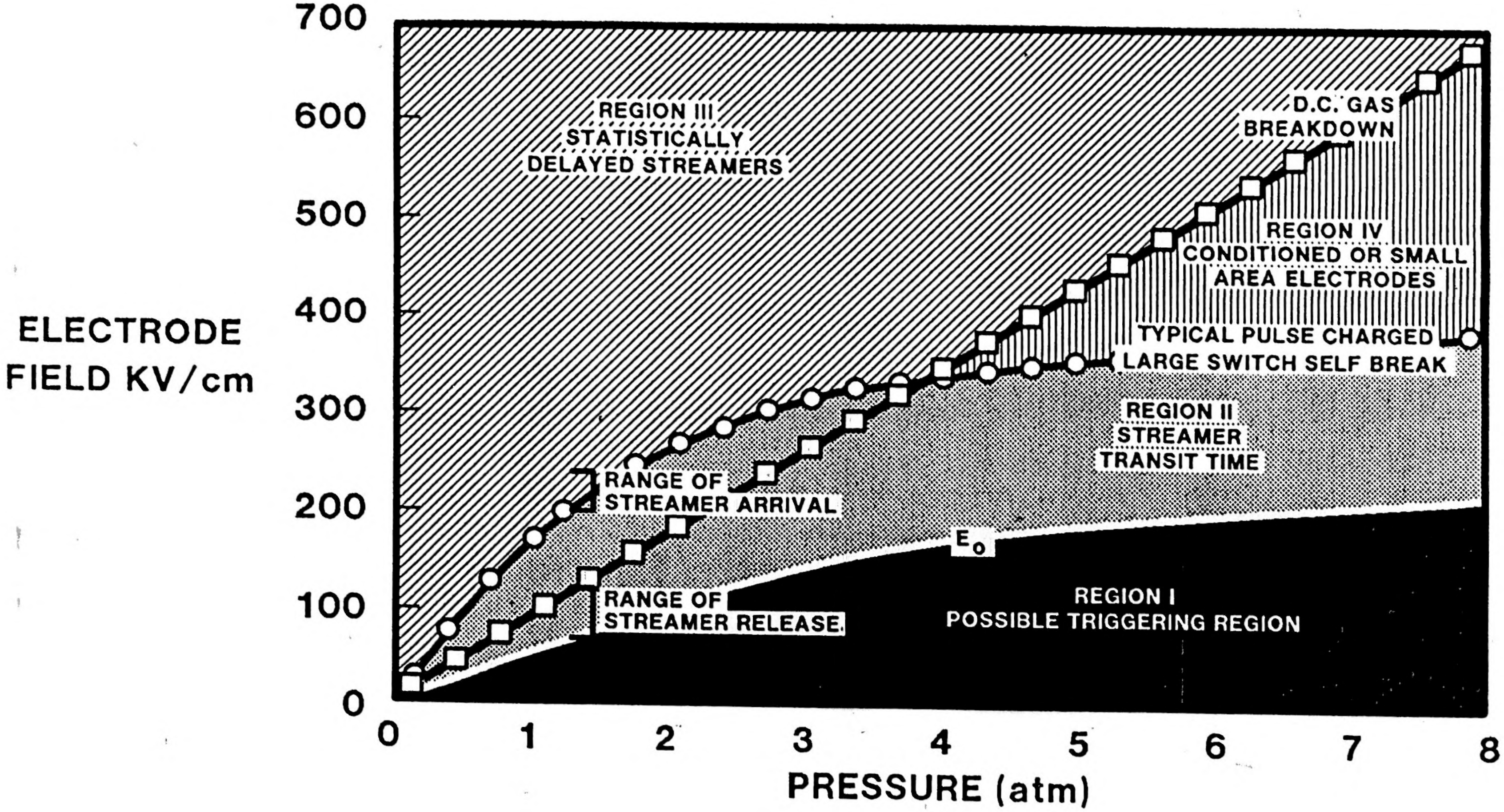
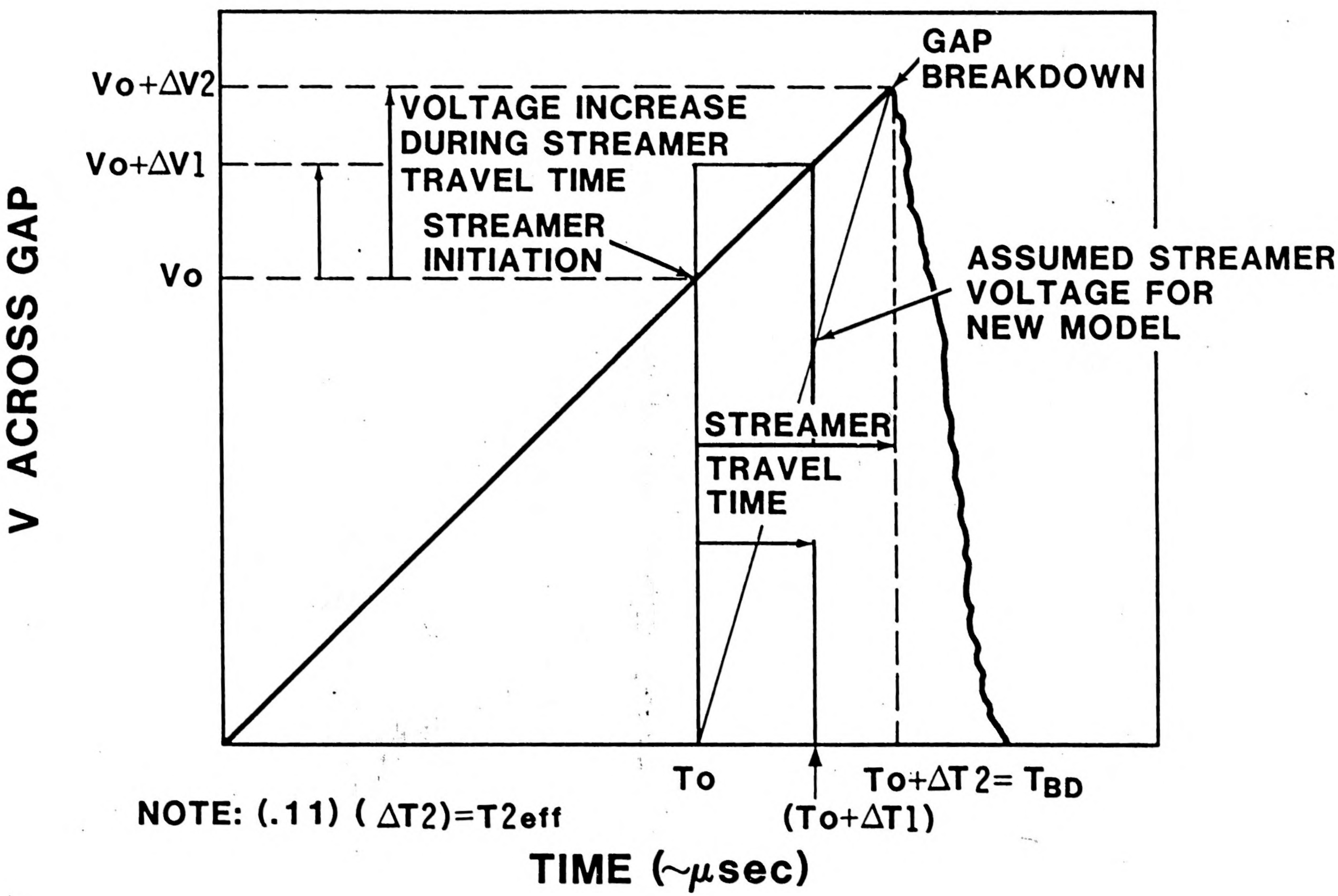
PULSE CHARGED SWITCH PHENOMENA




GAP
BREAKDOWN
Vo+ΔV2
Vo+ΔV1
Vo
VOLTAGE INCREASE
DURING STREAMER
TRAVEL TIME
STREAMER
INITIATION
ASSUMED STREAMER
VOLTAGE FOR
NEW MODEL
STREAMER
TRAVEL
TIME
V ACROSS GAP
To
(To+ΔT1)
To+ΔT2= TBD
NOTE: (.11) (ΔT2)=T2eff
TIME (~μsec)

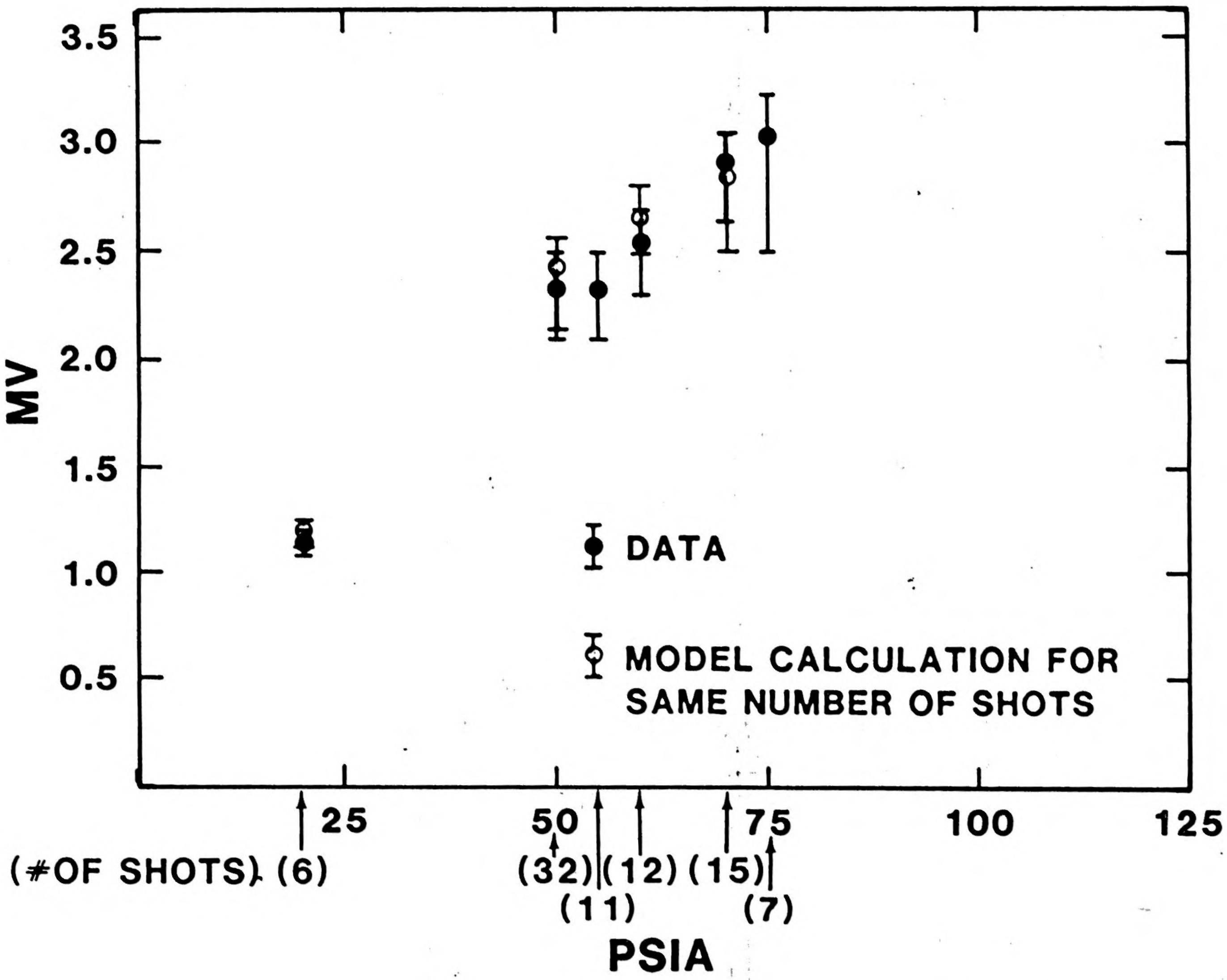
```
      PROGRAM HVSWLS
C
C
C
      REAL NFEF,NFIELD
      DIMENSION TITLE(80)
      DIMENSION B(201),C(201),DD(201),E(201),F(201),G(201),H(201)
      DIMENSION BB(201),CC(201)
      DOUBLE PRECISION ZOTEXP
      DO 1 I=1,200
      B(I)=0.0
      C(I)=0.0
      DD(I)=0.0
      E(I)=0.0
      F(I)=0.0
      G(I)=0.0
      H(I)=0.0
      BB(I)=0.0
1     CC(I)=0.0
      TYPE 5
5     FORMAT('$ENTER TITLE FOR SWITCH RUN:  ')
      READ(5,7) NT,TITLE
7     FORMAT(Q,80A1)
      TYPE 20
20    FORMAT('$ENTER TIME TO PEAK IN MICROSECONDS:  ')
      ACCEPT*,TPK
      TYPE 30
30    FORMAT('$ENTER GAP LENGTH IN CENTIMETERS:  ')
      ACCEPT*,D
      TYPE 35
35    FORMAT('$ENTER NEGATIVE ELECTRODE FIELD ENHANCEMENT FACTOR:  ')
      ACCEPT*,MFEF
      TYPE 40
40    FORMAT('$ENTER ACTIVE GAP AREA IN SQUARE CENTIMETERS:  ')
      ACCEPT*,A
      TYPE 50
50    FORMAT('$ENTER STARTING GAP PRESSURE IN PSIA:  ')
      ACCEPT*,PSIA
60    CONTINUE
      VONE=55.0*PSIA/14.5
      VTWO=31.0+40.0*PSIA/14.5
      VTHRE=79.0+28.0*PSIA/14.5
      VFOR=180.0+11.2*PSIA/14.5
      VFIV=240.0+2.6*PSIA/14.5
      EINIT=AMIN1(VONE,VTWO,VTHRE,VFOR,VFIV)
      VINIT=EINIT*D/MFEF*1.2
      V=VINIT
      PBARS=PSIA/14.5
      DO 300 I=1,200
      NFIELD=V/D*MFEF
      EONE=55.0*PBARS
      ETWO=31.0+40.0*PBARS
      ETHRE=79.0+28.0*PBARS
      EFOR=180.0+11.2*PBARS
      EFIV=240.0+2.6*PBARS
      EZERO=AMIN1(EONE,ETWO,ETHRE,EFOR,EFIV)
      AA=NFIELD-EZERO
      IF(AA.LT.0.0)STOP 'NEGATIVE AA'
      PGBD=1-EXP((AA**6.3)*A*-7.2435E-16)
      CGBD=1-EXP(-4.6870E-38*A*(AA**14.7))
      ZOT=NFIELD/PBARS*1.06951E-2
      TEMP=-ZOT**22.2
      GGBD=1-EXP(TEMP)
      PONET=1-(1-GGBD)*(1-PGBD)
      PTWOT=1-(1-GGBD)*(1-CGBD)
      CONST=((114.*((.9864*PBARS)**.5631)*(D**.833))/V)**6
      EPS=.0005
      CALL SOL(TPK,CONST,EPS,ANS)
      T=ANS
      ACTBDV=V+V*T/TPK
      ACTFLD=NFIELD*(1+T/TPK)
      B(I)=V
      C(I)=PGBD
      DD(I)=CGBD
      E(I)=GGBD
      F(I)=PONET
      G(I)=PTWOT
      H(I)=T
      BB(I)=ACTBDV
      CC(I)=ACTFLD
      NPRT=I
      IF(PONET.GE.0.9) GOTO 200
      IF(PTWOT.GE.0.9) GOTO 200
      V=V+0.02*VINIT
300   CONTINUE
200   CONTINUE
      DO 201 I=1,NPRT
201   H(I)=H(I)*1.E3
      WRITE(10,202) TITLE
202   FORMAT(1H1,80A1//)
      WRITE(10,204) TPK,D,MFEF,A,PSIA
204   FORMAT(' TIME TO PEAK IN MICROSECONDS = ',F5.3,/
     1 ' GAP LENGTH IN CENTIMETERS = ',F6.3,/
     2 ' NEGATIVE ELECTRODE FEF = ',F5.3,/
     3 ' ACTIVE GAP AREA IN SQUARE CENTIMETERS = ',F5.1,/
     4 ' GAP PRESSURE IN PSIA = ',F5.1//)
      WRITE(10,206)
206   FORMAT(2X,'V (KV)',2X,'P<PGBD>',2X,'P<CGBD>',2X,
     1 'P<GGBD>',2X,'P<P1TOT>',2X,'P<P2TOT>',2X,'T (NS)',2X,
     2 'ACTBDV',2X,'ACTFLD'//)
      WRITE(10,208) (B(I),C(I),DD(I),E(I),F(I),G(I),H(I),
     1BB(I),CC(I),I=1,NPRT)
208   FORMAT(1X,F6.1,2X,F7.4,3X,F7.4,2X,F7.4,2X,F7.4,2X,F7.4,3X,F6.1,
     1 3X,F6.1,2X,F6.1)
      PSIA=PSIA+10
      IF(PSIA.GE.121.) GOTO 1000
      GOTO 60
C      WRITE(*,100) V,PGBD,CGBD,GGBD,PONET,PTWOT,T,ACTBDV,ACTFLD
C100   FORMAT(' V(kV)   = ',1PE12.3,/' P<PGBD>   = ',1PE12.3,/
C     2' P<CGBD>    = ',1PE12.3,/
C     3' P<GGBD>    = ',1PE12.3,/
C     4' P<P1TOT>  = ',1PE12.3,/
C     5' P<P2TOT>  = ',1PE12.3,/
C     6' T         = ',1PE12.3,/
C     7' ACTBDV = ',1PE12.3,/
C     8' ACTFLD = ',1PE12.3//)
1000  CALL EXIT
      END
      SUBROUTINE SOL(A,K,EPS,ANSWER)
C
      REAL K
C

      TOLD  = .5
      T     = .5
      N  = 0
      TOLERANCE = 1.0
C
        IF (K .LE. 0.0 .OR. A .LE. 0.0) THEN
          STOP 'YOU GOOFED IN S.R. SOL'
        ENDIF
C
          DO WHILE (TOLERANCE .GT. EPS .AND. N .LT. 100)
            N = N+1
            FOLD = T*(1.0+T/A)**6-K
            DFDT = (1.0+T/A)**6 + 6.0*T*(1.0+T/A)**5/A
C
C SOLVE (DFDT = FOLD - FNEW)/(TOLD - TNEW)  WITH FNEW=0
C
             TOLD = T
             TNEW = TOLD - FOLD/DFDT
             T    = TNEW
             TOLERANCE = ABS(TNEW - TOLD)
C            WRITE(*,100) N,T,FOLD
           ENDDO
        IF (N .GT. 100) THEN
          STOP 'NO CONVERGENCE'
        ENDIF
      ANSWER = T
C100  FORMAT(' N,T,FOLD=',I4,2E12.4)
      RETURN
      END
```

MITE 9.2 CM B MOORE NEW EZERO SS

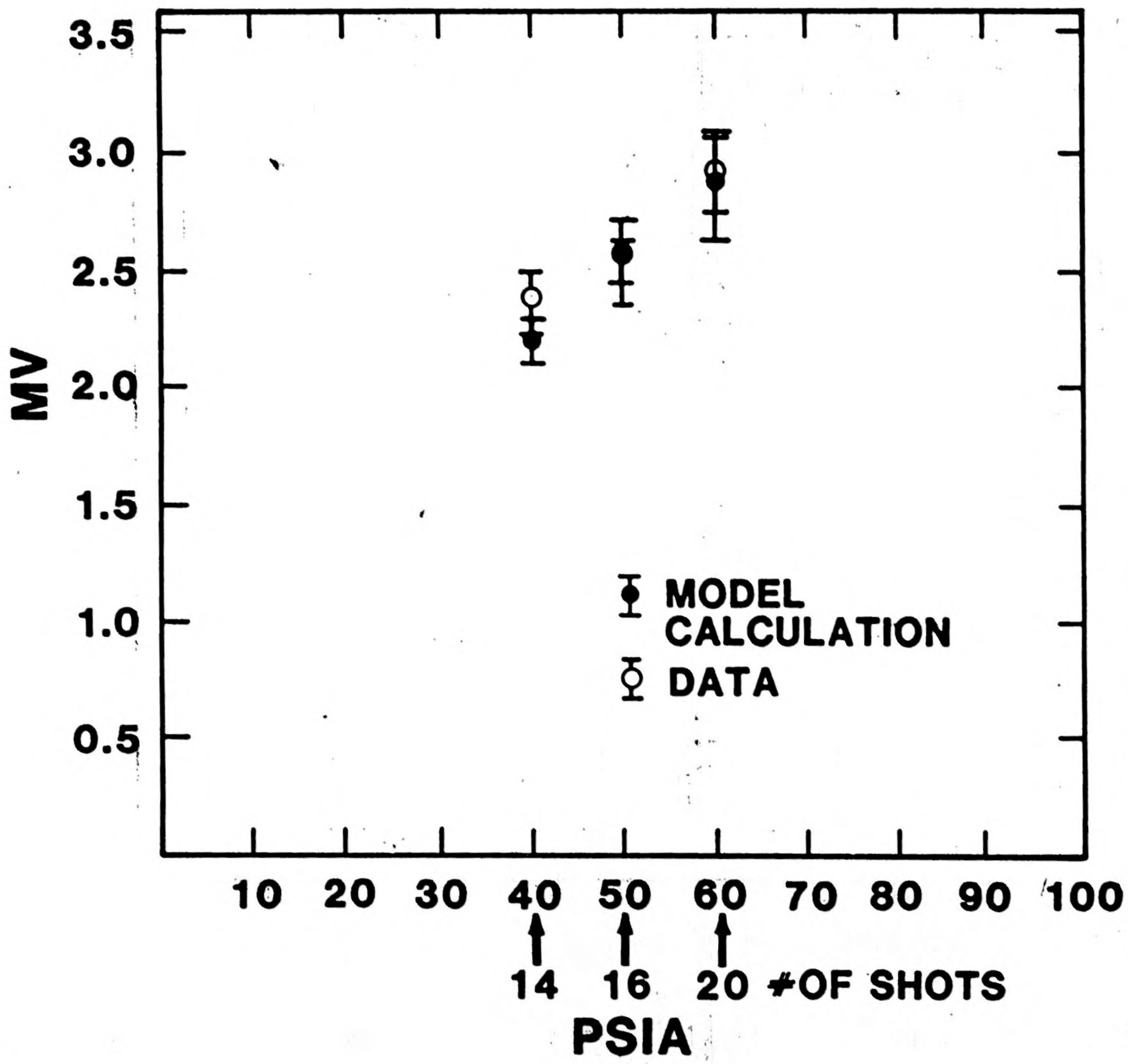
TIME TO PEAK IN MICROSECONDS = 0.400
GAP LENGTH IN CENTIMETERS = 9.200
NEGATIVE ELECTRODE FEF = 1.310
ACTIVE GAP AREA IN SQUARE CENTIMETERS = 20.0
GAP PRESSURE IN PSIA = 40.0

V (KV)	P<PQBD>	P<CQBD>	P<GQBD>	P<P1TOT>	P<P2TOT>	T (NS)	ACTBDV	ACTFLD
1191.2	0.0000	0.0000	0.0001	0.0001	0.0001	118.1	1542.7	219.7
1215.0	0.0000	0.0000	0.0001	0.0001	0.0001	112.2	1555.8	221.5
1238.8	0.0000	0.0000	0.0002	0.0002	0.0002	106.6	1569.1	223.4
1262.7	0.0000	0.0000	0.0003	0.0004	0.0003	101.3	1582.5	225.3
1286.5	0.0000	0.0000	0.0005	0.0005	0.0005	96.3	1596.1	227.3
1310.3	0.0001	0.0000	0.0008	0.0008	0.0008	91.4	1609.8	229.2
1334.1	0.0001	0.0000	0.0011	0.0013	0.0011	86.8	1623.8	231.2
1357.9	0.0002	0.0000	0.0017	0.0019	0.0017	82.4	1637.8	233.2
1381.8	0.0004	0.0000	0.0024	0.0028	0.0024	78.3	1652.1	235.2
1405.6	0.0006	0.0000	0.0036	0.0042	0.0036	74.3	1666.6	237.3
1429.4	0.0009	0.0000	0.0052	0.0061	0.0052	70.5	1681.3	239.4
1453.2	0.0014	0.0000	0.0075	0.0088	0.0075	66.9	1696.1	241.5
1477.1	0.0020	0.0000	0.0107	0.0127	0.0107	63.4	1711.2	243.7
1500.9	0.0028	0.0000	0.0153	0.0180	0.0153	60.1	1726.4	245.8
1524.7	0.0040	0.0000	0.0216	0.0254	0.0216	57.0	1741.9	248.0
1548.5	0.0054	0.0000	0.0303	0.0356	0.0303	54.0	1757.6	250.3
1572.4	0.0074	0.0000	0.0423	0.0493	0.0423	51.2	1773.5	252.5
1596.2	0.0098	0.0000	0.0585	0.0678	0.0585	48.5	1789.6	254.8
1620.0	0.0129	0.0000	0.0804	0.0923	0.0804	45.9	1805.9	257.1
1643.8	0.0168	0.0000	0.1094	0.1244	0.1094	43.4	1822.4	259.5
1667.7	0.0216	0.0000	0.1474	0.1658	0.1474	41.1	1839.1	261.9
1691.5	0.0275	0.0000	0.1962	0.2184	0.1962	38.9	1856.1	264.3
1715.3	0.0347	0.0000	0.2577	0.2835	0.2577	36.8	1873.3	266.7
1739.1	0.0434	0.0000	0.3329	0.3618	0.3329	34.8	1890.6	269.2
1762.9	0.0537	0.0000	0.4216	0.4527	0.4216	33.0	1908.2	271.7
1786.8	0.0659	0.0000	0.5217	0.5533	0.5217	31.2	1926.0	274.3
1810.6	0.0803	0.0000	0.6283	0.6582	0.6283	29.5	1944.1	276.8
1834.4	0.0970	0.0000	0.7336	0.7595	0.7336	27.9	1962.3	279.4
1858.2	0.1163	0.0000	0.8283	0.8482	0.8283	26.4	1980.7	282.0
1882.1	0.1385	0.0000	0.9034	0.9168	0.9034	24.9	1999.3	284.7

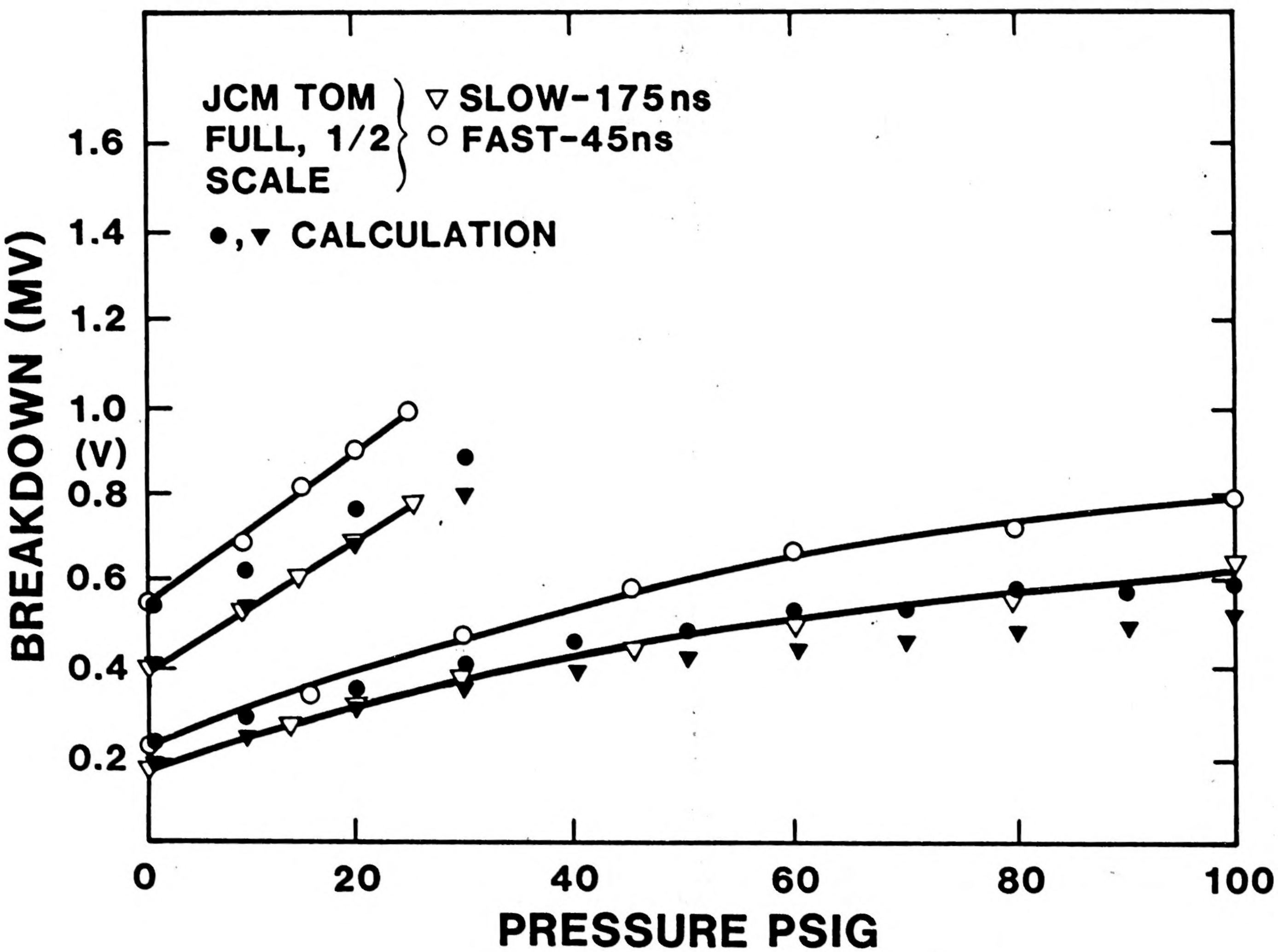
PBFA-1 GAS SWITCH (MITE)
9.2cm SOLID ELECTRODES



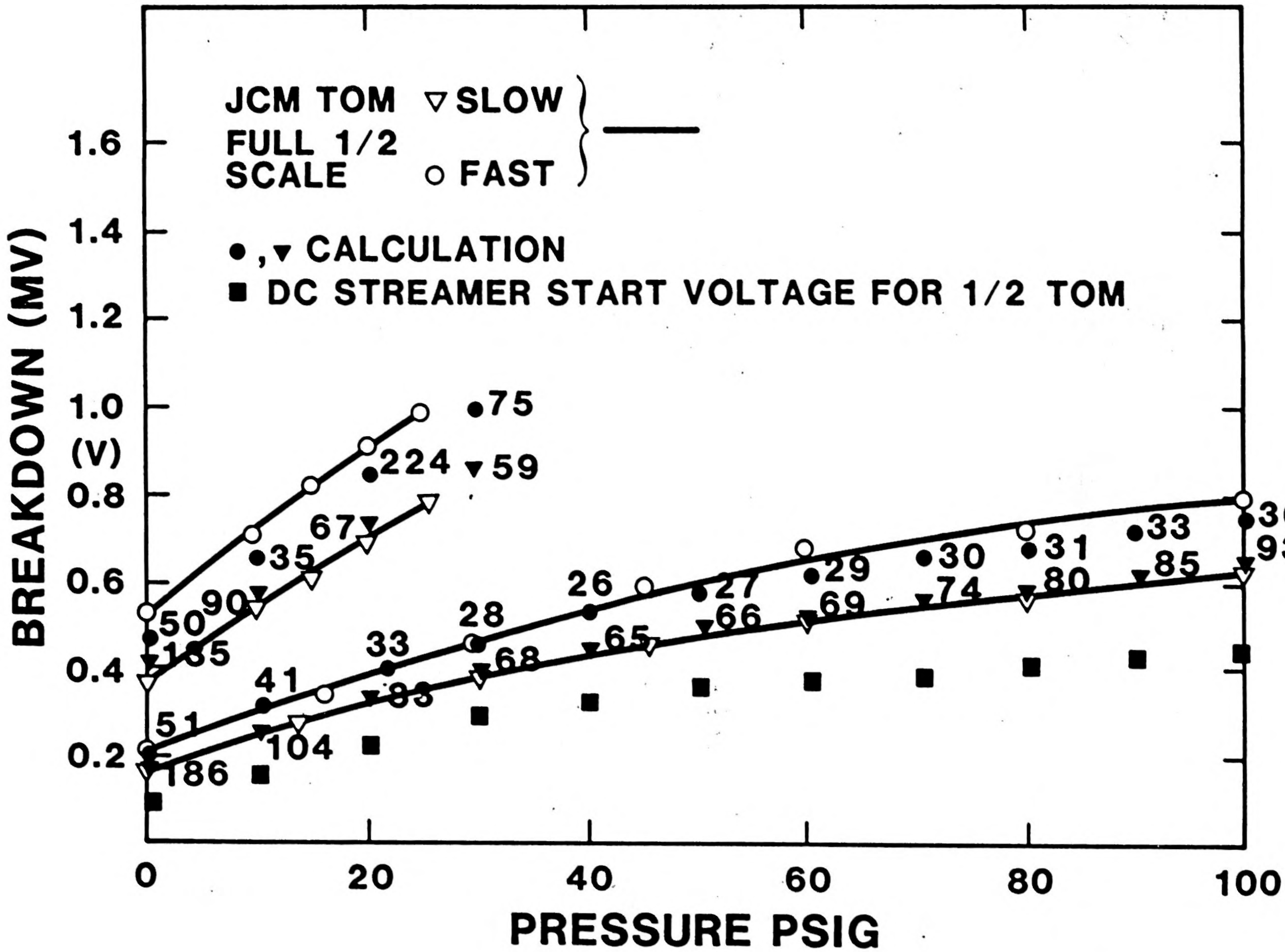
PBFA-I GAS SWITCH (MITE)
11.2cm SOLID ELECTRODES



AWRE SF_6 DATA



REVISED MODEL AND AWRE SF_6 DATA



70kV CHARGE - TRIGGER CHARACTERISTICS