Switching Notes
Note 25

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An Auto Irradiated Pulse Charged Divertor Gap

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1 INTRODUCTION

Nuclear weapons detonated under certain conditions can give rise to large radiated electromagnetic fields (EMP). Tall metallic structures, such as transmitter aerials, can pick up this EMP and give rise to very large voltages at their bases. In a calculation kindly supplied by Roger Oats of SWLR, a maximum voltage of some 4 MV, rising at a rate of 20 kV/ns, was estimated to be produced under worst circumstances. Transmitter aerials are provided with lightning-diverting ball spark gaps but, irradiated, these would break at 400 kV in the case of the tallest mast. Unirradiated, these gaps would close with a large variation or voltage jitter, but on occasions, it is estimated, could break at up to 2 MV. Indeed, because the RF is continually on these ball gaps, it is to be expected that any small whiskers or other protuberances would be removed, so while the gaps might look rather scrofulous, electrically they would be very smooth and well conditioned. Thus the unirradiated EMP breakdown of the lightning arrestor gaps would be expected to be between 1 and 2 MV for the largest aerial.

While the base insulator would not be expected to flash over, because of the relatively short duration of the pulse and its massive construction, some significant fraction of this voltage would feed through into the transmitter and probably do it no good at all.

While it would be possible to use a radioactive source to irradiate continuously the ball gaps, this would need to be a fairly substantial one and would represent a possible hazard as well as causing enhanced metal rot. It is also true that the nuclear weapon itself might provide adequate ionisation in the gaps to prevent the ball gap breakdown voltage from rising to these large values; however, in general, there is too much attenuation in the atmosphere for this to be relied upon.

When this problem was suggested we proposed that it might be possible to use the large frequency difference between the fast EMP signal and the relatively slow RF signal to overvolt an auxiliary gap and so uv-irradiate the main gap before the volts on this had risen to breakdown levels. It was estimated that breakdown voltages of no more than 300 to 400 kV might then be assurable and the resultant voltage pulse would have a time width of some 10 ns or so (F.W.H.H). Such a pulse, while still large, would not propagate very well into the transmitter house and in any case would not reach important and vulnerable components with an amplitude big enough to damage these.

This note summarises some rough quick work to investigate one form such a self-irradiated gap can take. The total time that could be devoted to this work has been about four man-weeks and quite a lot of that time has had to be spent in building test generators, test rigs, and monitors, so the quantity of data is not large and the results obtained not of great accuracy. However, it is felt that the performance of gap to EMP can now be guaranteed to an adequate accuracy and that a properly engineered version of it should now be made by others and tested in situ to ensure its survival during lightning strokes, RF breakdowns, etc.

2 POSSIBLE GAP DESIGNS

Because the clipped EMP has frequencies of around 50 MHz or so in it, while the RF of the transmitter is more like 1 MHz, it is possible to include a filter in the gap design so that the auxiliary uv-producing gap operates with the EMP pulse but does not have any ionisation occurring in it during the trillions of RF pulses applied to it during normal usage. Figure 1A shows the basic arrangement for this, S_1 being the auxiliary uv gap (an edge/plane or edge/edge one), S_2 being the main gap. The capacitors are built in as the stray capacities of the gap and it is obviously desirable to make C_1 comparable to or greater than C_2. The value of the inductance is chosen so that only a few hundred volts appear across S_1 during the normal operation of the transmitter, while during the fast rising EMP pulse its impedance is large compared with that of C_1 and C_2.

The first arrangement considered is shown schematically in Figure 1B. In this, S_1 is an edge/plane gap and would have a spacing of the order of 1 cm, while S_2, the main gap, would be about 6 cm maximum. In order to have C_2 less than C_1 the diameter of the electrodes needs to be around 20 cm, or so. The disadvantage of this arrangement is that any lightning strokes would pass through the edge/plane gap and might erode and condition this so that it loses its sharpness. Under these circumstances it was thought possible, though unlikely, that, with use, the pulse breakdown voltage of S_1 might rise to become significant with that of S_2.

Consequently the version shown in Figure 1C was devised. This has the advantage that any lightning strokes will either close S_1 (an edge/edge gap) and so operate the main gap, or, if very slow rising, will close directly, between the raised main electrodes. In addition, RF breakdowns will, in general, directly close S_2, or, on the few occasions when they fail to do this, will not seriously erode S_1, which takes the form of three separate E/E gaps, each of significant width.

A further version was considered and this is shown schematically in Figure 1D. In this, S_1 has been transferred to the ground electrode and the outer parts of the upper electrode are also isolated by an inductance. This inductance should be around a third of the lower one and the stray capacities are arranged so that $C_3 < C_2 < C_1$. As the EMP pulse arrives, S_1 closes, but this still leaves the outer part of the upper electrode at about half the voltage of the top electrode of S_2. Such a situation distorts the field around this electrode very considerably, leading to a large increase in the field on the outer parts of the upper main gap electrode. For pulses with a rise time of tens of nanoseconds a spark gap breaks down when the field reaches a critical value on either of the electrodes. Hence increasing the electrode field by a factor which might be as much as 1.5 times as big as that applicable to version 1C would lower the breakdown voltage by roughly this factor. However, for few ns breakdown times the situation is more complicated as there is now a finite plasma channel closure transit time. Since these channels would be expected to follow the dotted line shown in Figure 1D, this phase would take longer and there might well not be the expected drop in breakdown voltage for very fast pulses.

In view of the limited time available and because of the possibility that there might not be much advantage in version 1D over 1C for EMP breakdown, it was decided to investigate the latter in the first instance. The authors regret this, as 1D is rather a nice concept and might well be considerably better in other, slightly slower, applications.

3 PHYSICAL DESCRIPTION OF INITIAL TEST GAP

This was made in a couple of days from bits and pieces which were to hand; consequently some aspects of its construction were dictated by chance rather than choice. Figure 2 gives a sketch of the gap as first built for the DC breakdown tests and slower pulse breakdown experiments. The main on-axis central electrodes were made of brass and roughly contoured as shown. The outer electrodes were made of polyurethane foam covered with .005 cm aluminum foil (see Ref. 1). The aluminum foil in the outer regions of the top electrode was slit, and the slits recessed so as to reduce its effect on the inductance of the coil. This was almost certainly unnecessary, but as it was easy to do with a foam electrode, it was done. The coil was 25 cm long and wound out of PVC-insulated wire. As the gap was to be tested DC to over 140 kV, aluminum covered foam grading toroids were provided at both ends of the gaps.

The edge/edge gaps were made out of .005 cm thick steel shim which was smoothed with emery paper to avoid the sharp cut edges and so simulate some degree of erosion. There were three edge/edge gaps symmetrically located around the central electrode, only one of which is shown in Figure 2. These gaps were intentionally located out near the edge of the hole in the outer electrode to ensure good irradiation of the bottom volume of the gap and in particular the bottom electrode.

In the first version of the gap the aluminum of the bottom electrode was not joined to the 15 cm diameter bottom stalk, the current path from the bottom brass electrode being taken through the foam and then out to the stalk. This was done so that there would be no danger of erosion and later sparking at the aluminum-brass contact joint, which might accidentally illuminate the main gap.

The initial gap was subsequently modified to reduce its inductance for the fast high voltage tests and its second form will be described in a later section.

4 EXPECTED SPACINGS AND DC BREAKDOWN CHARACTERISTICS

For two cases of interest existing lightning ball gap spacings were known which hold off the RF satisfactorily. The DC breakdown voltages of these were calculated, that of gap A being 75 kV and gap B being 140 kV. While it is possible that the ratio of RF breakdown voltage to DC breakdown voltage might be dependent on the exact geometry of the gap, it was assumed that to the first approximation it does not change between gaps. This assumption is almost certainly true of gap A, where the balls are close together and the gap is a reasonably uniform field one; however, it may not be so true of gap B, where the balls are separated by their diameter.

In order to decide the equivalent spacings for the auto irradiated gaps, the DC breakdown voltage of the new gap as a function of the spacing was measured. This was done in two sets of tests. In one, a flat plane electrode was placed halfway across the gap. This enabled the breakdown voltages to be extended to larger voltages than was the case with the full gap. Also the effect of the degree of stick out of the central brass in the top electrode could be investigated. These experiments showed that the stick out could be as low as 4 mm without sparking taking place to the outer electrode. In the full gap DC breakdown tests and all other tests this stick out was fixed at 1.0 cm.

Figure 3 shows the DC breakdown voltages both for the full gap and also the breakdown voltages doubled for the half gap measurements. From this curve the following equivalent spacings to the existing lightning gaps are taken as

Gap A	2.8 cm
Gap B	6.0 cm

The full gap tests were only taken to 145 kV, although the power pack has given over 200 kV (±100 kV). This was because the pack had not been dusted for a long time and some of the pasticine bits had fallen off. Consequently it was not thought worthwhile to push it, in its slightly dilapidated state. The accuracy of the voltage measurements is about ±2%.

Also shown in Figure 3 is the field enhancement factor (FEF) of the gap. This is obtained by dividing the calculated uniform field breakdown voltage by the observed value. Multiplying the average field by the FEF gives the maximum field on the electrodes. It is perhaps interesting to note that to give the same breakdown voltage at 6 cm spacing, a ball gap would have to have spheres of 27 cm diameter.

5 CAPACITY RATIOS AND PREDICTED VOLTAGE DURING A PULSE ON THE OUTER ELECTRODE

In order to estimate the voltage appearing on the outer electrode during a pulse and hence that appearing on the edge/edge gaps, the various capacities of the components have to be known. These measurements were not made with great accuracy but are believed to be good to some ±10%.

In order to simulate the capacity effect of the inductance (which was assumed to have a linear voltage gradient down it), a metal cylinder of height equal to one-third of the coil length was placed on the outer upper electrode. In addition dummy edge/edge gaps were put in the gap. Figure 4 shows the various capacities measured and gives their variation as a function of gap spacing. Table I summarises the data for the spacings 2.8 cm and 6 cm.

TABLE I

	Gap Spacing	
	2.8 cm	6.0 cm
C_1	14.7	8.3
C_2	3.9	4.5
C_3	∿0.9	∿0.5
$C_2 + 1.5$	5.4	6.0
$\frac{C_1}{C_1 + C_2 + 1.5}$ (A)	.73	.58
$C_1 + C_2 + 1.5$ (B)	20	14
$C_1 + C_2$ (C)	∿16	∿9
Resonant Frequency (L = 240 μH)	2.3 MHz	2.7 MHz
Transformer Frequency	5.6 MHz	5.6 MHz

TABLE I (Cont'd.)

Notes:

(A) is the voltage ratio appearing across the E/E gaps at high frequencies

(B) is the capacity the inductance is feeding before the E/E gaps break

(C) is approximately the capacity being fed after E/E closure

In order to check these values the gap was fed with a rather unreliable variable frequency oscillator whose top frequency was 12 MHz. The voltage on the outer top electrode was measured with a Tektronix oscilloscope with a probe with internal capacity of about 4.4 pF. This value changed on some of the amplifier ranges and this restricted the ranges of gain that could be used. The tests were done with a spacing of 2.5 cm, where the resonating capacity, including that of the probe, was a total 25 pF.

The coil (42 turns wound on a former of 22 cm diameter and of length 25 cm) was measured to be 260 µH at 1.60 kHz. When a slotted thick metal plate was added to simulate the effect of the foil-covered electrodes at the relevant frequencies, the coil inductance was measured to be nearer 240 µH. Using the value of 240 µH, which applies to these tests, a resonant frequency of 2.05 MHz is calculated, to be compared with a measured one of 2.12 MHz. For this arrangement a voltage ratio across the E/E gaps of about 0.76 is also calculated for frequencies much higher than the resonant one.

The coil inductance was made intentionally big because the initial pulse tests were to be made with a pulse transformer (whose output approximates to 1 - cos nt for the first pulse) with a frequency of only 5.6 MHz.

Measuring the fractional voltage appearing across the E/E gap as the frequency was scanned, various other minor resonances were found, but these are not plotted in Figure 5, which shows only the smooth response. The solid line is the calculated one. At the high frequency limit an experimental limit of about 0.65 was found, to be compared with a calculated one of 0.76, in reasonable but not excellent agreement. The experimental points below the resonant frequency fell significantly below the calculated curve, but because the gain could not be increased on the oscilloscope the measured amplitudes were becoming very small. However, the discrepancy was consistent and unexplained, apart from measuring errors.

The dotted curve in Figure 5 is the calculated peak amplitude of the first cycle of the waveform across the E/E gap, which occurs close to the first peak of the applied waveform. At 5.6 MHz it is seen that the voltage on the E/E gap is about 0.5 of the peak applied voltage with a 2.5 cm spacing. As the E/E gaps were found to 'close' rather early in the waveform, this is a lower limit to this ratio. Indeed to an adequate accuracy (±10%) for both gap spacings, the voltage appearing across the E/E gaps is 0.5 of the applied voltage at the time of their closure.

In choosing the inductance for a given set of conditions, the RF voltage appearing across the E/E gaps is selected at some value (provisionally around 500 volts). This, with the value of the RF applied to the gap, then allows the resonant frequency to be specified. Using the values of Table I, the inductance can then be obtained, allowing for the shorted turn effects of any metal plates on the ends of the coil at the frequencies of interest.

The results of this section are not of high accuracy. However, fortunately they do not have to be, as it was found that the E/E gap 'closed' at a voltage of around 25 kV for a separation of 0.7 cm. This corresponds to 40 to 50 kV on the gap, the pulse closure voltage of which was about 160 and 280 kV for the cases of interest. In practical terms, it is the possibility of a factor of 3 or 4 increase in prolonged use of the value of 25 kV (which is possible, but unlikely) rather than ±20% variations in the value of voltage ratio appearing across the gap that is important.

6 TRANSFORMER BREAKDOWN TESTS

6.1 Definition of Effective Pulse Time τ

In the time range of interest here for both uniform field gaps and edge/plane or edge/edge gaps, the breakdown voltages and, more fundamentally, fields have a functional dependency on the time, which approximates to $Ft^{1/6}$ being a constant. Assuming this relationship for pulses which are not square, the effective pulse duration τ that applies is the time width of the pulse at 89% of the peak voltage. Of course the 'scope measurements have to be corrected for the various integrating effects present and for τ values of a few ns its value may be up to 30% in error. However, because the sixth power of the time is what is used, this only corresponds to some 5% error in the final answer. It should be stressed that the sixth power dependency is only an approximation and applies only over a reasonable range of times. Typically, for the gaps of interest, the time dependency disappears for τ values of around 100 ns, while at the other end of the range the time dependency has not been experimentally well established for τ values under a ns or so. However, to the accuracy to which this note aspires, the relationship was found to apply in essentially all the results obtained.

In the rest of this note times are given in nanoseconds, distances in centimetres and voltages in kilovolts, where these are not otherwise specified.

6.2 Pulsed Gap Breakdown Voltages

In these experiments two air cored pulsed transformers were used to give breakdown voltages up to 200 kV with values of τ varying between 8 and 80 ns or so. A short series of unirradiated breakdown tests were run where the voltages scattered up to about a factor of 2 above the irradiated values. This factor is lower than the one suggested earlier in this note, for two reasons. Firstly and most importantly, the electrodes were freshly made, crudely turned, rather ineffectually polished, and essentially unconditioned. All these factors tend to mean that initiating electrons are emitted at quite low fields on the electrodes compared with those that would be expected to apply to well conditioned or RF 'smoothed' electrodes. Of secondary importance is the fact that these tests were done with τ values an order of magnitude and more greater than those that would apply to operation of the gap with the worst case EMP transient.

When the E/E irradiating gaps were operated, the gap breakdown dropped substantially and became very reproduceable. No direct measurements were made of the voltage jitter of the irradiated gap breakdown, but it was certainly under 1% and other evidence suggested it was around 1/3% or less.

The discharge was straight between the centres of the brass electrodes and this was slightly surprising at first, because only the outer regions of the top negative electrode were illuminated, so looping discharges might have been expected. However, experience from CO_2 laser pumping suggests that the worst way to obtain a uniform glow discharge is non-uniform uv irradiation. That is, non-uniform irradiation is best from a sparking point of view. In the present gap about two-thirds of the column of air on axis is illuminated and this may well be a good thing to do in the present application.

In all the pulse tests done negative volts were applied to the upper E/E gap containing electrode, although, from other work, it is not expected that there would be any difference in behaviour if the polarity were reversed.

Breakdown voltage runs were made at 1.2, 1.8, 2.4, 3.0, 4.2 and 6 cm spacings, with varying values of τ. The observed voltages were converted to a uniform field by dividing by the gap spacing and then, using the FEF given in Figure 3, the maximum field on the electrode (F) was calculated. $F\tau^{1/6}$ was then obtained and this proved to be sensibly constant, so the average of the readings was used, with τ in ns. For all the gaps but the 1.2 cm one, the average value was 62 $ns^{1/6}$ kV/cm. For the 1.2 cm gap the value was slightly higher at 64, but this difference may not be a real one. The relative accuracy of these answers was about ±2%, but their absolute accuracy could be more like ±4%. In these tests the smallest values of τ were around 10 ns for the larger gaps, so for these an extrapolation of a factor of 1.47 was involved in the time dependency of the field. In later tests with a faster set up this extrapolation was significantly reduced.

6.3 Edge/Edge Gap Breakdown Voltages

By using the fact that there were 3 E/E gaps in the assembly, three sets of tests were run without disassembly of the spark gap. The gaps were set at about 0.48, 0.82, and 1.15 cm and after the data on the smallest gap had been obtained this was bent back to enable tests to be done on the next gap, and so on. The voltage across the edge/plane gap could not be easily monitored directly, but on the voltage waveform across the entire gap a slight hesitation in the rise could be seen as the E/E gap 'closed' and switched more capacity into the main circuit. The location of the start of this inflection was not accurately measurable but was determinable to ±10% absolutely and maybe ±3% relatively.

By operating the gap at voltages where the main spark between the brass electrodes did not occur, it was shown that the E/E gap 'closure' was not a fully developed plasma column breakdown, but rather a uniform glow type of breakdown. This was established by noting that the inflection occurred on the back side of the first pulse at approximately the same difference in the voltage from the peak as it had in the first instance on the initial rise of the pulse. Figure 6A shows a sketch of what the 'scope records showed. The interpretation is that at peak voltage the current through the E/E gap goes to zero and attachment and recombination lead to a rapid loss of electrons and the glow discharge resistance rises very rapidly to a large value. When the voltage difference across the gap approximately regains its previous value on the back side of the pulse, the residual ionisation re-avalanches and again creates a glow discharge gap closure. This view was reinforced by the fact that the voltages were a little under a half of those necessary to close an edge/plane gap with a proper plasma column. These latter voltages were calculated from relationships found to apply in previous experiments and which had been used to provide a prediction of the necessary voltages before the gap was built.

Visibly there was a plasma column spark between the two edges, but it is very likely that this closed later on after some cycles of the transformer ringing waveform.

Such a glow closure is perfectly suitable for uv-irradiating the main gap and calculations using the Townsend coefficient of ionisation indicated that the fields were just adequate to provide the required multiplication. The reason the glow closure was readily apparent and well separated from the plasma column spark closure voltage was the high impedance of the circuit driving it (∿ 10 pF), the fast nature of the applied waveform, and the low current the discharge had to take (∿ 100 amps).

In order to distinguish the mean fields (voltage divided by edge/edge spacing) for the two types of closure, the symbols F_g and F_s will be used.

The closure voltages of the E/E gaps were shown to be a function of the mean field over the limited range of gaps studied and also approximately obeyed a relation

$$F_g \, \tau^{1/6} \sim 35 \text{ ns}^{1/6} \text{ kV/cm}$$

The constant in this relation is only good to ±20% because (a) the fraction of the applied voltage appearing across the E/E was only approximately known; and (b) the closure voltage was only roughly determinable from the waveform.

From other work (mainly edge/plane data, but some edge/edge results), the corresponding prompt sparking relation for air at atmospheric pressure is

$$F_s \, \tau^{1/6} \sim 70$$

It was also observed that even when there was no sign of glow closure on the first pulse of the waveform chain of oscillations, weak plasma channel closure (i.e., sparking) could still occur at mean fields down to 15 kV/cm, presumably very late on in the waveform. Such sparks were long looping ones and very weak in appearance.

Returning to the E/E glow closure conditions, the values of τ estimated from the waveforms went down to about 2 ns in the tests. For an EMP waveform the relevant values are more like 0.3 ns, but consideration of the Townsend coefficient suggests that the $\tau^{1/6}$ time scaling should apply well for this time difference.

As a result of these tests and other considerations, such as the gap capacity, the E/E gaps were all set at approximately 0.7 cm spacing. For τ values of 1 ns or so, the mean voltage in the E/E gap reaches around 24 kV. From some other work, the FEF for the metal edges (assumed smooth) is around 8, so that the smooth electrode field had a maximum value of some 200 kV/cm. From other work, the field necessary to give the emission of a few electrons is very approximately 50 kV/cm for the relevant areas, providing the edges have not been well conditioned. Thus, even with conditioning, it is not expected that the E/E gap glow field will increase significantly and in any case the gap is designed to keep the mean RF field on the edge/edge gaps down to around 0.7 kV/cm, so there should be no conditioning. However, as mentioned towards the end of the note, this is a point that should be checked with a properly built gap when it has been in service for a reasonable time, if one is built.

7 MODIFICATIONS TO GAP FOR HIGHER SPEED TESTS

While the authors had little doubt about the validity of the sixth power scaling of the time, it was considered desirable to test the larger of the gaps with a somewhat faster pulse. In addition it was felt that the inductance of the gap after closure could also be reduced below that of the original version without sacrificing anything. It was originally proposed to test the modified gap on one of the test rigs in CPA and an offer was kindly made by them to do this. However, partly because the CPA pulser was rather booked up, and partly because its output was a little marginal, it was decided to lash up a test rig out of bits available in SSWA. So, in the event, the extra tests were done in-house.

Because of the inductance of the stalk feeding the brass electrode and the capacity of the gap after the E/E closure, the voltage between the electrodes is less than the voltage across the ends, for very fast pulses. In order (a) to get as much of the available volts onto the gap as possible, and (b) to reduce this extra correction to the minimum, the inductance of the stalk and the body of the gap was reduced to a minimum. Figure 7A shows a sketch of the gap in its second configuration.

The major changes were: firstly to reduce the length of the coil to about 17 cm. As the coil only has to hold off about 30 kV for a very short pulse during the EMP waveform it could have been made about 2 cm long, from the point of view of flashover. However, from a capacity ratio point of view and also because occasionally the RF might appear across it briefly before the E/E gaps close, the longer length was chosen. Secondly the 1.25 cm diameter feed stalk had a metal cone added to it, to reduce its inductance substantially, as well, of course, as being shorter than previously. Thirdly the aluminium foil of the bottom electrode was now connected to the outside of the 15 cm diameter stalk.

These changes were crudely calculated to give an inductance (before main gap breakdown) of about 110 nH with the E/E gap conducting. Measurements of the gap inductance with a short of about 15 cm diameter across it gave a value of around 100 nH, with an error of ±15% or so. This error occurs because the monitoring loop did not couple all the flux associated with the gap and hence had to be corrected up significantly from the raw measurement value of 70 nH.

Taking a value of 110 nH for the inductance and an effective capacity of 8 pF after E/E gap closure, a resonant frequency of 170 MHz is calculated. The effective capacity of 8 pF is a little lower than the total capacity because the E/E gap does not close in a plasma channel but has a relatively small voltage across it after the glow discharge closure. The fastest 10% to 90% rise time used in the high speed tests was 7 ns and this corresponds to a frequency of about 42 MHz. At this frequency the voltage across the gap is 5% lower than that applied to the feed points. For all slower waveforms the correction is smaller.

While the gap was being rebuilt the coil was changed to 27 turns on a length of approximately 17 cm. This gave an inductance, measured at 1.60 kHz of 137 μH. With thick walled metal plates and a cone to represent the feeds and end plates this fell to 108 μH. At the resonant frequency it is estimated that the coil inductance with the foil electrode cover would be about 115 μH. With the probe attached, the resonance frequency measured with a 5.4 cm spacing was as 3.20 MHz, in good agreement with a calculated value of 3.25 MHz. Without the probe on, the resonant frequency would be 3.7 MHz, which was little less than the design objective of 4 MHz. However, with the gap at 6 cm, the resonant frequency would have been 3.95 MHz. The reason why the gap could not be opened to the intended spacing was that one of the authors (JCM) had mislaid a centimetre in making the space frame that supported the halves of the gap and it did not seem worthwhile to tear it apart and rebuild it.

At 12 MHz 0.42 of the applied voltage appeared on the outer electrode. For much higher frequencies this fraction would be about 0.45. This is significantly lower than the calculated value of 0.6, but these calculations were made with the capacities which applied to the gap in its original form and the modifications will have reduced this ratio somewhat. So the agreement is adequate and again suggests that at E/E plane closure time the ratio is 0.5, within ±10%.

8 FAST PULSE BREAKDOWN VOLTAGES

Photograph 1 shows the high speed test pulse assembly. On the right hand side of the photograph is the condenser bank with its spark gap. Next to this is the air cored transformer, which is charging a 0.6 μF low inductance capacitor. This capacitor is very considerably larger than it need have been, but was conveniently to hand.

To the left of the pulse charged capacitor is a rail spark gap, which again was far larger than it need have been, but had the great virtue that it existed. The electrode spacing in this gap was 3 cm. The output of this self-closing gap is fed into a 210 ohm transmission line which is joined to the gap by a 30 ohm, 15 cm diameter annular copper sulphate solution resistor which damps the output after gap closure.

Beyond this and tapping off the 40 cm tall gap is a small tapered strip line which links it to a copper sulphate/resistor chain combination terminator and attenuator. The attenuator is made out of 32 old-fashioned 1 watt, 33 ohm resistors, while this in parallel with two copper sulphate resistors gives an impedance of 290 ohms. For a frequency of about 50 MHz the impedance of the gap before it switches, but after the E/E gap has closed, is about 460 ohms. These two impedances in parallel equal about 180 ohms which, with the 30 ohm low inductance resistance, terminates the line at high frequencies with 210 ohms.

The exact frequency response of the monitor is very complicated, but to an adequate accuracy was estimated to be about 1 ns. The step response of the oscilloscope is closely approximated to by a linear rise to 0.8 of the low frequency sensitivity in about 2 ns, followed by a very much slower rise. The combination of the monitor response the the 'scope response is thus a rise to the 0.8 level in 3 ns, followed by a longer rise. The observed waveforms were corrected for this response. The 10% to 90% rise time measured with the gap in position was 8 ns, which on correction gives a rise time of about 7 ns.

Photograph 2 shows a close-up of the gap, looking upwards, and in the background can be seen the combined terminating-cum-monitor resistor assembly.

Electrically the system operated in the following manner for the highest voltage shots. The capacitors were DC charged to 25 kV and the transformer charged the 0.6 nF capacitor to 320 kV. At about 280 kV the output gap (working at 21 psig) closed and delivered a pulse rising to about 240 kV across the gap plus monitor.

Table II lists the results obtained on the breakdown voltage at 5.4 cm spacing, for various values of τ.

TABLE II
BREAKDOWN VOLTAGES
AFTER CORRECTION FOR 'SCOPE AND ATTENUATOR RESPONSE
(GAP SPACING 5.4 cm)

Breakdown Voltage (kV)	τ (ns)	$Vt^{1/3}$	
143	70	290)	average 282
152	42	284)	
170	24	289)	
195[+]	8	277)	
224[+]	3	270	

[+] These results have been corrected for the lag in volts on the gap electrodes compared with that at the monitoring point.

Using Figure 3, the FEF is 1.12 for a 5.4 cm gap, giving a value of

$$F\ \tau^{1/6} = 59\ \text{ns}^{1/6}\ \text{kV/cm}$$

This is a bit lower than the value previously obtained of 62. However, now the system is an entirely different one and the data in Table II suggests that, if anything, the above value will slightly over-estimate the maximum electrode breakdown field.

Averaging the two sets of values suggests that the best value is

$$F\ \tau^{1/6} = 60$$

and that this value may slightly over-estimate the 1.5 ns breakdown field.

Using this relation, the predicted breakdown voltages for the two gaps are

Gap A	2.8 cm	165 kV
Gap B	6 cm	290 kV

Figure 8 plots the predicted breakdown voltage for other gap spacings and also gives the values of τ taken which are based on a worst case pulse rising in 20 kV/ns.

The edge/edge gaps are calculated to close when there is about 60 kV on the gap.

With regard to the pulse width, the fall time was about twice that calculated from the constants of the circuit and gap and this at first was a surprise. However, the explanation lies in the observed behaviour of both the output gap of the pulse charged capacitor and also the test gap when it is not uv-irradiated. Both of these gaps exhibited a glow discharge phase before plasma channel closure. Figure 6B shows a sketch of the waveform observed with the unirradiated gap closure. After the pulse has risen to peak volts there is a fast fall to a plateau which is variable in length but averages about 15 ns. Then there is a further voltage drop as the plasma channel closes. The mean field in the gap which corresponds to the plateau voltage is about 25 kV/cm, at which field the e-folding time of the ionisation in the discharge has risen to some tens of nanoseconds. The pulse charged capacitor output switch gave an output pulse which again had a step part way up when operated at atmospheric pressure. When the pressure in this gap was raised to 15 psig this step almost completely vanished and the rise time became that which had been calculated.

The behaviour of the irradiated test gap was not as clear-cut, but again was longer than the circuit constants would indicate. In order to check that the same behaviour explained the slow fall, the series copper sulphate resistance was increased from 30 ohms to 70 ohms. This should have reduced the fall time to about 5 ns if the gap had closed immediately in a plasma channel. However, the change had no effect on the fall time, as was expected.

Taking the measured fall time, the time width of the pulse at half height is expected to be about 30 ns.

If the gap can be installed as is suggested in the last section of this note, the total inductance will be about 500 nH after the switch has closed. Using the current waveform calculated by Roger Oats and the above data, Figure 9 gives the predicted waveform across the base of the aerial with a 6 cm gap spacing, and for a rate of rise of the pulse of 20 kV/ns.

9 COMPARISON WITH PREVIOUS DATA

In Reference 2, which mainly deals with the nanosecond breakdown of small uniform field gaps and surface tracking gaps, Figure 3 shows the data for mm spaced gaps and also some data for 1/2 to 3 cm gaps breaking with τ = 2 1/2 ns. The curve suggests that over the range 1/2 to 3 cm the field increases from about 52 kV/cm to 66 kV/cm. This data was collected from a range of gaps, only one of which was irradiated. The present data, scaled to a τ of 2 1/2 ns, gives a breakdown electrode field of 52 kV essentially independent of spacing from 1.2 to 6 cm.

A quite possible explanation for the discrepancy is that the original measurements were in error, or were comparing apples with pears. That is, the breakdown data of some of the gaps was contaminated by not being uv-irradiated. However, there is a second possible explanation and that is that the particular mode of uv-irradiation employed in the gap reported in this note has been particularly effective in causing breakdown of the longer gaps. As was mentioned earlier, there is a region under the top brass electrode which is unirradiated and this might have speeded up the breakdown processes.

10 POSSIBLE FUTURE WORK PROGRAMME

10.1 Properly Engineered Gap Construction

It is suggested that the present general dimensions be used, except that the feed cylinders should be about 20 cm in diameter. The only slightly complex shapes involved are the two electrodes, presently made of aluminium covered foam. These can be fairly thin metal spinnings; it is quite possible that suitable car hub caps can be found. The outer electrode with the 8 cm diameter hole in it will need to be thickened over the inner part so that the present inner radius to the hole edge can be maintained. In addition it is rather desirable to provide a bit of a roll over where the coil starts. The stalk carrying the brass main electrodes can be made 2 cm in diameter and the metal cone will help to stiffen this against electromagnetic impulse forces during lightning strokes. The edge/edge gap electrodes should remain .005 cm thick, but about 4 mm back from the edges they should be clamped between tapered metal pieces to make them more robust.

10.2 Installation of Gap at the Aerial Base

Figure 7B shows a sketch of a possible method of mounting gap B in a low inductance fashion to the base of the mast. It is estimated that if this method of mounting the gap is possible, the inductance of the gap after closure will be about 500 nH. Some method of adjusting the gap will be necessary; possibly a coarse thread cut in the base of the lower feed stalk can be used. The centre of the gap should be located on the half potential line, presumably about half-way up the mast support.

10.3 Additional Testing

If and when a fully engineered gap is available, the spacing required to hold off the RF should be measured. In addition a few RF breakdowns via the outer parts of the gap should be intentionally produced. This is to ensure the survival of the coil and the E/E gaps under these circumstances. A possible test would be to arrange for the gap to be exposed to simulated lightning pulses to ensure its mechanical survival: however, operation on the aerial for a while will prove this point, one way or the other, rather more cheaply.

Since there are three E/E gaps, it might be worth while using different metals in each of them in the first gap. Suggested materials are steel, brass, and tantalum, each .005 cm thick. After, say, a couple of months' operation in the field, the closure voltages of these gaps can be rechecked to ensure that these have not increased greatly. Apart from testing that the properly constructed gap survives the various high energy discharges it will inevitably be exposed to, checking that RF conditioning of the E/E gaps does not seriously occur is the only other vital test.

10.4 Inductance for Gap A

Gap A has a more complex waveform on it and I am not sure what this is. However, a crude estimate suggests that the resonant frequency of the coil plus electrode capacity should be around 6 MHz for this gap. If this is so, the coil should have 13 to 14 turns wound on the same former.

11 CONCLUSIONS

A possible EMP divertor gap is described and tests on a 'breadboard' model are given. Predicted breakdown voltage and resulting waveform at the base of the aerial are provided. While the work has been done in too short a time to ensure great accuracy, which in any case is unnecessary, the estimates of breakdown voltage are probably good to around 10% and, if anything, the predictions are considered to be slight over-estimates. In the event that it is decided to build such a gap, some suggestions are made as to its manufacture, mode of installation and testing. If this should be done, the authors will be delighted to assist in any way short of actual help.

ACKNOWLEDGMENTS

The authors would like to thank Roger Oats very much indeed for his help and advice. It has been a pleasure to work with him. In addition the authors would like to wish Derek Garrard all the best in his imminent retirement, and to thank him for introducing them to a rather amusing problem. Without his enthusiasm and help nothing would have happened.

REFERENCES

(1) Electrostatic Grading Structures. High Voltage Note 1, June 1970. J. C. Martin.

(2) High Speed Breakdown of Small Air Gaps in Both Uniform Field and Surface Tracking Geometries. Switching Note 24, April 1977. J. C. Martin.

Possible Gap Configurations

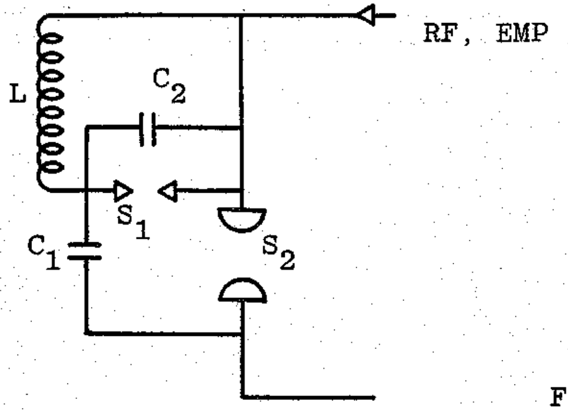


Fig. 1A

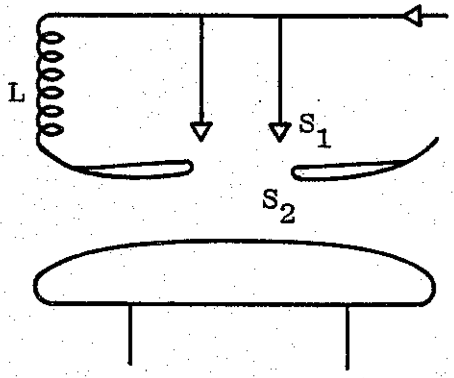


Fig. 1B

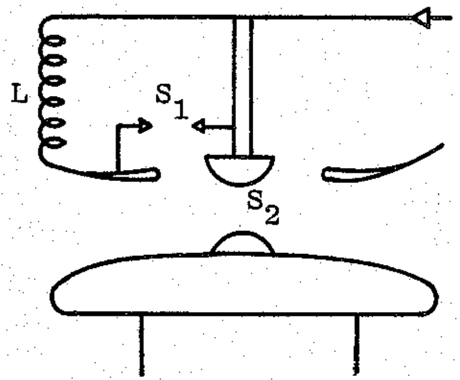


Fig. 1C

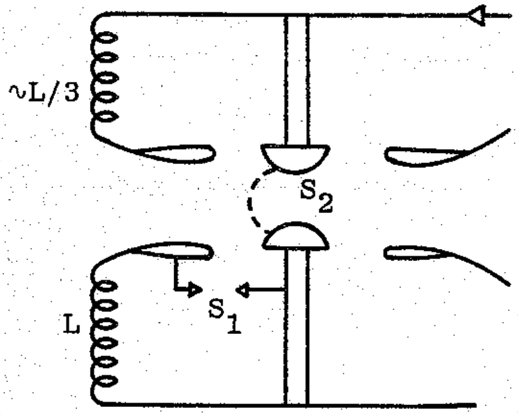


Fig. 1D

Sketch of Gap (1/2 scale)

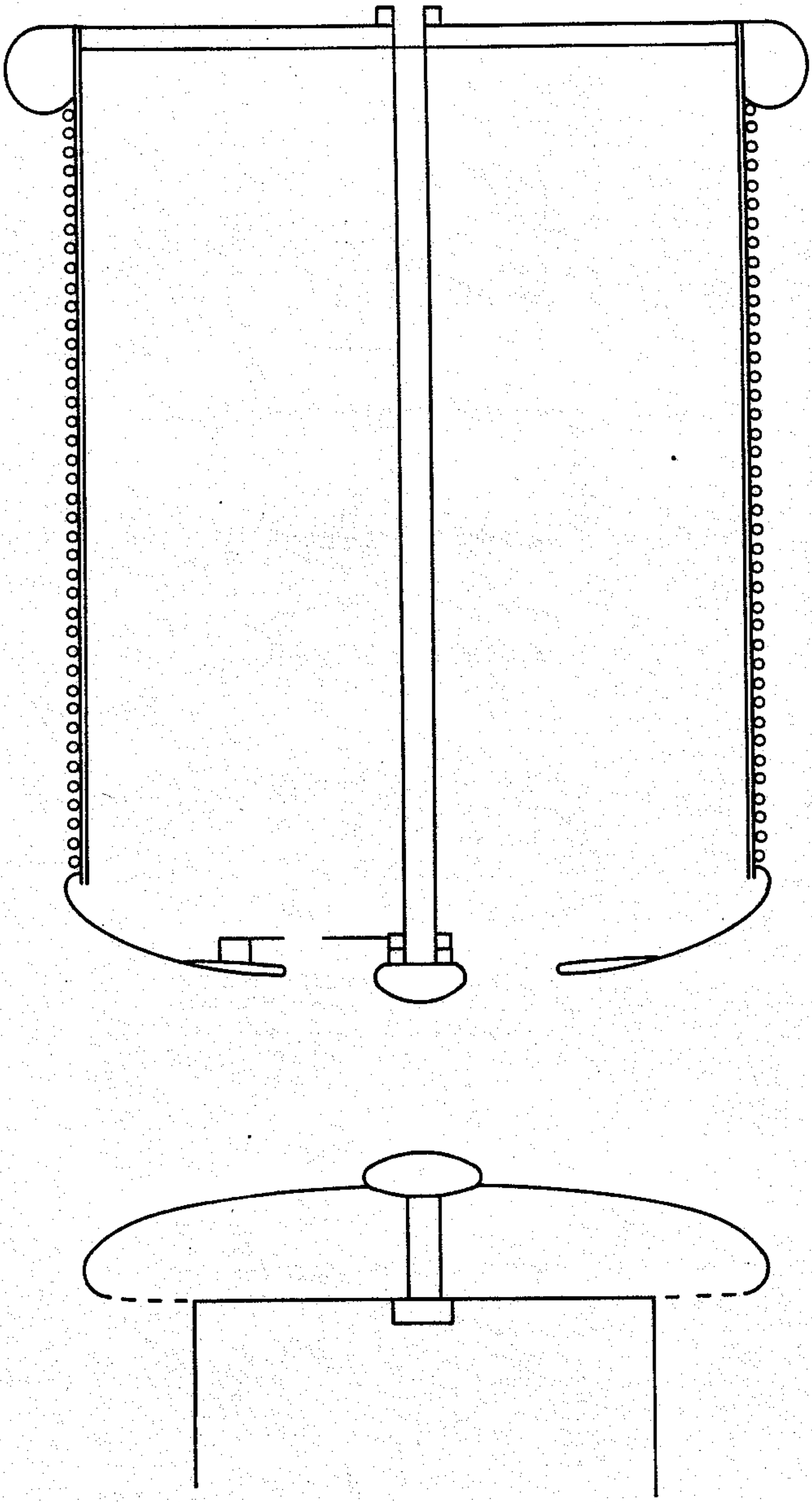


Figure 2.

Gap Breakdown Voltage D.C.

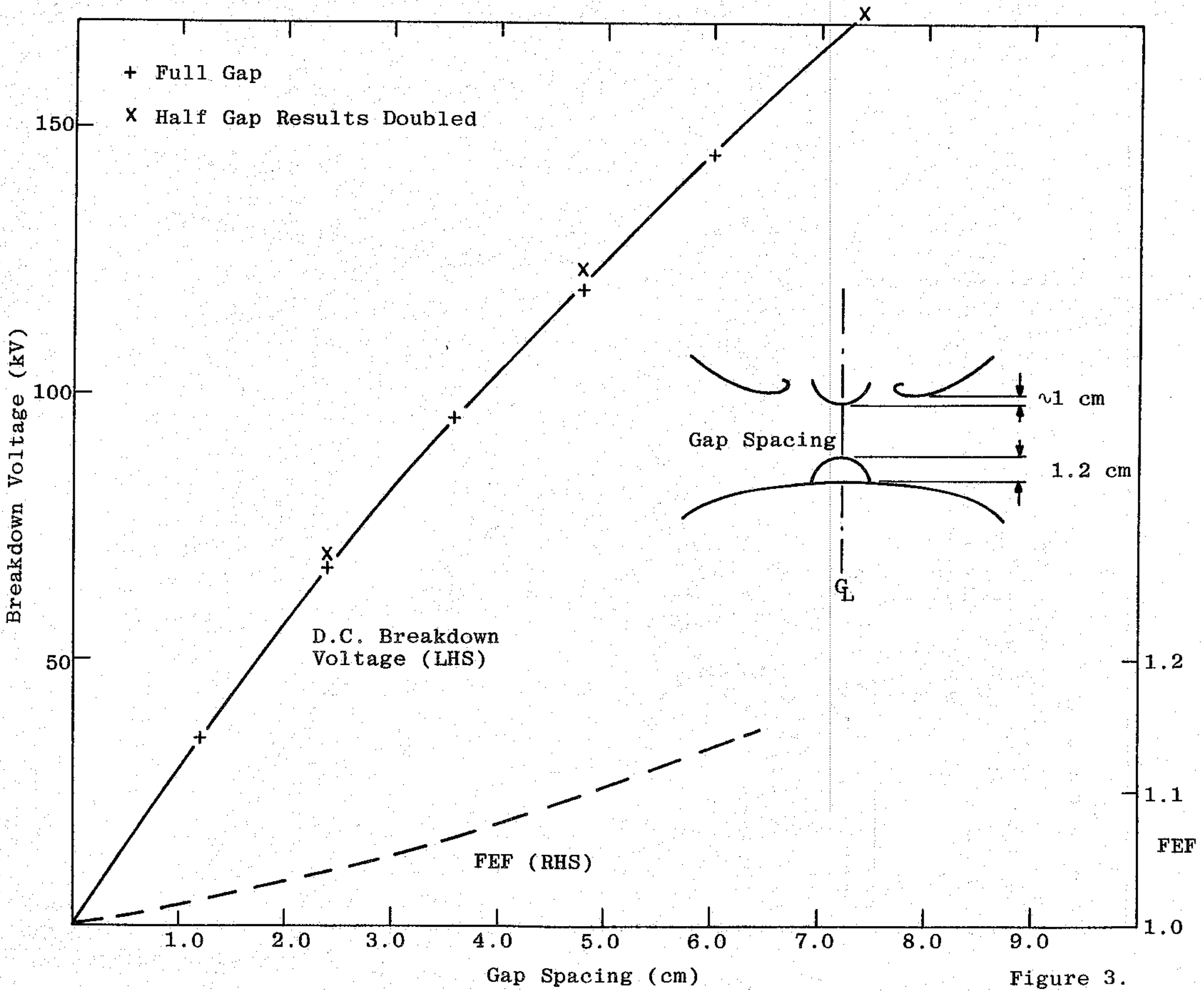


Figure 3.

Gap Capacities in pF's

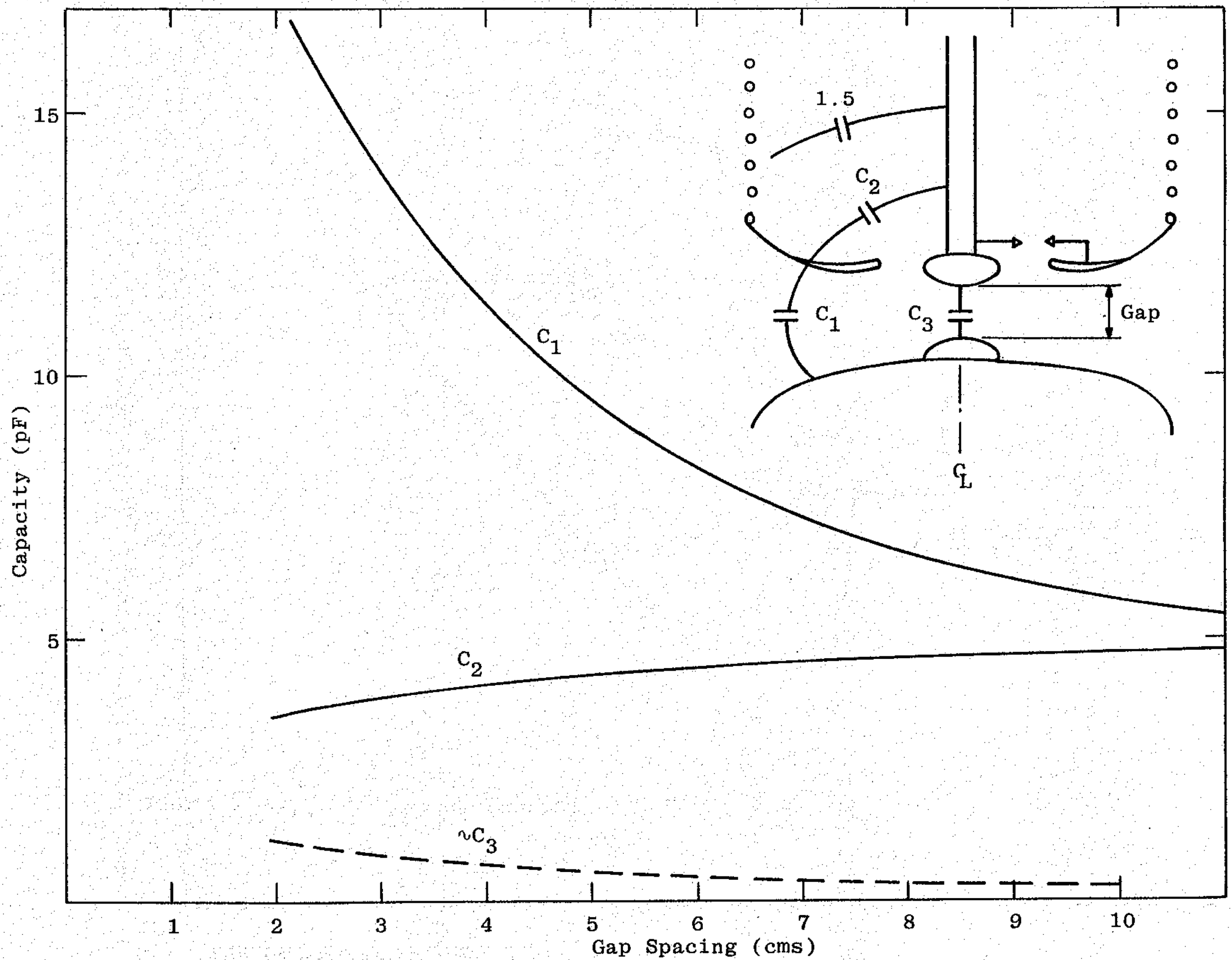
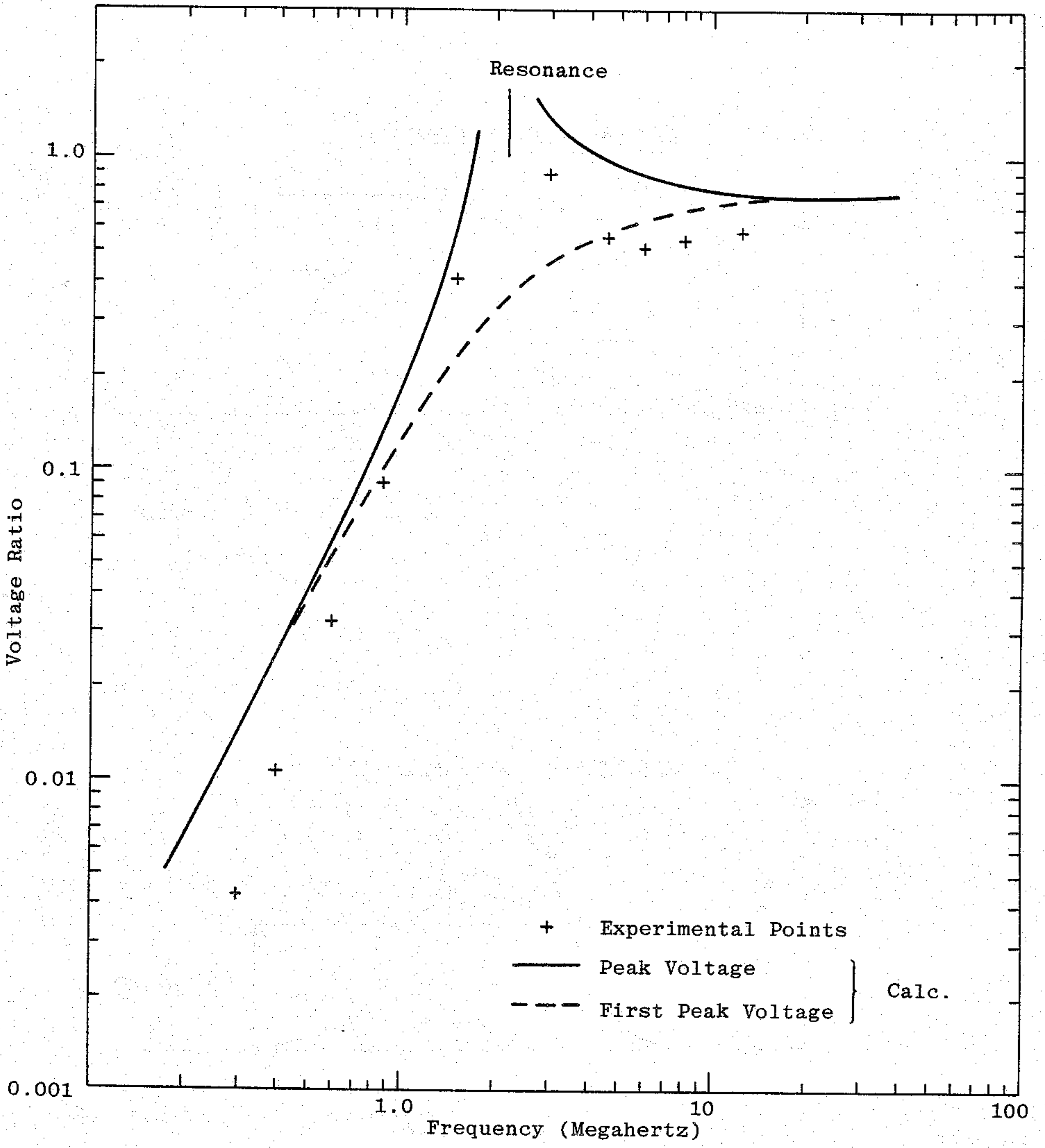


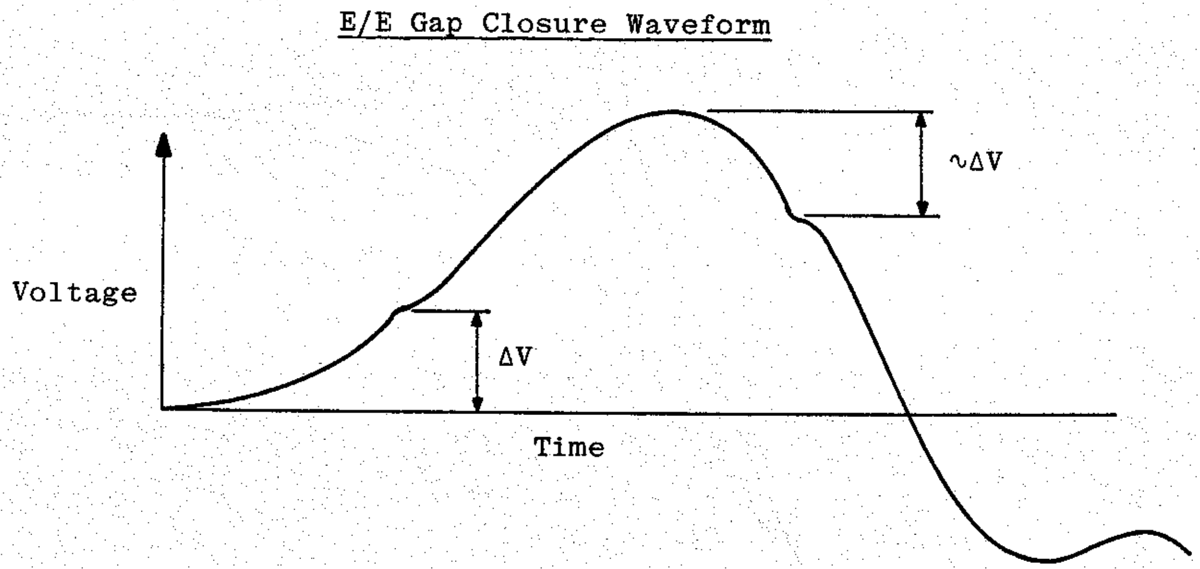
Figure 4.

E/E Gap Fractional Voltage for 2.5 cms Gap Spacing



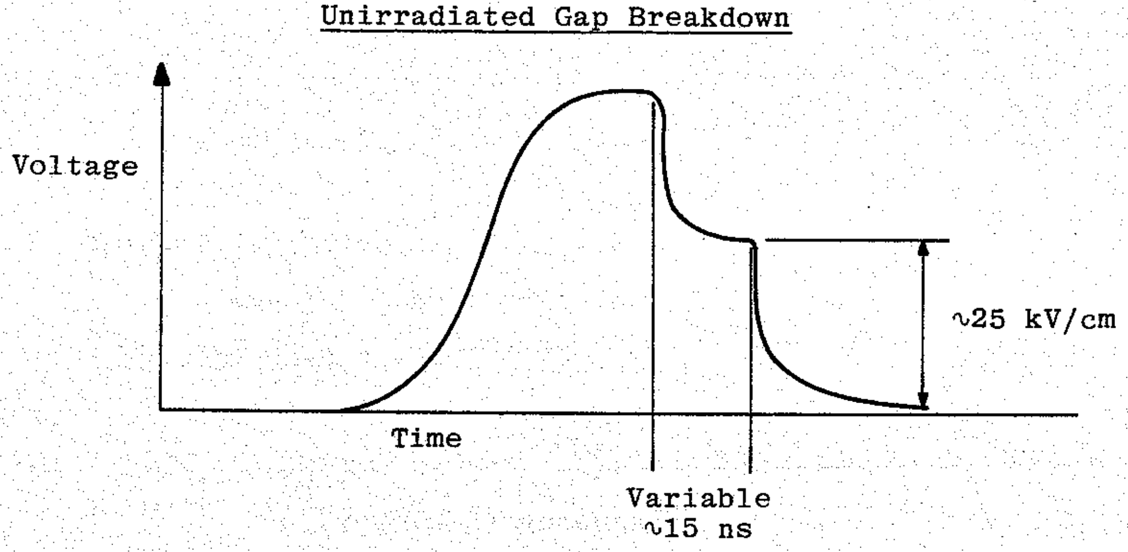
$$\text{Voltage Ratio} \equiv \frac{\text{Voltage Across E/E Gap}}{\text{Applied Voltage}}$$

Figure 5.



E/E Gap Closure Waveform

Figure 6A.



Unirradiated Gap Breakdown

Figure 6B.

Low Inductance Version

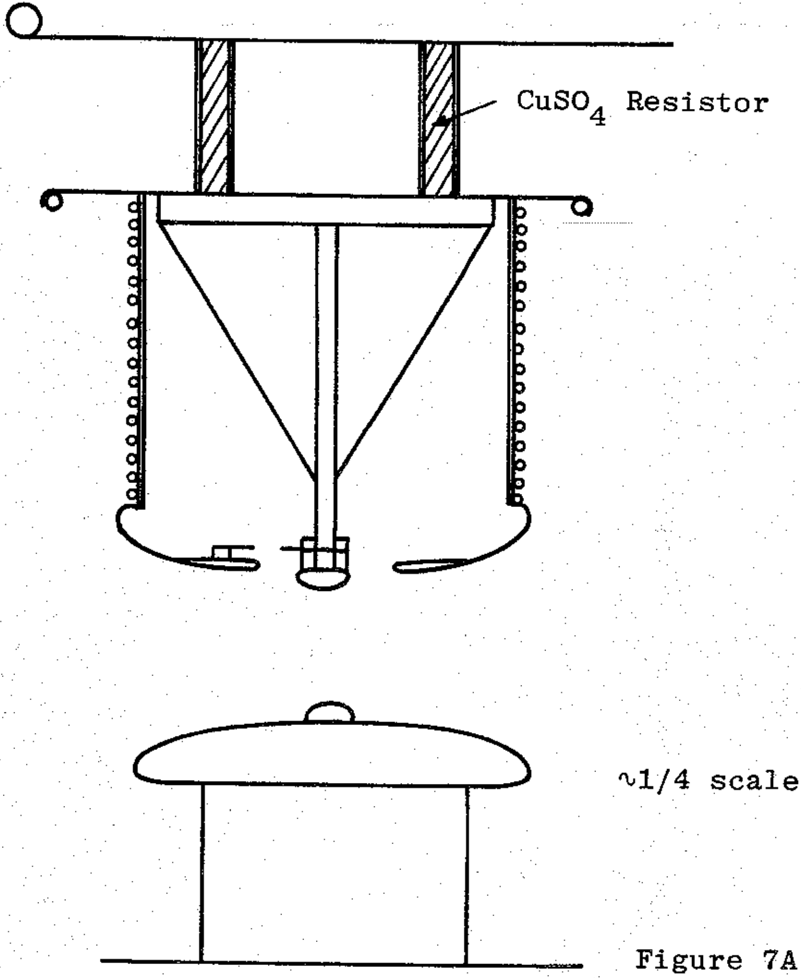


Figure 7A.

Possible Mode of Installation

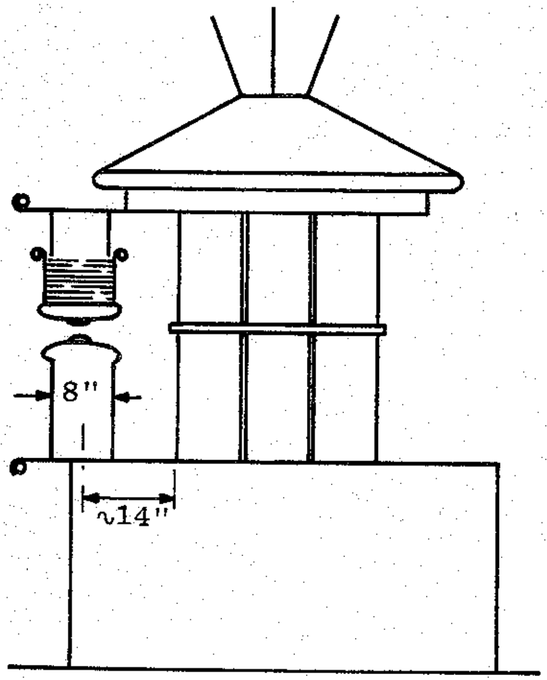


Figure 7B.

Predicted Breakdown Voltages for Pulse Rising at 20 kV/ns

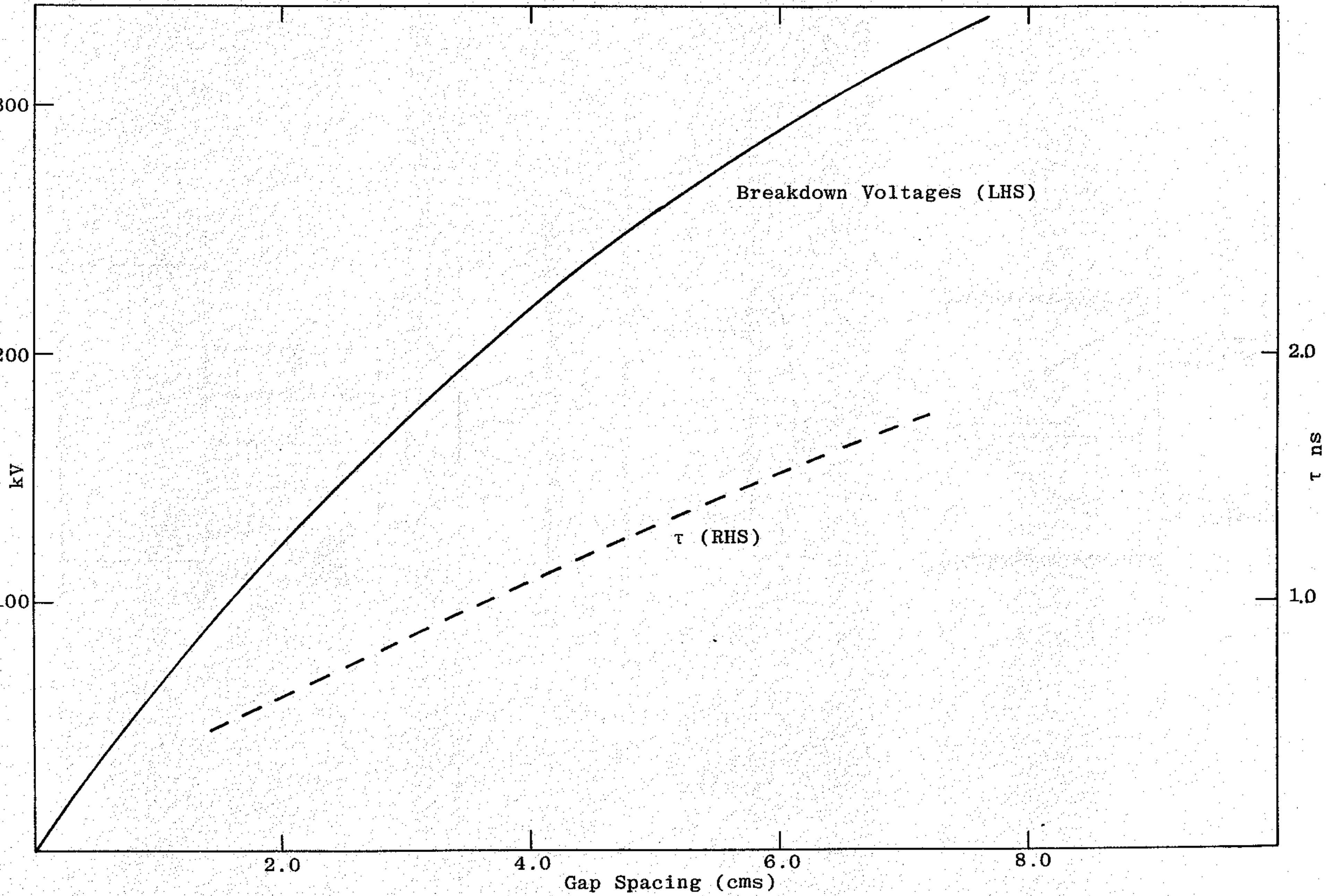


Figure 8.

Approximate Waveform Across Gap B

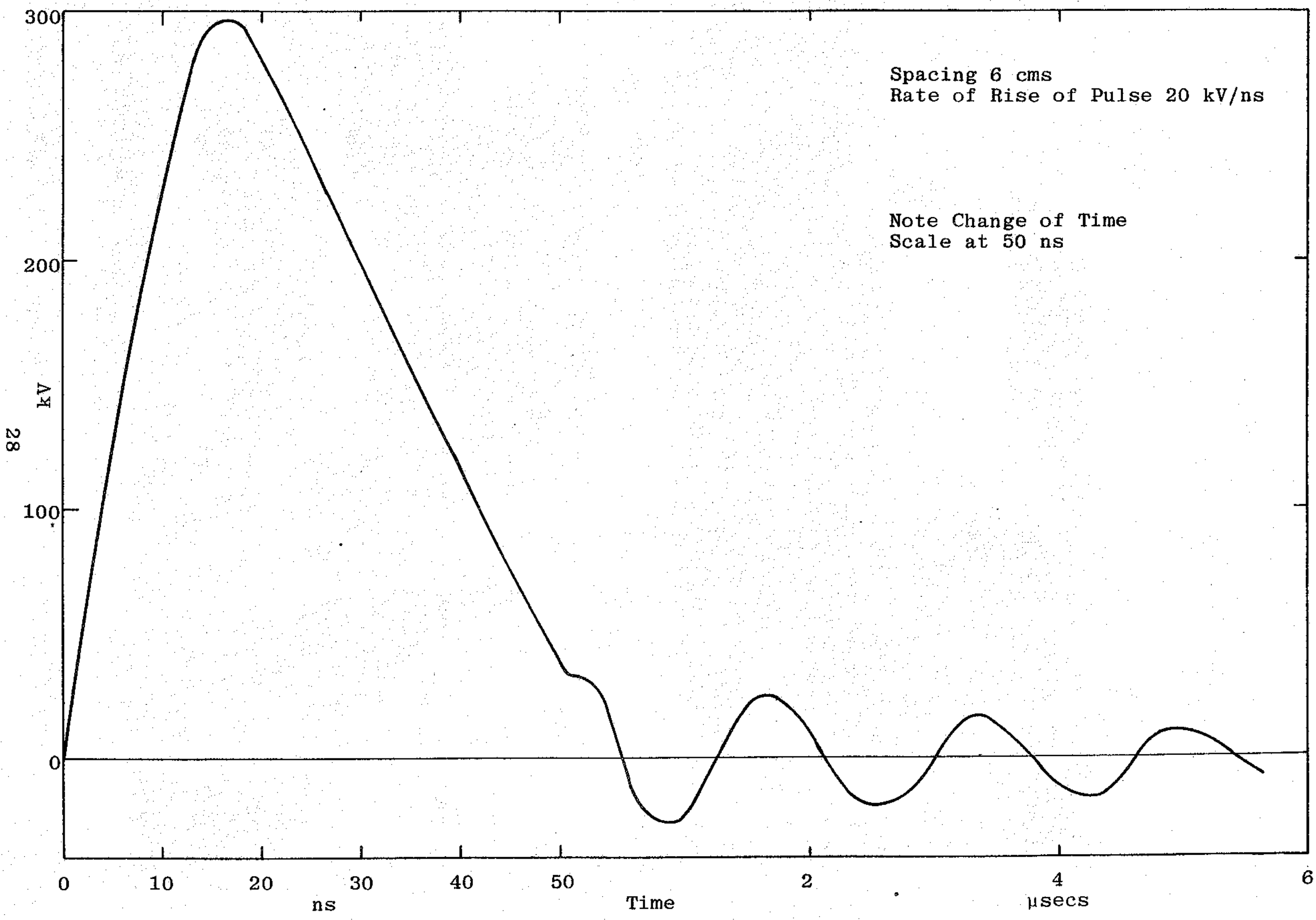


Figure 9.

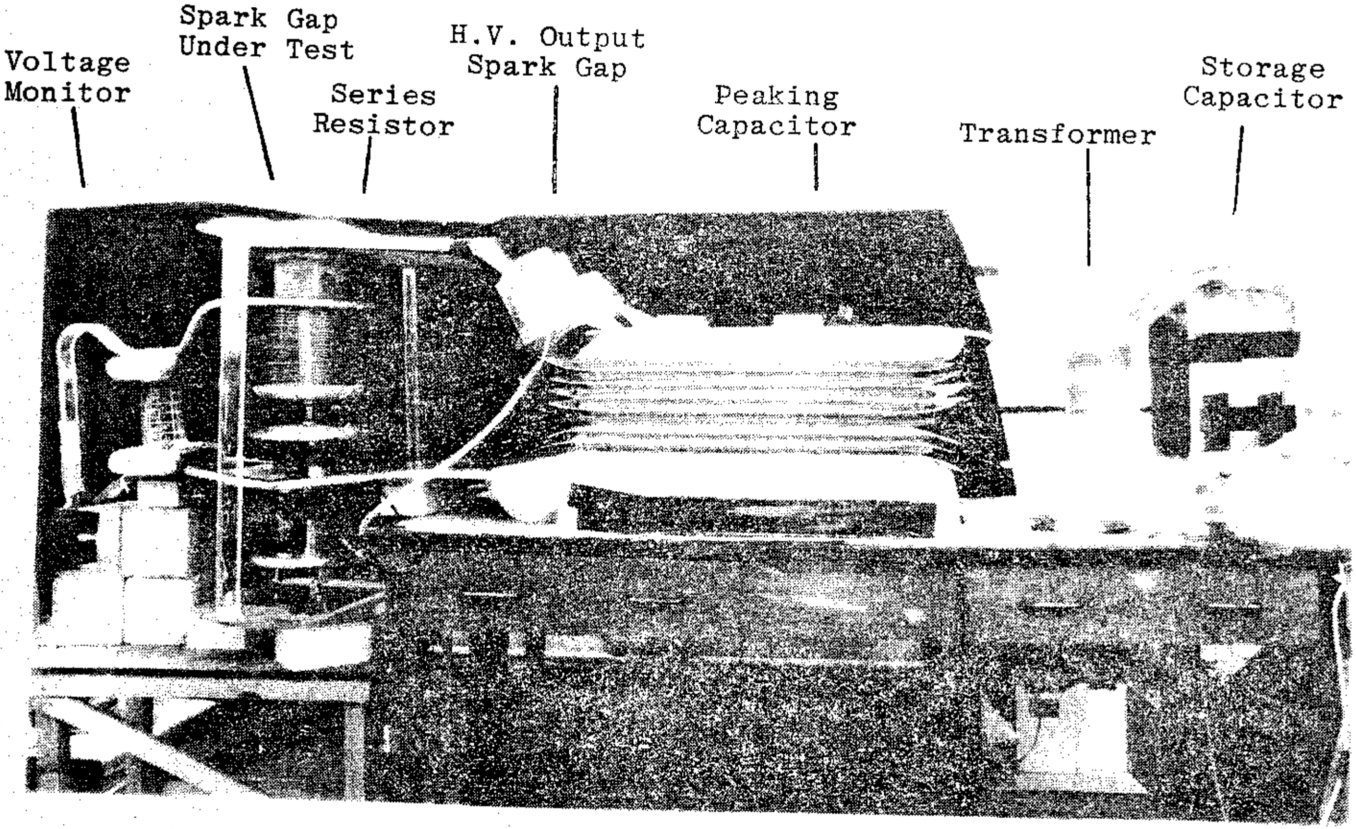


Photo 1. General Test Layout

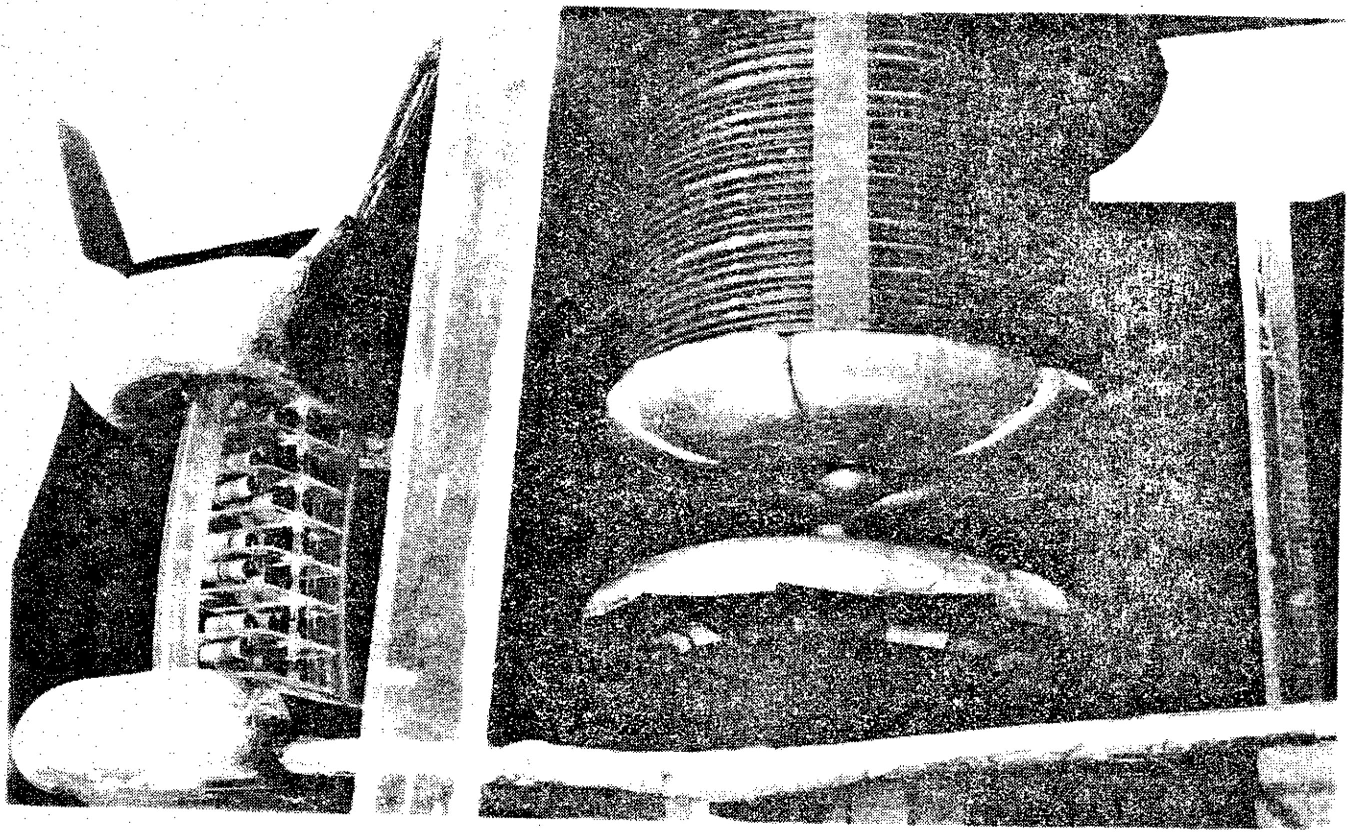


Photo 2. Test Gap Detail