Switching Notes
Note 10

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Multichannel Gaps

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"It is too rash, too unadvised, too sudden,
Too like the lightning, which doth cease to be
Ere one can say it lightens."
(Romeo and Juliet)

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1. Introduction

In the general field of high speed pulse generators, the breakdown strengths of gases, liquids and solids in uniform and non-uniform fields can be estimated well enough for design purposes, using approximate relations and measurements obtained in the past few years. This suffices to do a first design for the high speed section and the feed from this to the load. If a single channel gap is used, approximate treatments exist to enable the rise time of the pulse to be obtained to a rough but adequate accuracy. However, if this rise time is inadequate, the position becomes more complicated. Single gaps, transit time separated, can be employed in some designs, but then the resulting combined pulse must have a rise time comparable with the jitter of the individual gaps. Such an approach is usually expensive and where low impedances and high voltages are required, it may be physically impossible to realise.

Several years ago, when the stabbed solid dielectric switch was developed, multichannel operation of a number of closely spaced spark channels was readily obtained. The corresponding development of liquid and gaseous multichannel gaps has only occurred in the last couple of years. The reason why multichannel operation of solid switches was obtained so easily is a combination of the relatively long resistive phase of the spark channels and the fact that trigger pulses of several hundred kilovolts rising in a few nanoseconds were easily generated by using a solid master gap.

In contrast to an array of single gaps, where transit time isolation is used, multichannel gaps have continuous electrodes. Transit time isolation may play some part in enabling a number of spark channels to take comparable currents, but this is usually of minor importance and is only included in the analysis for completion. The continuous electrodes of the gap may be serrated or have localised raised areas on them, but this is used to stabilise the number of channels formed at a number lower than that which would have been obtained with continuous electrodes.

There are several reasons why multichannel gaps may be useful, but in general they fall into two classes. Firstly a lower inductance is obtainable and to a lesser extent a reduced resistive phase. Thus faster rise time pulses may be generated and in high voltage, low impedance systems, the rise time can be made to decrease an order of magnitude. Secondly electrode erosion may be very serious in a single channel gap and this is reduced drastically where the current is carried in a reasonable number of channels. A second effect of using large continuous electrodes is that such erosion as does take place causes little change in the geometry of the gap and, in addition, magnetic forces and high current density blow up are considerably reduced.

In preliminary experiments I assumed that if the jitter in closure of the channels in the gap was of the order of the fall time of the voltage across the spark channels, multiple operation should result. A couple of failures over a period of a year convinced me that a time more like a tenth of this was required before the desired end could be achieved. Consideration of the operation of a couple of different solid dielectric gaps and of a surface air gap confirmed that in my early experiments to obtain multichannel gas gaps I was being wildly optimistic and, sadder but possibly wiser, I designed an overdrived mid plane gap which indeed managed to achieve a number of channels. Needless to say, this number was always less than my expectations but at least I was making progress. Over a couple of years the analysis of a number of cases where multichannel operation was intentionally or accidentally observed enabled a rough relation to be developed which worked crudely over a wide range of conditions.

The work reported here was brought on by an attack of conscience because while I was happy my approximate relation worked, I was reluctant to write it up without something more respectable in the way of experimental backing. Within the limits of the experiments reported, I consider that this has now been done. As usual, accuracies of a few percent are neither sought nor needed for design purposes and all the following should be read in the light of this requirement.

If the relationship is accepted, and if the jitter of a single gap or portion of a gap can be estimated or measured, the trigger pulse required to obtain any number of channels can then be calculated. In general, some threshold rate of rise of the trigger pulse is required and provided the trigger pulse circuit can exceed this, adequate performance will result. Thus it is hoped that the treatment suggested can be used to solve at the design stage the switch problems of advanced pulse generators.

In addition to the experimental work reported, a number of other points are covered, including some of the many ways of not getting multichannel operation. I live in hope that I have uncovered most of these, but continued experience convinces me that in the field of multichannel operation Dame Nature is unusually inventive in finding evasive tactics and frustrating the ardent experimenter. However, as in another field of endeavour, success is even sweeter when it is ultimately obtained.

2. The Approximate Relation

In a multichannel gas gap as the first closing channel starts to take substantial current, the voltage on the electrodes begins to collapse. Other channels closing after the first will have less volts across them and hence will finish up carrying significantly less current when the gap voltage has fallen to a low value. After this phase is over, the currents carried by the various channels will redistribute themselves over a very much longer time scale. The current eventually finishes up flowing in one channel, after a time typically three or more orders of magnitude longer than in the first phase. The analysis given here is restricted in general to the first phase, when the gap voltage falls to a low value, although some data on the long term current rearrangement is given towards the end of this note.

In the case of channels where the current is largely controlled by the inductance of the spark, a naive approximate theoretical treatment is given in the next section which shows that if a second channel closes after the voltage has fallen by 15 per cent, the ultimate current in the two channels is divided roughly in the ratio of two to one at the time of major interest. The resistive phase is even more voltage dependent and a channel going over to the plasma phase after such a 15 per cent voltage drop has taken place has an even greater ratio of currents carried. Unfortunately the approximate relation which gives the duration of the resistive phase does not give any information about the form of the early voltage time history. However, as the plasma channel has a strong negative resistance, it is reasonable that small drops of voltage across later channels should have a disproportionately large effect on the currents they finally carry.

The rate of rise of a voltage pulse from a single spark channel (and hence fall of voltage across the electrodes) has been treated in "Duration of the Resistive Phase and Inductance of Spark Channels", reference SSWA/JCM/1065/25.[1] In this, two phases are considered, the inductive (τ_L) and the resistive phase (τ_R). These are both e-folding times and to obtain the resulting τ_{tot} they are added. The treatment only applies to sparks where reasonable currents are carried and is restricted to those cases where the impedance feeding each channel is a few hundred ohms at most.

In any multichannel gap a whole spectrum of current carrying channels close and in obtaining an effective number of channels it is necessary to decide at what fraction of the current carried by the earliest channel a cut off is to be applied. Some of the difficulties about this are mentioned in the next section but even if these were solved in any given application, in order to decide the effective number of full current channels any particular gap is giving, the distribution function of the actual currents would have to be known. In order to simplify a very complex situation, two cut off levels of current are used below, one counting all channels with about 45 per cent or more of the channel with maximum current. The other level corresponds roughly to 35 per cent of this current. I personally

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[1]. Switching Note 9

prefer to use the first cut off level in calculations, but in order to increase the statistics in most of the experiments described the second lower level has been used, to give a larger number of channels to compare with the calculations. The two criteria are referred to as A and B respectively in what follows. While it is realised that the two extreme cases of purely inductively and resistively controlled spark channels are different, the relatively crude analysis proposed does not take this into account and the time span during which effective additional channels can complete is obtained by taking a fraction of the total τ_{tot}. Thus the time ΔT during which useful channels may form is given by

$$\Delta T = f\ \tau_{tot}$$

For condition A $f = 0.1$ and for condition B $f = 0.15$. To this time must be added an allowance for transit time isolation. If the electrodes are of length l then the velocity of light isolation is $l \div nc$ where n is the number of channels and c is the local velocity of light in the dielectric. The whole of this time (τ_{trans}) is not added to ΔT because the channels are not uniformly distributed and hence only 0.8 of it is added to make a rough allowance for this and other effects. Thus the expression for the useful interval during which additional channels may close is (for condition A)

$$\Delta T = 0.1\ \tau_{tot} + 0.8\ \tau_{trans} \qquad \ldots\ldots (1)$$

Now τ_{tot} depends on the effective number of channels carrying current (n), the inductive term going as 1/n and the resistive phase as $1/n^{1/3}$. The transit time isolation term also goes as 1/n, of course.

Any gap operated in a single channel mode has a scatter in its breakdown voltage which can be characterised by a standard deviation $\sigma(V)$ and this is the quantity experimentally measured, as a rule. For a trigger pulse rising at a reasonable rate, this can be turned into a real deviation in time, $\delta(t)$, by using the following relation

$$\delta(t) = \sigma(V)\ V\ (dV/dt)^{-1} = \sigma(t)\ T$$

where dV/dt is evaluated at the point on the rising wave form at which the gap fires.

To an adequate degree of accuracy the value of ΔT calculated from equation (1) is equated to $2\ \sigma(t)\ T$.

For example, an edge plane gap pulse charged linearly in about 100 ns can have a $\sigma(V)$ of the order of 0.3 per cent. Thus ΔT has a value of 0.6 ns. Given the physical characteristics of the gap and the electrical circuit feeding it, the number of channels which give values of the terms on the R.H.S. of the equation which satisfy equation (1) can now be obtained.

To obtain multichannel operation, two obvious ways of improving any system are: (a) to reduce $\sigma(V)$ of the gap; and (b) to increase dV/dt ; both of these reducing ΔT . In typical applications, initially the inductive term dominates the value of τ_{tot} and hence n increases inversely as ΔT . As the number of channels increases, the resistive phase term begins to dominate and n goes inversely as ΔT^3 eventually. In point or edge plane gaps in gases, increasing the rate of rise of the voltage also causes the $\sigma(V)$ to decrease and the two effects combine to improve the gap performance quickly. With edge plane gaps in good conditions, fed from a reasonably low impedance transmission line, multichannel operation can set in with pulses rising in 200 or 300 ns and a large number of channels can result from pulses rising in several tens of nanoseconds. With ordinary roughish gaps in gases, or with good liquid gaps, $\sigma(V)$ is more ordinarily of the order of 2 per cent and pulse rise times of tens of nanoseconds are needed to start multichannel operation. Solid gaps well made have similar standard deviations to those of liquids and pulses rising in 10 ns can cause substantial numbers of breakdown sites. As was mentioned earlier, the first strict multichannel operation achieved at AWRE was with solid gaps and pulse rise times of this order and less were certainly generated by the solid master gap.

Several examples of calculations using the proposed relation are given in the experimental and application sections below. It should be explained that in these examples, when evaluating equation (1) for various values of n , the value of τ_{trans} is evaluated for $n = 1$. This is obviously an absurdity and it is included partly because it is difficult to remember to leave it out and partly because it enables estimation of the operation where, say, 1 1/2 effective channels are produced. This of course is only a statistic average over a number of shots. The reader's indulgence is begged for the author's idiosynractic behaviour in this matter.

3. Inductive Calculations

The simple inductive fall time for a constant diameter conductor driven by a circuit of impedance Z is given by $\tau(L) = L/Z$ where L is the inductance of the conductor. The extra inductance from the transmission line to the conducting channel is ignored, of course, something that in practical cases is usually inaccurate. In this simplification that verges on the moronic, the effect of closing a second similar channel at an arbitrary time after the first one can be easily calculated. In Figure 1, curves A and B show the normalized voltage collapse for one and two channels respectively, where in the latter case both channels exist from $t = 0$. The units of time are normalized to L/Z . Curve C shows the voltage collapse when the second inductive path is added to the first at a time of 0.2. The current division between the two channels at a late time is in the ratio of 1.0 to 0.68. From this simple treatment a serious difficulty is already apparent, when the question is asked how much has the rise time been improved by the later addition of a second conductor. If the maximum slope of the voltage curve is taken as a criterion, the case shown is only a 10 per cent or so improvement on a single channel. If the criterion is the 10 per cent to 90 per cent pulse rise time, i.e. 90 per cent to 10 per cent fall time, the curve C is much better and is quite close to the value given by two independent conductors in parallel from $t = 0$. It is not unreasonable that a single parametric measurement of a complex waveform can give rise to paradoxes and considerably subjective decisions have to be made as to which parameter, if either, is applicable to a particular case.

For instance, for EMP and radiative work, the dV/dt maximum is probably most applicable, whereas for high voltage X-ray production the shape of the curve late on may be much more important. As this note attempts to give guidance to designers of pulse equipment, detailed and probably sterile debate is not relevant and I have no shame in declaring that in this instance I propose to take the time at which half the voltage fall has occurred as an approximate parameter. As such, the closure at $t = 0.2$ is rather over half as effective as a second channel from $t = 0$.

Also shown in Fig. 1 are curves D, E and F. These refer to the case where the inductance L is allowed to fall to 75 per cent of its initial value during a time $t = 1$. Something like this happens in real life as the plasma channel expands rapidly in its early phase and hence the assumption of a constant L is unrealistic. The value taken for the drop in inductance is fairly typical for spark channels of interest to this report. These curves show that the gap closing at $t = 0.2$ is about half as effective as it would have been if it had closed to $t = 0$. The current ratio in this case is 1.0 to 0.55. Now the rate of expansion of the channels is dependent on the energy flowing into it and hence the later closing channels will have a significantly higher inductance and smaller rate of change of inductance than the first channel. This effect again tends to reduce the effect of the later closing channels, but is difficult to calculate. However, some estimations suggest that closure at $t = 0.2$ will be less than half effective, and that closure at about $t = 0.15$ would be needed to produce an effect on the fall time of a half of that produced by two independent channels and that the current division will then be in the ratio of 1 : 0.5 very approximately.

It will be remembered that in section 2 it is suggested that channels closing at 0.1 of τ_{tot} would be taken as the cut off point in calculating the effective numbers and this corresponds to a current of some 45 per cent of that in the first forming channel. This statement applies to cases where both inductive and resistive phases are significant and it is very probable that in the resistive phase, where the heating of the channel is strongly dependent on the voltage across it, this case will be more sensitive to voltage drop than the inductive one estimated here. If the reader wishes, he can separate τ_{tot} into two parts and multiply τ_L by 0.15 and τ_R by 0.1, but it is my advice that such accuracy is scarcely justified by the simplicity of the analysis in this section. It is also the case that in nearly all practical calculations the net effect of this elaboration on the value of ΔT is 10 per cent or less and this is well within any accuracy claimed for the relation.

4. Comments on the Resistive Phase Formula

The relation for the duration of the resistive phase given in the note referred to in section 2 has the form for gases of

$$\tau_R = \frac{88}{Z^{1/3}F^{4/3}} \left(\frac{\rho}{\rho_o}\right)^{1/2}$$

where the time is in nanoseconds and Z is the impedance driving the plasma channel in ohms, and F is the field along the channel in units of 10 kV per cm, and ρ is the density of the gas used, while ρ_o is the density of air at NTP.

In a report from Maxwell Laboratories, MLR24, volume 2, Dr. Ray O'Rourke has theoretically derived a relationship closely resembling the above and this has the form

$$\tau_R' \propto \frac{I^{1/3}}{Z^{1/3}F^{4/3}} \left(\frac{\rho}{\rho_o}\right)^{1/3}$$

A significant difference between the two relations is the power of the density of the medium in which the spark channel forms. In the original measurements on which the relation was based the density effect of various gases from hydrogen to freon and sulphur hexafluoride at various pressures was investigated and the density variation was quite closely a power of

1/2. In addition, if the large jump is made from densities like 10^{-3} to densities like 1, the original relation rather accurately predicts the resistive phase duration for water, transformer oil and polythene, using the density to the 1/2 power. This touches on a rather important point as far as I am concerned, and that is that the larger the range over which a formula holds, the better it is, and that rather than try very accurate experiments over small ranges of variables, it is better to look less accurately at cases where big jumps in the variables are involved. Thus for density one materials the 4/3 power of the field was checked rather accurately in an underwater experiment, where a resistive phase of nearly 2000 ns was measured for a series of parallel channels with a mean gradient of only 8 kV/cm down them, a result in agreement with the formula. Thus, while it is very pleasant to have a firm theoretical underpinning to the expression, and I would like to express my appreciation of the fine work of Ray O'Rourke, I feel that some additional effects such as the slow variation of some assumed constant in practice may give rise to the slightly different power. Thus I shall continue in this note to use the original relation.

Ian Smith of Physics International has also independently pointed out that the original expression is dimensionally undesirable, lacking an $l^{1/3}$ where l is the length of the spark channel. He points out that if a gap is divided in two and it is assumed that at all stages the voltage at the mid point stays at half that of the top, then two half generators, each of impedance $Z/2$, can be joined across the channel and now a resistive phase 2 1/3 longer is calculated. Ian Smith tentatively suggests an earlier form of the expression that was used at AWRE, of

$$\tau_R'' \propto \frac{l^{1/3}}{Z^{1/3}F}\left(\frac{\rho}{\rho_o}\right)^{1/2}$$

which does not suffer from this possible defect. For the reasons given above I would prefer a slightly different from of Dr. O'Rourke's expression

$$\tau_R'' \propto \frac{l^{1/3}}{Z^{1/3}F^{4/3}}\left(\frac{\rho}{\rho_o}\right)^{1/2}$$

It is true that in the original experiments no large change of length was attempted. The longest gaps to which the calculation was applied was some 30 cm surface gaps which operated at voltages down to 15 kV, giving very long resistive phases once again. However, the accuracy was not high and while I am sure an $1^{1/3}$ term would have been found, it can be argued that surface gaps may be a bit odd. I have applied the original relation to data from some 3 metre gaps, driven by slightly ill defined impedance of an impulse Marx, and found quite reasonable agreement. Once again I think that new small effects may come in to reduce, or even remove, the suggested $1^{1/3}$ effect. For instance, in breakdowns at 3 MV in a water coaxial system, the damage done to the metal walls was considerably different whether the streamers were moving inwards or outwards during the µsecond or so that the line was being pulse charged to breakdown. In this case photographs showed that uncompleted streamer bushes had main trunks that were plasma filled. This plasma was generated by energy from the dc/dt term as the bushes grew outwards and by the time they were well under half way across the main gap, the trunk of the bush had expanded to several x 10^{-2} cm and while not hot enough probably, did not have to expand any more when final closure occurred. As such, the voltage drop down the channel was nowhere near uniform; indeed I estimated that well over three-quarters of the voltage was dropped across the last half of the channel. Thus the resistive phase would be lower than in a uniform channel and the energy deposited in forming the channel would be largely concentrated away from the electrode from which the streamer had originated, in agreement with the observations.

In the section on applications of the multichannel relation, a case where a large dc/dt term is believed to have loaded the generator prior to streamer closure is referred to. The photographs of this set up showed partly completed streamers where the glowing core was seen projecting part way from the very long knife edge. This is the only time I have seen this in gases but this again would show that uniform conditions along the channel may not exist in all cases and hence the initial assumption may well be a bit idealistic. Once again I will continue to use the original relationship and while being very happy to acknowledge its theoretical blemishes, I believe in its practical performance. Again I would like to thank Ian Smith for his interest and active efforts to improve the prediction of rise times from spark gaps.

It is probably worth pointing out that there are a number of known circumstances where rise times faster than that given by τ_{tot} have probably been observed. One of these is the non uniform channel conditions mentioned above, which can lead to reductions of rise time of up to a factor of 2. Another case is branching, where the rise time may be better by about the same factor. A particular case of this could exist in some laser triggered gaps, where very extensive branching can be seen for at least half the spark channel and this branching may of course exist all the way, but so closely spaced that the expansion of the plasma channel after the resistive phase is over joins them up into one photographically recordable channel.

Again, with laser triggering it is possible that enough energy can be coupled into the gas to heat a wide plasma column which would then have an essentially zero resistive phase, since there is no need for an expansion phase to occur at all.

5. Jitter Measurements

Initially it was hoped to obtain the data for this section from the literature but it rapidly became obvious that such data as existed was fragmentary and sometimes contradictory and in any case was restricted for the most part to pulses longer than a microsecond. A very useful summary of data is contained in an ERA report No. 5080 entitled "The Switching Surge Strength of Insulating Arrangements for Systems Operating at Voltages Above 100 kV", by A. Morris Thomas. An additional source of much good material is IEEE Transactions paper 63-1040, "Sparkover Characteristics of Large Gap spaces and Long Insulation Strings", by T. Udo. This covers the longer pulse jitters reasonably well, but the picture for the jitter of a negative point plane for long times is rather confused, to put it mildly. Indeed the review article declined to produce a summary for this particular quantity because of the scatter of the quoted experimental results. In addition to the uncertainty in long pulse data, I had some evidence that the jitter fell as the pulse length was reduced and published data for this did not seem to exist. With manifest reluctance a grand research programme was drawn up. At this point I must apologise for the lack of new data in practically every respect. It had been intended to measure the scatter of both positive points and edges as well as the negative ones. However, as the whole experimental programme, including the building of various experimental set ups, had to be done in a period of six weeks without assistance (except where noted), the grand design shrank irresistably under the pressure of time. As such, no useful positive data was collected for air and this was the only gas investigated. For liquids the position was even more extreme, where liquid data was collected for only one effective pulse length and again only for hegative pulses. The predilection for negative pulses is explained by the fact that negative edges will in general hold more voltage for a given gap length than positive ones and sometimes considerably more. Hence τ_{tot} can be quite a lot down on the value for a positive point or edge. However, to set against this is the suggestion that under unfavourable conditions the jitter of a negative gap can be artificially increased by backfiring, a matter dealt with below. Still, this was the reason for the concentration on the negative data in the experiments to be described.

The measurement of a jitter of a fraction of a percent presents some difficulties. It is relatively easy to make sure the spacing is held constant to a tenth of a percent or so, but to ensure that the oscilloscope measurements do not have too much drift and inherent scatter is rather more difficult. In the case of the experimental data given below, the longer period points were obtained with a 'scope with a spot that provided an image diameter on the polaroid print of 0.2 mm width and side experiments indicated that the error in measurement due to the resistor chain and 'scope together was about ± 0.2 per cent. The measurements were performed with both points and short edges. In the case of the liquid measurements, some significant difficulty was experienced in not getting several channels; this was of course because multichannel operation was not wanted.

The test set ups were driven from a Marx generator of stacked capacity 1.2 nanofarad and inductance 7 microhenries. This was capable of going to about 500 kV in air and had a decay period of about 100 microseconds. The different pulse lengths were obtained by feeding the output of the Marx into an air insulated low inductance capacitor by varying inductances. The value of the capacitor was 400 pF and additional inductances up to 40 microhenries were used to slow up the pulse rise time. Relatively small value resistors were included in the circuit to damp out some ringing and to limit current reversal when the point plane closed. The additional air insulated capacity was closely positioned across the point plane gap to which it was joined in a reasonably low inductive way. The height of this capacitor was 6" and for short pulses it could be rung up to over 400 kV.

Table I gives the results for negative pulses for different values of t_{eff}. This single parameter measurement of the effective pulse length is traditionally the full time width at 63 per cent of the peak of the voltage. There is no justification for its selection for gases and only a little for the liquid. However, being traditional, it enables various quantities to be compared easily with previous tabulations and relations.

TABLE I

Material Air - Negative Polarity

t_{eff} (μsec)	d (cm)	V (kV)	σ(V) (%)	F (kV/cm)	
11	4.15	108	± 1.7	24.0	Point Plane
2	7.14	184	± 2.0	25.8	
0.75	7.14	200	± 1.3	28.0	
0.23	7.14	208	± 0.6	29.2	
2	7.14	191	± 1.2	26.8	Edge Plane
0.4	7.14	205	± 0.5	28.8	

Another point for inclusion is one at 0.03 μseconds where a jitter of 0.3 per cent was measured. The field data does show a small and almost certainly real difference between point plane and edge plane results, with the edge plane requiring more volts to break it down. This effect was confirmed more fully with liquids, where it is somewhat bigger. This result at first sight is rather surprising, since an edge can apparently be considered as an array of points. If this were so, the lowest voltage point would break first and it would then be the case that the edge plane would hold a lower voltage and have a better standard deviation. However, both of these conclusions do not follow. Regarding the breakdown voltage effect first, what probably happens is that in a point, the energy from a diverging cone is fed back to heat up the channel near the point and this enables it to progress slightly faster than streamers heated by energy flowing into a wedge shaped sector. A similar phenomenon was observed some years ago in a series of tracking experiments. In these a square piece of copper foil was stuck onto thin mylar, which was in turn stuck onto an extensive ground plane. Where the surface had been properly discharged (something that was not easy to do) and when an adequately low inductive capacitor was used to pulse charge the top square electrode, streamers ran out from all round the edges to a quite regular, finite distance. This distance had a powerful dependency on the pulse voltage. The point of interest here was that much stronger streamers ran out from the corners of the square and obviously charged a much bigger area than the closely packed uniform array along the edges of the copper. These corner surface streamers went much further than the edge ones, indeed going a bit more than $\sqrt{2}$ their length. With regard to the jitter of an edge when viewed as a large number of points, this might be supposed to have a jitter several times smaller than that of a single point, but for this to be so the distribution of breakdown voltages has to be Gaussian. This is in general not so, although it requires fairly refined measurements to prove this. If, as is much more likely, the distribution is of the self-replication form discussed in the note on the "Volume Effect of the Pulse Breakdown Voltage of Plastics", then an array of points or edges will have the same jitter as a single point. Indeed, the measurements tend to show that the situation approximates much closer to this case than to that appertaining when the breakdown of a single point is truly Gaussian.

Figure 2 shows the new data plotted; in addition some data from UDO for negative points and an average number for a positive point is shown. The errors shown for the data quoted in Table I are not firm statistical ones, which are in fact rather less than those shown, but attempt to include factors for consistency, etc. While there appears to be some small difference between points and edges, the curve shown probably is as good as the accuracy of the data warrants.

While performing these measurements, a number of incidental points came up and these will be dealt with separately below.

(a) Extra zigzag length estimation

As the effective pulse duration was reduced, it was observed that the path of the streamer got a lot straighter. Indeed, by roughly following the zigzag for pulses with times longer than a couple of microseconds, it could be estimated that some had path lengths at least 3 per cent longer than the shortest route. As the pulse decreased to significantly less than 1 μsecond, the channels became much straighter, until for pulses of tens of nanoseconds duration the channels were nearly all dead straight. Thus if the set up is geometrically stable and no backfiring is occurring, it seems possible to look at an open shutter photograph of the streamer channel and to estimate the jitter to a factor of 2 or so.

(b) Backfiring

For pulses of duration in the region of 2 μseconds or longer it was found occasionally that a fraction of breakdowns would occur at voltages significantly less than the mean of the usual group. The spark channel on these occasions seemed usually to have a pronounced kink a cm or so off the plane and then the track went straight down. It was found that when the plane was roughly cleaned and dust, etc. removed, this second population vanished, and indeed when half the discharges were of this lower well-scattered variety, a couple of wipes would eliminate the effect completely. The explanation advanced is that a positive bush has grown out from the plane and met the negative one on its way down at a point fairly close to the plane's surface. The result of this is two populations, the regular zigzagged channel type and breakdowns depending on two bushes. When both populations are included in the analysis, the jitter can get as big as 8 per cent. It is suggested that in out-of-door experiments such as Udo, dirt on the earth plan could well have caused a variable number of occasions on which backfiring took place, leading to large and variable jitters. The reason that the phenomenon does not seem to take place with negative pulses of less than 1 μsecond or positive pulses of any duration is interesting to speculate on and may have consequences of importance to triggered gaps in general. For negative point plane breakdowns for short pulses, an approximate relation has been derived in "Pressure Dependency of Pulse Breakdown of Gases"(SSWA/JCM/679/71).[2] There was an earlier paper on the subject that seems to have vanished from the face of the earth. This approximate relationship has a weak dependency on t (a 1/6th power, in fact) but for negative points this dependency disappears for times in the region of a microsecond. The positive point plane relation continues to fall out to times of several hundred microseconds, at which times it

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[2] Dielectric Strength Note 15

will only hold half the voltage that a negative point will. The point at which the negative breakdown mean field becomes time independent appears to depend on the length of the gap being about 7 μseconds for 6 metre gaps and about 0.1 μsecond for 7 cm gaps, suggesting a relationship of the form $t_{crit} = .013\ d$ where d is the point plane gap in cms and t_{crit} is the pulse duration at which the negative pulse becomes time independent. For times greater than this, the strength of the positive gap becomes significantly less. Thus as a positive bush grows out during a long pulse, any dirt or defects on the negative plane will be much less likely to cause a bush to grow back during the last stages of closure than in the case with reversed polarities. For pressurised hard gases the negative point is always stronger (usually by 50 per cent or more) than the positive one, so that if a rough "plane" surface exists, some form of backfiring may occur. In this case a point or edge plane gap pulse charged positive will have a lower breakdown voltage but may well have a somewhat smaller jitter. I gather from Ian Smith that this phenomenon has indeed been observed.

(c) dc/dt loading

This is of more importance to multichannel operation with long gaps and indeed is mainly dealt with in the very long gap described near the end of this note. It is also very much more applicable to liquid gaps and in particular to water gaps. The name by which the effect is described may be misleading since it has yet to be really proved that streamers exist on the time scales in question and while I feel that those from negative points are a reality, I am a little less certain about positive points in gases. However, assuming that streamers do move in the way the approximate relations already mentioned suggest, then a differential velocity for the streamer front can be found. For instance, for gases $dx/dt \propto V^6 x^{-4}$ where x is the distance from the tip and V the voltage on it. This shows that if it applies, the streamer moves out rapidly, slowing up as it goes and takes quite a long while to cross the last few percent of its travel. If the streamer is in air and it spreads out like it does in liquids and solids, then quite a large change in capacity occurs as the streamer is in the last phases of closure. For fast pulses and/or high impedance driving circuits, the loading caused by the $(dc/dt)^{-1}$ term can be quite severe and cause the voltage on the point to fall before the streamers close and the real plasma channels start to form. This phenomenon has been observed by Harlan Aslin of Physics International and I am indebted to him for the observation. The phenomenon can also be seen in some oscillographic records of 6 million volt point plane gap work on a much longer time scale than the present observations. The dc/dt explanation is not the only one that is tenable since photo-ionisation of the gas ahead of the streamers could also account for it, but some very indirect evidence mentioned in the later sections tends to support the proposed explanation. In any case, whichever is the correct explanation, the rather slower fall in voltage before the main heavy current carrying channels close would be expected to increase the jitter somewhat and this has possibly been observed in the very long gap experiment described in a later section of this note. It is therefore important in jitter measurements to ensure that this does not happen appreciably by having a low impedance source coupled by the minimum inductance across the gap when fast breakdown measurements are attempted in gases and, in particular, in work with liquids.

Liquid Breakdown Jitter

The liquid employed in the multichannel edge plane experiments described in the next section was carbon tetrachloride and for the pulse duration used in these experiments the jitter was measured. As will be described in the following section, it is necessary not only to keep the spacing of the gap constant but also to have an adequately sharp edge, so that the rather large jitter in voltage at which the streamers start out will have a negligible effect on the final jitter at closure time. This effect also applies to gas edge plane gaps but here the radius of the edge can be ten mils. or more and is easily obtainable. However, with liquids, working at only 400 kV or so, the edge needs to have a radius of a couple of mils. or less. This matter is dealt with further in the section on the multichannel liquid gap. In the jitter experiments, as indeed with all the liquid point and edge plane experiments, the points and edges were frequently sharpened, to ensure that the streamers started out at a low voltage. Table II gives the breakdown voltages and jitters for an effective pulse time of 80 ns.

TABLE II

Material - Carbon Tetrachloride

Gap 2.05 cms $t_{eff} = 80$ ns

Experiment No.	Gap Type	Voltage (kV)	Jitter (%)
1	Point Plane	428	±1.3
3		420	±1.1
2	Edge Plane	504	±1.4
4		492	±1.1

Mean point plane breakdown voltage 424 kV
Mean edge plane breakdown voltage 498 kV
Ratio point to edge 1 : 1.18

As can be seen, the jitter is approximately 1 per cent and the edge plane holds off some 18 per cent more volts than the point plane. As was mentioned earlier, even though the edge was only some 3 cms long (excluding the roll up at its ends) multichannel breakdowns were frequently observed. The streamer channels were not straight but were mildly zigzagged in reasonable visual agreement with the jitter of 1 per cent. The measurements with the multichannel gap, using slightly longer pulses, also gave jitters of about 1 per cent. Graph 3 shows the jitter curve for air again and also the carbon tetrachloride point. Also shown is a point which Mr. George Herbert of AWRE got in an experiment with water with both an edge plane gap and also with a version of this called the I.B. gap. This stands for intentionally messed up gap and consists of a sharp edge sticking out a small controlled distance from a cylinder. Basically it was invented a year or so ago to obtain higher breakdown fields than the edge plane gap would give, but with the low jitter associated with these. Typically rod gaps in water can have jitters of 10 per cent. The IB gap can also be used in gases where the fin should stick out about 0.5 cms, or hard gases, where smaller projections are necessary to get fields up near those obtainable for uniform field breakdown. Also included is a point deduced from some data kindly provided by Ian Smith on a triggered multichannel oil gap. This point was partly obtained by using the proposed relationship in reverse, but the jitters calculated were in rough agreement with oscillographic measurements made of the variation of time of gap operation. Also on the graph is the jitter measured for some pressurised SF_6 gaps working at a density about midway between that of air and water; these too have been provided by Ian Smith to whom my thanks are again due. It will be a brave man who will draw curves through this meagre and rather scattered data and I for one will only do so in private.

It should be emphasised that the jitters shown in graphs 2 and 3 are the minimum that have been measured under good conditions. A gap poorly constructed or working with an inadequate driving circuit can well have a considerably worse jitter and hence fail to operate in a multichannel mode when it is expected to. Triggered gaps in at least one form are just a pair of edge plane gaps back to back and an example of this type of gap is mentioned at the end of this note. If such a mid plane is used, then inadequate sharpness of the trigger edge may give enhanced jitter and very rough main electrodes may lead to backfiring, especially if the trigger edge is being driven negative.

6. Multichannel Experiments

In this set of experiments the marx generator mentioned in the previous section was used to pulse charge a polythene insulated transmission line. Ideally this line would have had an electrical length rather longer than the longest τ_{tot} it was to be used with, but this was unfortunately impracticable, especially in the case when the line's impedance was low. As a compromise, the line was made physically 5 feet long, corresponding to a two-way electrical length of some 16 ns. The line was made from a total of 4 sets of sheets of insulation and these were separated by three boards of 1" plywood which were covered with a thin layer of spongy rubber and then sheathed in thin copper foil. The distance between the two outside output lines was about 9 cms but the total thickness of insulator was only some 0.6 cms for the case of the line with 2 1/2 ohms impedance. The width of the line was 18 inches and loading with lead bricks pushed the assembly together. The capacity measured after a few shots (when electrostatic forces helped) was within about 10 per cent of that calculated from its dimensions. This result was achieved largely because of the way the layer of spongy rubber took up small imperfections and assisted in spreading the localised loads of the lead bricks. In the 8 ohm version, which had about 2 cm of solid insulation in it, the line could be pulse charged to over 400 kV and at no time was any flashover experienced, despite the fact that the line was in air. For fairly fast charging it is considered that in a 10 cms height of line some 600 kV could have been held off in air.

The particular technique described here is rather useful in providing pulse charged high voltage condensers with very low output inductances. For instance if the line described is used to feed a closely coupled load some 10 cms high along its 150 cms length, the output inductance of it, viewed as a capacity, would be under 1 nanohenry for the case with a total of 0.6 cms of insulation. Unfortunately there are not too many loads that can be closely coupled into such a condenser cum line and in the case of the multichannel gaps described below, the main inductance was in the feed from the line to the edge plane gap. Considerable efforts were made to reduce this feed inductance to as small a value as possible. However, it still remained a significant additional impedance and to allow for this in calculating the number of channels to be expected, an effective impedance of the system was deduced, given by the relation

$$Z_{eff} = Z_{line} + 2L_{excess} / \tau_{tot} ,$$

where τ_{tot} was an average value for the set of experiments under consideration. In general, the extra term was less than 40 per cent of the final assumed effective impedance and usually significantly less. In the case where a reasonable number of channels was being formed, the resistive phase term was dominant and this only uses the impedance of the generator to the one-third power, so any error introduced in the calculations was small. However, for cases with a small number of channels, the use of a constant Z_{eff} might have been a bit pessimistic, since τ_{tot} was considerably bigger under these conditions. However, it is in just this case that the finite length of line might have begun to have an effect and this would presumably have slightly lowered the number of channels observed against the number calculated. Thus the two approximations tend to work in opposite directions and while it would be the wildest fluke if they cancelled, to the accuracy to which this work has any pretensions, the combined effects were probably tolerable.

Multichannel experiments in air

In the experiments, lines of two impedances were used, 2 1/2 ohms and 8 ohms respectively, and also two lengths of edges were employed, namely 40 and 80 cms. In the case of the 80 cm length edge, the inductance of the feed out to the outer parts of the edge plane gap became important and as it was practically very difficult to reduce this to a small value, the gap was reduced by a few percent, so that a very roughly uniform distribution of channels was obtained. This correction was not made very accurately and the effective length of the edge was therefore probably rather smaller than its physical length. One important feature of the experiments was to decide the criterion on which to count the effective number of channels. Ideally this would have been based on measurements of the current in the individual channels and then counting all those with currents over 45 per cent or 35 per cent of the maximum recorded. This would have been prohibitively expensive in equipment and very time-consuming and a simpler technique was employed based on photographically recording the light output. In previous work it had been established that for channels driven by relatively short current pulses, nearly all the light was emitted by the plasma channel up until the time it had expanded and become self-transparent. At this stage it had also cooled somewhat and the combined effect of these two phenomena was that typically the full width at half height of the visible light output was well under one microsecond. This simple picture of the plasma channel suggests that if the energy deposited in the channel is doubled, the width of the cylindrical channel at which the luminosity falls sharply goes up by $\sqrt{2}$ and the duration of the light pulse scales up by the same factor. Thus the photographically integrated light output should be proportional to the energy deposited in the channel, since the luminosity at which the channel ceases to be black body is quite closely constant. This proportionality was checked by using a single spark channel and driving it by the lowest impedance version of the line with a number of different resistances in series with it. These resistances took the form of low inductive networks and had values of approximately 30, 60 and 120 ohms. From the previously mentioned note the prompt energy deposited in the channel scaled as $Z^{-4/3}$ and indeed the photographically integrated light was in the ratio of 1 : 0.4 : 0.2 which was close enough. In order to avoid absolute densitometry, these test channels had 0.3 and 0.6 neutral density filters placed over 1.5 cms each of the 4.5 cms channel length. It had previously been established that the channels were uniformly bright along their lengths in all these and the following experiments and the use of neutral density filters placed close to the channels themselves simply calibrated the density of the photographic images on polaroid type 55 negative/positive film. Film from the same batch was employed and was fully developed and fixed. Since in these subsidiary tests a range of channel brightnesses of 5:1 was covered, the additional filtered sections covered a total range of 20:1. In counting the effective number of channels in any shot, the brightness of the most luminous image was matched and then all those down to one-third of this were counted (criterion A) or down to one-quarter of this (criterion B). The effective aperture of the camera was changed so that the brightness of the most luminous channel was within the dynamic range of the print, since as the number of channels increased their brightness decreased, of course. As was expected from the simple theory of the plasma channel and its dynamics, the brightness of the liquid channels was the same as that of those in air under corresponding conditions, which, considering the very different conditions existing in the two cases, was reassuring that the simple theory of the channel was applicable. In deducing the approximate current being carried by a channel whose integrated luminosity was down by 3 and 4 respectively, use is made of the fact that the energy deposited in the channel is given by

$$E \propto V^{2/3} Z^{-4/3}$$

Thus where the voltage across the channel has fallen by 0.9 and 0.85 respectively, the following table of very approximate data is obtained.

TABLE III

Criterion	E	V	Z	i
A	0.33	0.9	2.1	0.43
B	0.25	0.85	2.6	0.33

The values given above are fractions of those applying to the heaviest current carrying channels. No great accuracy is claimed for these figures of course and it would have been considerably better to have measured the currents directly. However, in view of the fundamental uncertainty in how a given current ratio reflects into the effective number of channels and rise time, I do not consider them to be too bad.

One minor consequence of the above analysis is that unless the effective aperture of the camera is increased as the number of channels gets larger in a series of tests, an erroneous visual impression of the density of channels will result. This is because the impedance driving each channel increases as the number of channels increases and hence their image brightness falls. This means that for each doubling of their number the camera ought to be effectively opened one stop approximately. When this is done the mean brightness of the first channel should remain roughly constant.

One further point should be mentioned with regard to the photographic recording used and this is that the image should be faintly out of focus unless the actual channels are extremely fine. This is so that the image on the print is reasonably uniform across its width and that this width is more a function of camera lens than of the actual image. This requirement is not an exact one but dictates that it is desirable to put in or remove neutral density filters rather than simply closing or opening the iris of the camera by large amounts. This effect was allowed for to a considerable degree by the use of neutral density filters in front of the reference single channels, and the whole effect is made more complex by the non-uniformity of point image size across the image plane of the lens. Consequently a very detailed analysis of the effect would be necessary to obtain accurate answers by the use of the technique described above, but due to the limited density ranges used in the experiments and the approximate nature of these, this was deemed not necessary. In a series of shots, the same piece of film was used and the camera tilted upwards so that about seven images were placed one above the other, thus saving film and allowing each set to be internally more consistent.

Low impedance line results

The impedance of the line was 2 1/2 ohms and Z_{eff} was 3 ohms. The length of the channels was 4.5 cms and the length of the edge was 40 cms. The following gives the details of the calculations for this case.

$$L \text{ spark channels} = 2 \times 4.5 \times 7 = 63 \text{ nH}$$

and $\tau_L = 21/n$ ns.

For the resistive phase $F = 30$ kV/cm

and $\tau_R = 88/1.4 \times 4.6 \times n^{1/3} = 14/n^{1/3}$ ns

$\tau_{trans} = 40/30 \times n = 1.3/n$ ns.

TABLE IV

Times in ns

n	τ_L	τ_R	τ_{tot}	$0.1\ \tau_{tot} + 0.8\ \tau_{trans}$	ΔT	$0.15\tau_{tot} + 0.8\ \tau_{trans}$	ΔT
1	21	14	35	3.5 + 1.1	4.6	5.2 + 1.1	6.3
2	10.5	11	23	2.3 + 0.6	2.9	3.4 + 0.6	4.0
4	5.2	8.8	14	1.4 + 0.3	1.7	2.1 + 0.3	2.4
8	2.5	7	9.5	.95 + 0.15	1.1	1.4 + 0.15	1.5
16	1.3	5.6	7	.7 + 0.07	.8	1.0 + 0.07	1.1

For the two criteria used above the number of observed channels are given in Table V below. Each number generally represents the average of seven shots. Also given is the observed value of T from $T = V\ (dV/dt)^{-1}$ where dV/dt is evaluated at the point of channel closure on the charging waveform.

The correction for "dead space" is analogous to the correction for dead time in counting random events, say in radioactive decay. The distance between channels was plotted out and while there was a reasonable distribution of channels, the ones close together tended to be fainter. This meant that there was a dearth of small gaps and a correction is applied on the basis that the streamers do affect each other slightly when they are close together. The correction for a channel length of 4 1/2 cm is very approximately $N = P\ (1 - .025\ P)^{-1}$ where P is the number of channels observed and N would be the

TABLE V

Observed Number of Channels

Value of T ns	n criterion		n corrected for Dead Space		ΔT calc.	
	A	B	A	B	A	B
350	2.3	3.0	2.5	3.4	2.4	2.6
230	3.2	5.1	3.6	5.9	1.7	1.8
170	5.0	8.0	5.8	10.1	1.3	1.3

number with no dead space. For the 80 cm long edge, the constant inside the bracket is halved. The correction is not large for all the experiments in this section, but in the last section the long edge gap has a fairly big correction which is certainly not well established. However, for the present experiments it is really included only for completeness and is very approximate. Table VI gives the values of ΔT obtained from the jitter experiments. The value of t_{eff} to be used with Figure 2 is obtained from the pulse charging waveform, but is approximately equal to 0.4 T.

TABLE VI

T_{ns}	σ (%)	$\Delta T = 2\sigma T$	ΔT from Table V
350	0.5	3.5	2.5
230	0.45	2.1	1.8
170	0.4	1.4	1.3

The agreement is quite reasonable, except for the first entry, and this is in the region previously discussed where the approximations used are not very good. However, to 30 per cent or so the agreement is satisfactory.

For all the subsequent measurements criterion B is used to improve the statistics. For the case of $T = 170$ ns a series of determinations of n were done at different times and these gave values of 8.0, 7.9, 8.4, 8.3 and 7.6 uncorrected for dead space effects. The reproducibility was rather surprisingly good. Considering the individual numbers of effective channels in each set of seven shots gives a standard deviation in the number per shot of ± 20 per cent for this case.

Summary of results for both lines and gaps

Table VII summarises the data for the 40 and 80 cms gaps and for the two effective line impedances of 3 and 9 ohms. The observed effective number of channels has been corrected for dead space effects. These are compared with the number of channels predicted by the relation given in section 2, using the jitter values given in section 5.

TABLE VII

Negative Edge - Criterion B

Gap 4.5 cms corrected dead space

T	N_{40}	N_{80}	N_{40}	N_{80}	
	Observed		Calculated		
350	3.4		2.3		Z_{eff} = 3 ohms
230	5.9		4.8		
170	10.1	10.4	9.2	10.6	
220	1.4	2.0	2.3	3.1	Z_{eff} = 9 ohms
170	3.2	3.7	4.0	5.1	
140	4.1	4.8	6.5	8.0	

Figure 4 shows N_{40} data plotted out.

Comparing the number of channels is a more sensitive measure of agreement than comparing values of ΔT as the effective number is a higher power than one of ΔT. In particular the disagreement at the bottom of the table reflects no more than a 40 per cent difference in ΔT. The disagreement is in part due to the fact that the effective length of the edge is less than the full 80 cms. In general the agreement is quite reasonable, certainly within the limits hoped for for design purposes.

Figs. 5 and 6 are typical open shutter records of a series of shots using the 40 cm and 80 cm long edges respectively. Needless to say, the lowest impedance line and the smallest charging T given in Table VII were chosen in each case in order to give as many channels as possible but, this apart, the records are otherwise average ones. The faint set of fuzzy images down the left hand side of the prints are the spark gap columns in the Marx and should be ignored.

Multichannel experiments in liquid

The liquid chosen for these experiments was carbon tetrachloride. This was selected because in the compilation of mean streamer velocities given by George Herbert in "Velocity of Propagation of High Voltage Streamers in Various Liquids" (SSWA/HGH/6610/104)[3] this material has the highest velocity at voltages of about 400 kV. The high impedance line only was used in these tests in order to have as large a voltage available as possible. Even with these choices the gap was only 2.0 cms and extra care had to be taken to keep this rather small gap constant. In addition the higher impedance line was chosen to reduce the effect of the feed inductance which was slightly bigger in this arrangement, giving a Z_{eff} of about 10 ohms. The length of the edge was about 34 cms. As the experiments proceeded the carbon tetrachloride became quite dark with finely divided carbon, which was removed by filtering periodically or by the use of new liquid.

When the experimental set up was first used, multichannel operation was immediately obtained, but the channels came from both ends of the edge. These ends were gently curved up, rather like a double-ended ski in profile, as had been the edges used in air. There were incipient streamers along the main length of the edge, but few of these had closed in time. While it was not surprising that streamers could close first from square cut ends, because of the effects described earlier, it was felt that the "roll-off" of the edge had been well done. Closer examination of the edge showed that the 9 mil. thick phosphor bronze out of which it was made had lipped sideways, leaving a very sharp edge where it had been cut with scissors to form the ends. Thus the closure at the ends was being caused by the fact that the streamers were starting out earlier in the rising waveform than those from the blunter central region of the edge.

George Herbert's paper gives the mean stream velocity from a negative point as

$$\bar{U} = 166\ V^{1.71}$$

where the mean velocity is just the distance from the point to the plane in cms divided by the effective time of the pulse in microseconds. The amplitude of the pulse is in units of a million volts. This can be used to provide a differential velocity relation which on integrating with a linearly rising voltage pulse gives

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[3] Dielectric Strength Note 10

$$d = 62\, V^{1.71}\, t_2\left(1 - (t_1/t_2)^{2.71}\right)$$

where t_2 is the time of closure and t_1 is the average time at which the streamers start out. This time is likely to be very variable and in order to ensure that 100 per cent jitter in this time has an acceptable effect on gap operation, the value of $(t_1/t_2)^{2.71}$ should be less than .005, i.e. $t_1/t_2 \leq 1/7$.

This does not at first sight seem to be a very strict requirement but closer examination proves that it requires a rather sharp edge to the electrode. For the longer of the two pulses used in the experiments described below, $V \sim 0.3$ MV and hence the streamers should have started by the time the voltage on the edge has risen to 40 kV. The effective area of the edge is about 0.1 cm^2 and the t_{eff} is of the order 100 ns. Unfortunately we don't have the area effect curve for uniform breakdown in carbon tetrachloride but assuming that it is roughly the same as transformer oil, this means that surface fields of the order of 1.5 MV/cm are required. For an edge to achieve this sort of field with only 40 kV on it requires a radius of the order of 2 mils. or less. In the experiments the edge was sharpened to better than this and then reliable operation occurred from the main length of the edge. In order to ensure that the voltage of streamer initiation was adequately low, the edge was periodically sharpened during all liquid breakdown tests.

The streamer velocity data given by George Herbert can be integrated to give the gap that will break with a linearly rising pulse and the calculated and observed values are given below in Table VIII.

TABLE VIII

Negative Polarity

Voltage (MV)	T (ns)	d Breakdown Calculated (cms)
0.400	150	1.95
0.286	280	2.04

) Actual gap
) 1.95 cms.

The agreement shown in Table VIII is not as good as it seems, because George Herbert's data was obtained with points, while the experiments were conducted with edges. Thus it should have required voltages some 20 per cent more than were observed to get agreement. However, in view of the fact that the streamer velocity relation is only approximate and that a linearly rising waveform relies on the low voltage extrapolation of this relation, the agreement is acceptable. A second possibility is that the point in the liquid streamer work may not have been quite as sharp as the edge used in this work, although it too was regularly sharpened.

Liquid gap results

Two sets of experiments were conducted with different values of T . In the case of liquids, the breakdown field is much more heavily dependent on the value of T and this in its turn leads to a fairly strong dependency of τ_{tot} on T . Consequently fairly large changes in the rate of rise of the pulse have less effect on the number of channels, as they are partly compensated for by the change in field along the channel when it closes. This is shown by the calculations given below for the two cases used experimentally.

TABLE IX

Times in ns

(Z_{eff} = 10 ohms)

n	τ_L	τ_R	τ_{tot}	$0.15\ \tau_{tot} + 0.8\ \tau_{trans}$	ΔT
T = 150 ns $V_{breakdown}$ = 400 kV F = 0.2 MV/cm					
1	3.0	27	30	4.5 + 1.4	5.9
2	1.5	21.5	23	3.4 + 0.7	4.1
4	0.8	17	18	2.7 + 0.4	3.1
8	0.4	13.5	14	2.1 + 0.2	2.3
T = 290 ns $V_{breakdown}$ = 286 kV F = 0.14 MV/cm					
1	3.0	44	47	7.0 + 1.4	8.4
2	1.5	35	36	5.4 + 0.7	6.1
4	0.8	28	29	4.4 + 0.4	4.8
8	0.4	22	22	3.3 + 0.2	3.5

In obtaining the values for Table IX a couple of points have to be borne in mind. The equation for the resistive phase in materials of unit density has a constant of 5 in it. This has been increased to 6.5 to allow for the fact that the density of carbon tetrachloride is 1.60. In addition its local velocity of light is only two-thirds that of free space.

The jitter in closure of the gap was measured in the six separate sets of experiments and these averaged out at ± 1.0 per cent in reasonable agreement with the independent value determined in the experiments of section 5.

In the case of the liquid gap it is somewhat more difficult to determine the effective number of channels because branching occurs and it is not easy to decide how many effective channels a branched discharge corresponds to. Fig. 7 shows an example of multichannel liquid operation and shows the fairly extensive branching that can occur. In practice a somewhat subjective increase to the number of channels roots has been made; this in general increased this number by some 30 per cent. The dead space correction has not been applied but if it were, the same as for a scaled-down air case, it would be less than 10 per cent.

TABLE X

Negative Edge - Criterion B

Gap 2.0 cm
Uncorrected for any dead space

T (ns)	n observed	n calculated	ΔT from observation	ΔT σ = 1.0%
290	2.8	2.4	5.4	5.8
150	6.0	4.3	2.6	3.0

Table X compares both the predicted and actual number of channels and also gives the values for ΔT . Once again, very good agreement seems to have been obtained.

One of the points which has yet to be raised is the question of the simultaneity of the channels. Where a system contains a considerable excess of energy which can ring on for a long time and where the single spark gap channel is a substantial fraction of the total inductance, then big oscillating voltages caused by the L di/dt term can cause channels to complete on later current reversals. The circumstances have to be rather special for this to occur but it has been observed to happen. In the present instance, the spark channels themselves form a load for most of the energy in the line and the inductance of the channels compared with that of the feed and line is very small. Thus the current that oscillates is well down and the fraction of the inductive voltage appearing across the gap is less than 10 per cent of the initial charging pulse. It also lasts for a shorter t_{eff} than that of the pulse. This fact was checked by the voltage monitor whose output had to be corrected because the feed inductance was included in its tap off loop. Making a reasonable allowance for the effect of this, the measurements suggested that less than 5 per cent of peak voltage appeared across the channels after firing in the experiments with both gases and liquids. In the case of the experiments in air, integration of the streamer shows that any subsequent distance of closure was very small because of the $t^{1/6}$ dependence of the relationship. This shows that the 5 per cent voltage pulse would have had to have gone on for thousands of nanoseconds to have caused any additional closures. Even if these had taken place, because there could be no significant voltage across the channel, if it did manage to close, the current and hence light output would have been undetectable. However, it was felt necessary to check this point and the liquid tests were chosen because of their stronger dependence on t, which should lead to any effects being found in them ahead of the experiments in air. A set of experiments was done with a low inductance network of resistors whose value was 10 ohms in series with the gap, thus damping any oscillations in the line very quickly. Because the impedance of the generator was being doubled, the number of channels would of course be expected to decrease, but by nothing like as much, if most of the channels were due to late closure.

In the experiments with damping resistor in series with gap, the number of channels was 4.5 where previously it had been 6.0 without it. The calculated effect of increasing the generator resistance from 10 to 20 ohms would have been to drop the expected number fo 3.7. Thus there was, as expected, no evidence at all of late closure of channels in the experiments most likely to show any such effect.

7. Examples of Multichannel Gaps

As was mentioned earlier, while accurate experimental verification of an expression is of course useful, if this is limited to a relatively small range of parameters it may be less useful than a much rougher experimental agreement with many considerably different systems. As such, it is worth recording that, to a significantly lower accuracy than the work reported in this note, the suggested expression has been tested against three different multichannel gaps, three different liquid gaps, four different gaseous gaps and a surface air gap of vintage design. In general, the jitter is the factor which is least well determined and intelligent guesses have sometimes had to be made about this factor, but, with this reservation, reasonable agreement was obtained from these rough calculations. This in my opinion offers as much proof that the expression is valid as the data presented in section 6 of this note.

In this final section two examples of gaps will be briefly described, the first one because it bears on the effect of dc/dt loading and the second because it led to some work on the current stability and perseverance of heated plasma channels.

The Three Metre Edge Gap

This was a set up designed to demonstrate switching with about 200 channels. As ever, performance did not match up to expectations but in fact 140 channels were achieved with it. These channels closed within a span of 0.6 ns and the fall time of the voltage was about 5 ns. The measured time was about 8 ns but the location of the monitor and its response probably accounts for the difference. As the line had an effective impedance of 0.45 ohms and the switch closed at 105 kV, the short circuit current was about 230 kamps and the di/dt was about 5 x 10^{13} amps per second, achieved at a relatively modest voltage. The rise time of a single channel across the same impedance would have been about 110 ns; thus the multichannel switch outperforms the single channel gap by a factor of about 20.

In order to obtain many more channels than in the previous experiments, it was necessary to reduce the impedance of the line feeding the gap: at the same time the pulse rise time had to be decreased, if possible. The length of the edge had also to be increased considerably, in order to reduce the dead space correction to manageable proportions. The latter requirement led to a total width of edge of 3 metres and by folding it over on itself, so that there were two gaps back to back, the width of the lines could be held to 1.5 metres. The length of the line was made 84 cms so that 3 feet wide insulator could be used, leading to an electrical length of about 9 ns. The capacity of the first line was 8.5 nF, giving a transmission line impedance of about 0.5 Ω and a Z_{eff} of 0.8 Ω. In order to charge this capacity quickly, a new condenser set-up was built. This consisted of 8 condensers each 10 nF 100 kV, in two sets of 4, and were plus and minus charged as usual. A rather low inductance 200 kV pressurised spark gap (which had either air or SF_6 in it, according to the working voltage) joined the hot terminals of the condensers together, when the pressure was released and it broke down. The output capacity of this 200 kV unit was 20 nF and its inductance, including the feeds to the line, was 110 nH. The bank was not charged over 180 kV because it was not necessary, but it was fired a number of times at this voltage. As the condensers were rather long (45 cms) and not very low inductance, they contributed over half the inductance of the unit.

With no output leads and with capacitors of good design and large capacity, the inductance of the unit could have been about 60 nH. Thus if these units were stacked, which was inconvenient but possible, an inductance of 300 nH per million volts would have resulted: this number is contemporary. Figure 8 shows a schematic of the layout and also a cross-section of the line and the double sided gap. In the first set of experiments this was set at a gap of 3.7 cms and the breakdown voltage was 126 kV for fast charging. Table XI lists the total number of channels and compares the ΔT values deduced from these and the expected jitter.

TABLE XI

Negative Polarity - Material Air

Criterion B

$Z_{eff} = 0.8$ ohms

T (ns)	n observed	n corrected dead space	σ assumed (%)	ΔT from observations	ΔT calculated
118	49	59	0.35	1.04	.83
86	60	72	0.3	.93	.52
79	61	74	0.3	.91	.48
73	65	79	0.3	.89	.44
68	82	102	0.3	.78	.41

The agreement is not too bad at the top of the table but gets progressively worse for faster and faster charging times. The reason was clear from the 'scope records, which showed that the charging waveform curled over and had fallen significantly before a sharp break occurred, presumably at the time the plasma channels began to conduct in earnest. The earlier phase is attributed to the dc/dt term. This loading meant that roughly 10 kAmps were flowing prior to channel closure. This was more or less in line with some earlier measurements, where rather smaller effects had been noticed corresponding to a few tens of amps per cm of edge, when a gap had been fast charged.

If the dc/dt term is the explanation, then it would be expected that the load impedance would be proportional to the charging time and inversely proportional to the length of the edge. In the extreme condition of fast charging given in Table XI, the voltage was falling to about 75 per cent before the streamers finally closed. It should be repeated that the dc/dt picture is being used in the section but an equally valid (and rather similar) set of explanations can be built up on photoionisation ahead of the streamers. Figure 9 shows a photographic record of the gap operating under these conditions. One point of interest is the partially formed channels reaching out from the centre edge towards the plane electrode. The fact that these are already fairly luminous shows that substantial currents are flowing before streamer closure. They also indicate, as was mentioned earlier, that the assumption of uniform conditions up the incipient channel is not always tenable. It should be stated that it was only under these conditions that these partial channels have been recorded photographically in the experiments recorded in this note.

At this stage a very short series of experiments was performed with positive polarity on the edge. These showed about half the number of channels that the negative polarity gave. Because of the very brief nature of the series of shots, this result should be treated with considerable reserve. As was expected for air the breakdown voltage was closely similar to that measured with negative pulse charging.

In order to counteract the dc/dt effects, it was decided to rebuild the line with a real impedance of 0.3 ohms and an effective one of 0.45 ohms. In addition a small width raised portion was built up on the plane electrodes opposite the knife edges. This closed down the gap spacing to 3 cms and hence the breakdown voltage decreased to 105 kV. The effect of these changes was beneficial and the slower fall on the waveforms was small and confined to the fastest charging conditions. It is difficult to be sure that both changes had an effect but I consider that the higher capacity of the line on its own could not have accounted for all the improvement.

Table XII lists the same parameters as Table XI but for the new line and edge plane gap, of course.

TABLE XII

Z_{eff} = 0.45 ohms

T (ns)	n observed	n corrected dead space	σ assumed (%)	ΔT raw calculated	ΔT from observation	ΔT calculated
~220	54	64	0.4	1.8	1.2	1.6
~160	71	86	0.4	1.3	1.1	1.2
120	100	133	0.35	0.85	0.8	0.8
100	113	157	0.3	0.6	0.76	0.6
90	132	195	0.3	0.55	0.70	0.55
80	141	220	0.3	0.5	0.65	0.5

A small correction has been applied to the experiments with large values of T . This is because if a constant pulse were applied to a point or edge plane gap there will still be a finite jitter in closure time. Consequently when the streamers close to peak on the charging waveform, as T goes to infinity, ΔT remains finite.

The agreement shown by Table XII is much better than that in Table XI and since for very short values of T some residual dc/dt effect is still present, it probably helps to account for some of the difference here.

Figure 10 shows the record corresponding to the entry in Table XII where something like 140 channels have been obtained. Using the rather ill-established dead space correction (after correcting the correction for the shorter gap and much greater edge length), this number corresponds to about 220 channels, if the edge length were much bigger.

One further quick experiment was performed to display the possibility of locating the channels reasonably uniformly along the length of the gap. This took the form of a 5 mil. mylar sheet placed over the plane electrodes in which 100 small holes had been punched. Figure 11 shows a record taken with this arrangement. For various reasons the lower sheet of mylar sat down rather better on the bottom electrode than did the top one and this accounts for the considerable difference between the two halves of the gap. It is my opinion that if more time had been available, the top gap could have been made to work as well as the bottom one. In a real gap, such a way would not have been employed, of course. Probably the best way would be to provide smoothly raised bumps on the plane electrode such as would be produced by rivet heads. This, with a judicious cutting back of the knife edge between required sites, should be effective in localising the channels. The cutting back of the edge would have to be smoothly done and could not be very pronounced.

I would like to thank Chris Richmond for his kind assistance in the experiments described in the above section.

Triggered high current rail gap

This work was done rather over a year ago and was designed as a possible replacement for the solid dielectric multichannel gaps that had been in use for some years at AWRE. While it worked satisfactorily, the solid gaps have remained the preferred method of switching for the type of work that the division does. I would like to express my warmest appreciation to Rex Bealing and Pete Carpenter who were responsible for the experimental results briefly summarised in the section. The arrangement was almost perfect: they worked and I criticised.

A number of rail gaps were built, culminating in a four foot wide version which was tested in conjunction with one quarter of the megajoule bank. The gaps which were used differed only in length and consisted of two 3/4 inch brass rods bent back gently at the ends and separated by about 1.0 cms. A brass trigger electrode was set back from the central plane, in general with gaps of 0.8 and 0.4 cms to the rods from its edge. Three methods of producing the trigger pulse were employed, initially a Blumlein transmission line switched by a solid dielectric switch, then a low inductive mylar insulated capacity ringing into the capacity attached to the trigger edge. This was the method used in the large current tests and finally an improved double transmission feed system was developed to charge the capacity associated with the trigger in the shortest possible time. In general the gap was operated at 20 kV with a self break voltage of 30 kV. The trigger pulse used had a peak amplitude of about 40 kV and maximum rate of rise of about 8 ns. The trigger pulse was applied to the sharp trigger electrode in such a polarity as to break both portions of the gap simultaneously. Some care was taken to ensure that the pulse was applied to both portions of the gap, by having low impedance feeds to the main electrodes. In the final 4 foot wide version, some 40 and 70 channels were obtained in the two portions of the gaps when the feeds to it had an impedance of about 0.1 Ω. As such, the initial current established in the channels was about 200 kA and an important question was whether when the main current of some 4 MA was built up from the condensers several microseconds later, the current would still be well distributed. This question was important because it was known that the light pulse from channels driven by short bursts of current decayed in well under a microsecond. However, this merely meant that the hot channel had expanded into pressure equilibrium with the surrounding air and had become self-transparent in its own radiation. As such its emissivity dropped to a very low value even though the channel was still very hot. Various methods by which the channel might cool were investigated and it was concluded that thermal conductivity radially was probably the fastest mode and that this would take a time of the order of a few tens of microseconds. As such it was expected that the main bank current would establish itself satisfactorily in a number of channels. To check this a subsidiary experiment was performed with a 10 cm section of the gap fed by a 28 microfarad condenser and an inductance to give an 80 microsecond period. The peak current delivered by this intentionally slow system was about 50 kA. In this gap the trigger impedance was increased from a low value, when about 7 channels were observed to 14 ohms, when about 2 channels carried the main bank current. The trigger impedance at which the number of final channels was down by two was about 10 ohms. This meant that indeed even for very long bank periods the much larger bank current would still distribute itself reasonably between the briefly heated channels, even when these had been warmed to take only a few percent of the final current, and that the trigger impedance for the 4 foot gap should be a little under 1 ohm.

When the 4 foot gap was tested on the quarter clump it was no longer possible to photograph individual channels, because a diffuse glow filled some 20 per cent of the total rail length, but the relatively slight markings on the rail electrodes indicated that substantial areas carried the 4 MA, as expected. The inductance of the gap was about 1/2 nH, as calculated, and the DC hold off of the gap after carrying large current was within 10 per cent of its initial value. The rather flimsy nature of the feed to the trigger electrode suffered damage from the expanding hot gases, but, this apart, the gap survived well for a few shots, again indicating well distributed current carrying.

8. Envoi

When I first became reasonably sure that my treatment of the problem was adequate for design work, I was tempted to write a short note and leave it at that. If any readers have survived as far as this point, they may well be in heartfelt agreement with my original intent. One person I am certain who must have wished I had followed my first inclinations is Mrs. Vikki Horne, who has nobly deciphered my impossible handwriting and disentangled my incredible syntax. If by any chance there are any sentences in English in this note at all, the whole credit belongs to Vikki. I would like to express my warmest gratitude to her for attending to her multitudinous duties and also keeping up with me in the four days it has taken to write this note. I must accept all responsibility for the doubtless numerous errors and omissions and can only plead that it has been prepared on a rather short time scale. If anyone wants enlightenment on any particularly opaque passage, I will be delighted to try and understand it myself.

" The common cormorant or shag
Lays eggs inside a paper bag.
The reason you will see no doubt
It is to keep the lightning out.
But what these unobservant birds
Have never noticed is that herds
Of wandering bears may come with buns
And steal the bags to hold the crumbs. "

(Anon).

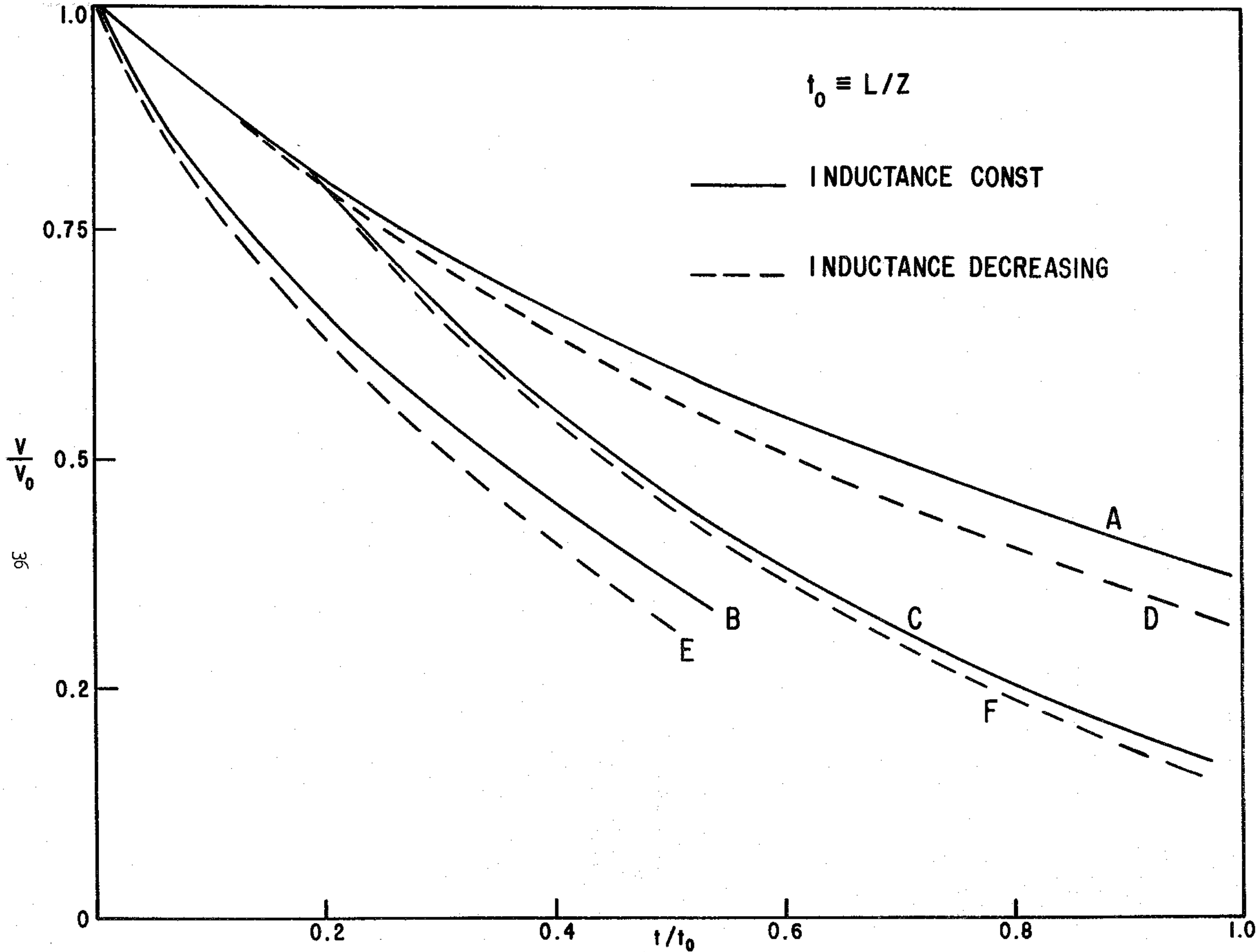
$t_0 \equiv L/Z$
INDUCTANCE CONST
INDUCTANCE DECREASING
A
B
C
D
E
F
$\frac{V}{V_0}$
1.0
0.75
0.5
0.2
0
0.2
0.4
0.6
0.8
1.0
t/t_0

FIGURE 1

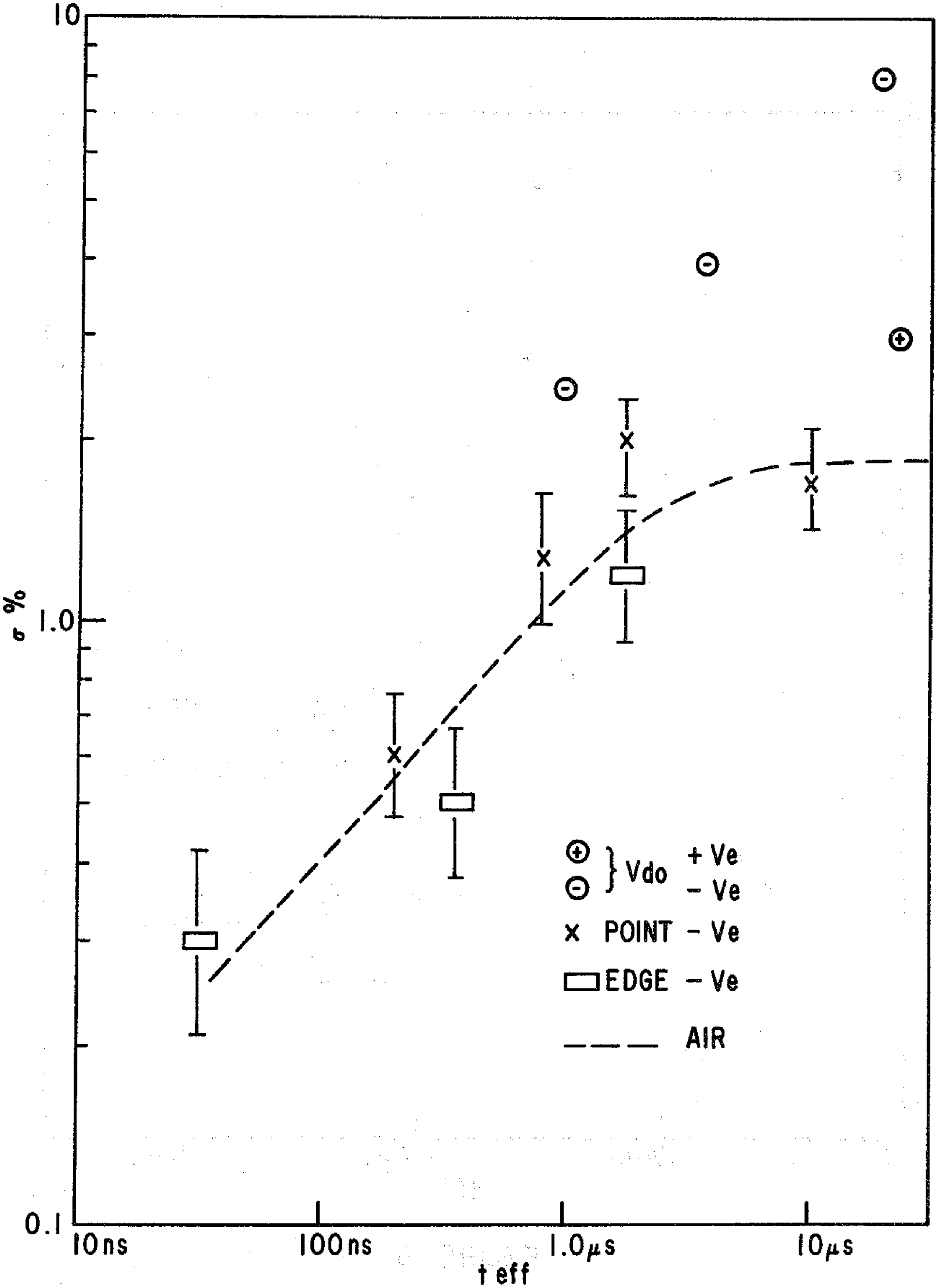
10
1.0
0.1
σ %
10ns
100ns
1.0μs
10μs
t eff
⊕ } Vdo + Ve
⊖ - Ve
× POINT - Ve
▭ EDGE - Ve
– – – AIR

FIGURE 2

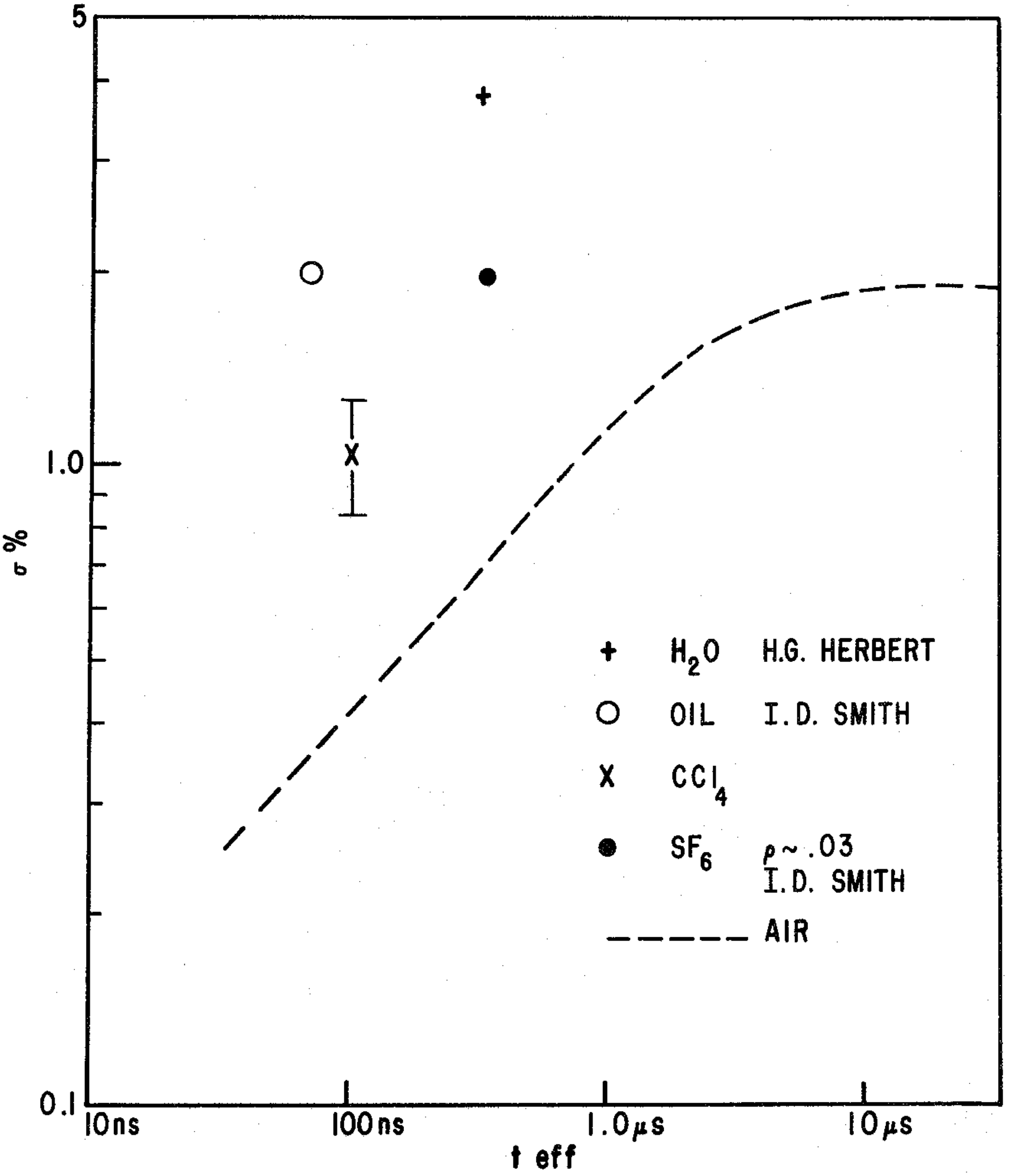
5
1.0
0.1
σ %
10ns
100ns
1.0μs
10μs
t eff
+ H₂O H.G. HERBERT
○ OIL I.D. SMITH
X CCl₄
● SF₆ ρ ~ .03 I.D. SMITH
– – – – – AIR

FIGURE 3

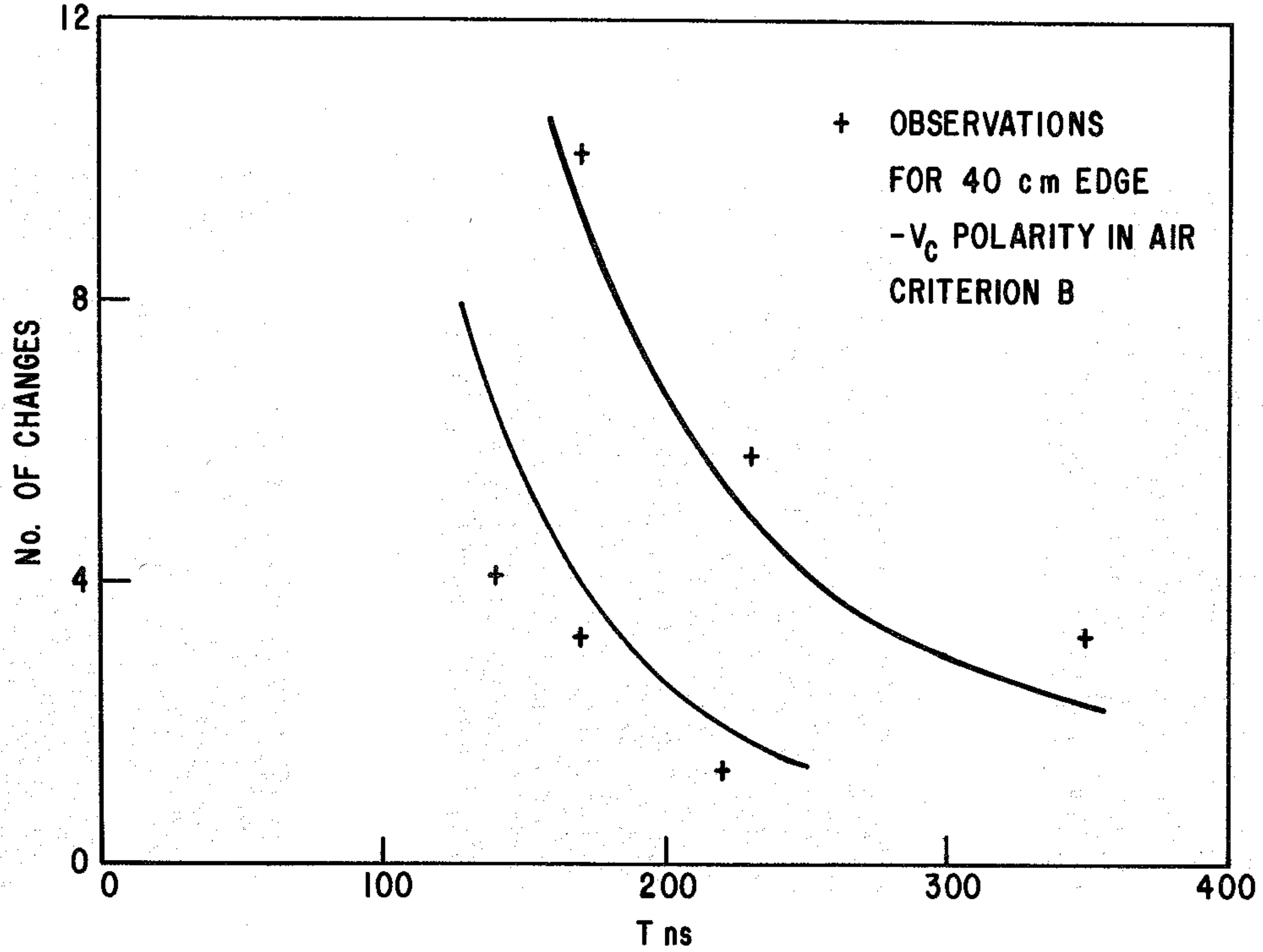
12
8
4
0
No. OF CHANGES
0
100
200
300
400
T ns
+ OBSERVATIONS
FOR 40 cm EDGE
$-V_C$ POLARITY IN AIR
CRITERION B

FIGURE 4

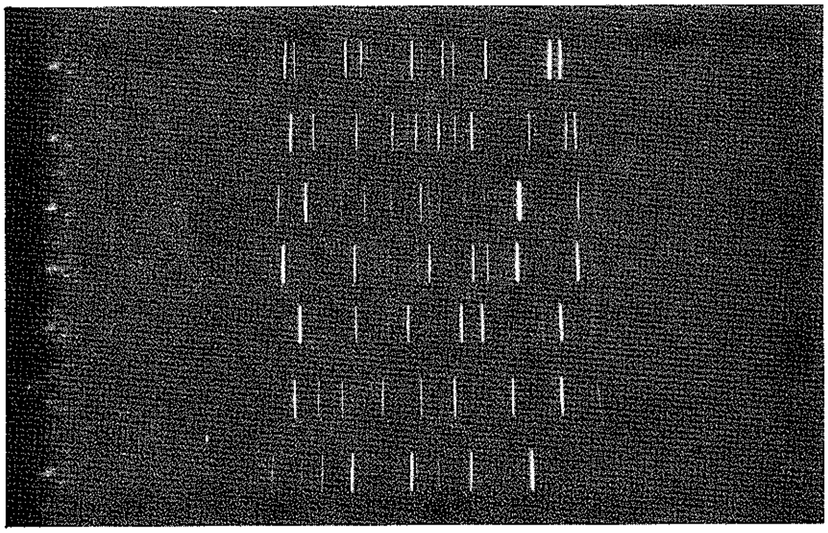

FIG. 5

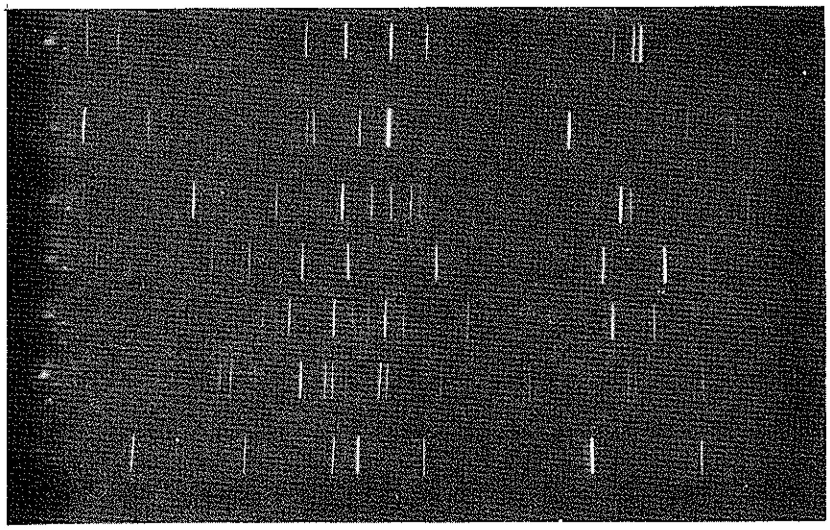

FIG. 6

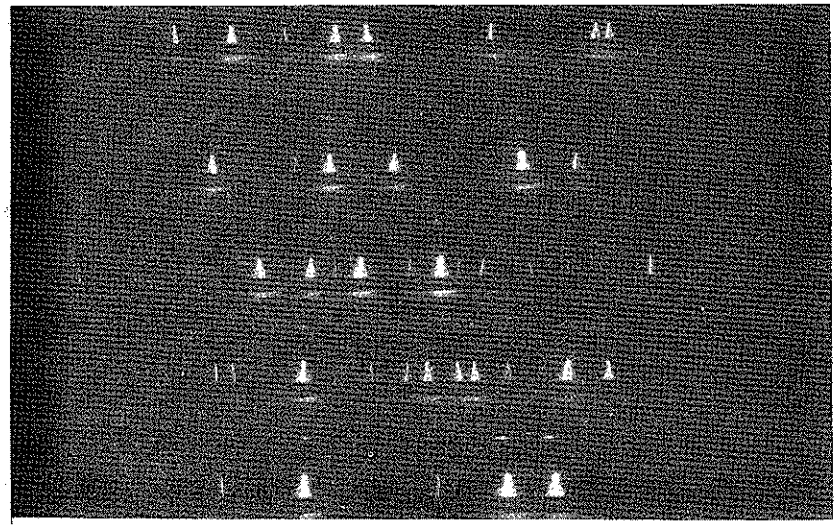

FIG. 7

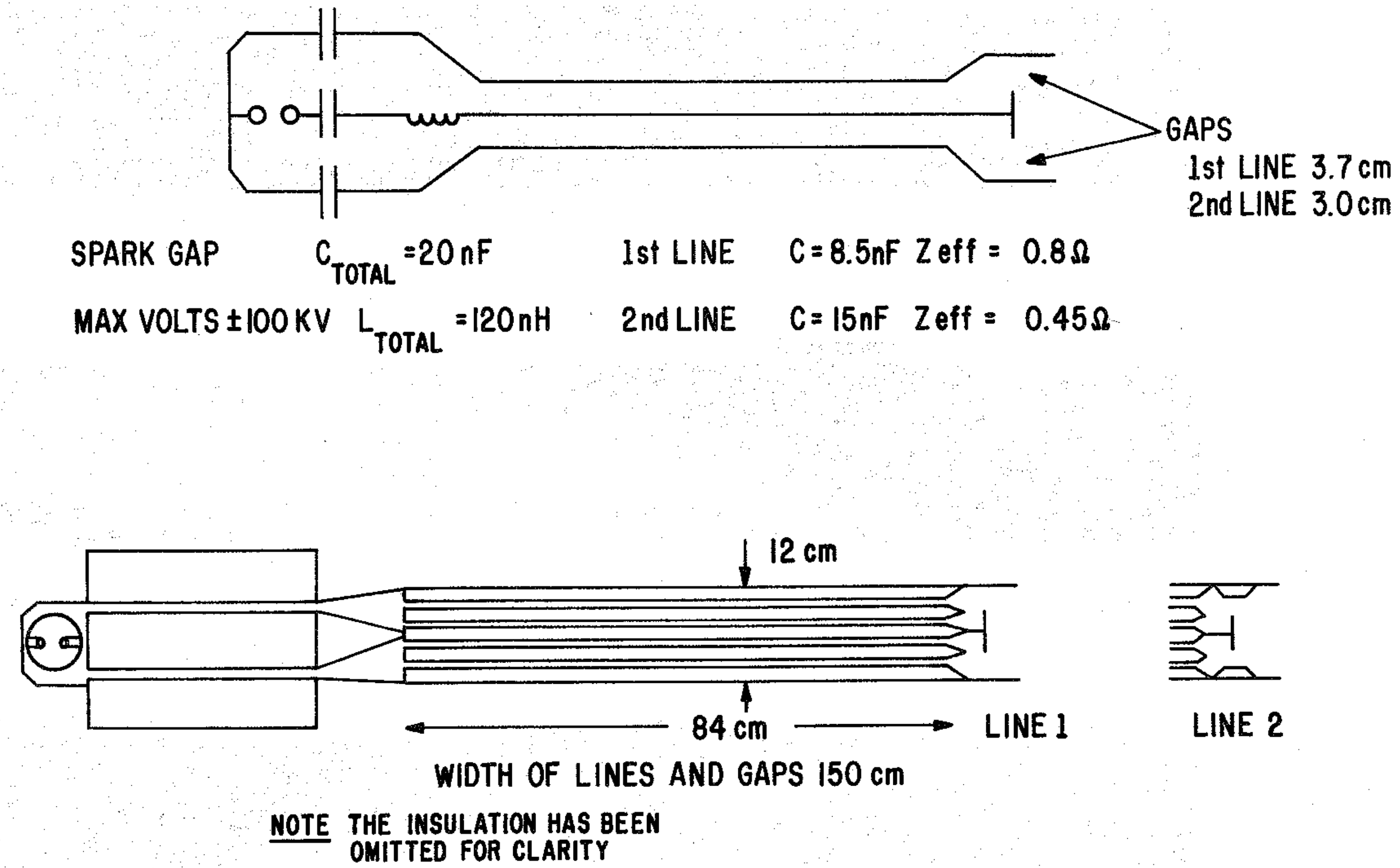
GAPS
1st LINE 3.7 cm
2nd LINE 3.0 cm
SPARK GAP
C_{TOTAL} = 20 nF
1st LINE
C = 8.5nF Zeff = 0.8Ω
MAX VOLTS ±100 KV
L_{TOTAL} = 120 nH
2nd LINE
C = 15nF Zeff = 0.45Ω
12 cm
84 cm
LINE 1
LINE 2
WIDTH OF LINES AND GAPS 150 cm
NOTE THE INSULATION HAS BEEN OMITTED FOR CLARITY

FIGURE 8

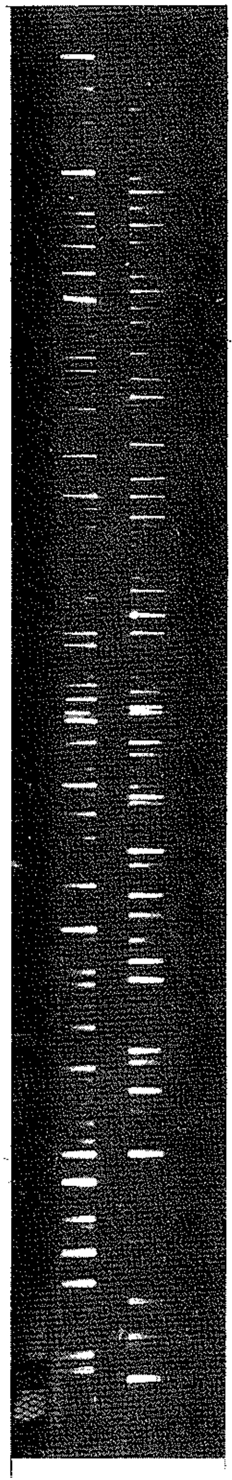

FIG. 9

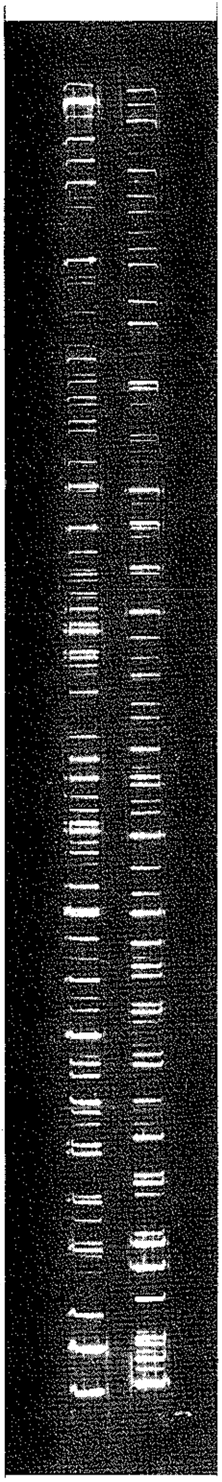

FIG. 10

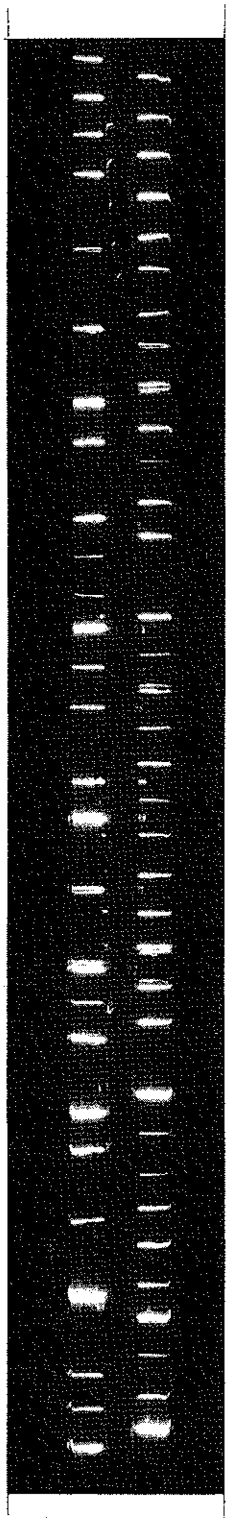

FIG. 11