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Nanosecond Pulse Techniques

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CONTENTS

1. Introduction

This review of pulsed high voltage techniques is of a rather personal nature and mainly reports on work done by the high voltage pulse group at AWRE, Aldermaston. I would like to acknowledge the efforts of this group, which over the past seven years has managed to elucidate some of the features of the design of high voltage pulsed systems. Reference will be made to the work of others and, where I fail to do so I would like to apologize in advance. Published references are not extensive and the lecturer must confess a weakness in not having searched diligently for these. There are a few general references at the back, Nos. (1) to (5) and in the note specific references are made to some sources of more recent material. This field has expanded rapidly in the last four years or so and very big, fast, high voltage systems are now in existence.

In general, high voltage pulsed systems may be DC charged or they can have their high speed section pulse charged. In the case of DC charged systems, where the voltages can rise to 12 million volts or more, the dielectric media employed for energy storage are gaseous or, at lower voltages, solid. Ion Physics Corporation, of Burlington, Massachusetts, are the prime practitioners of DC charged, pressurised gas insulated pulse systems. Such systems require very great engineering expertise and much experience and it is not in general within the ambit of the experimental worker to build his own. DC solid insulated systems take the form of a cable, fast Marx or strip transmission line systems and can be fairly easily built in the laboratory. The simplicity of the DC charged systems is obvious but this simplicity can sometimes be bought at a very considerable price and, in general, for the more demanding applications a pulse charged high speed section makes sense.

In a system which pulse charges a high speed section, much greater energy densities can be stored and higher breakdown gradients transiently achieved. The energy storage medium can now be gaseous, liquid, or solid, and indeed one of the best media is water, which would be quite impossible to use DC. In addition to the energy store there is an output switch or switches, which deliver the energy rapidly to the load and these, too, can have a higher performance when pulse charged. The pulse charging supply can be relatively slow, typically charging in times of about 1 μs, which in this note is referred to as the 'slow' time scale. The high speed store needs a fast, very low inductance switch or switches and must be designed using transmission line concepts so as to feed the energy into the load in a few tens of ns or less. This time scale is generally referred to as the 'fast' one.

In addition to having breakdown criteria which can be applied to prevent breakdown in the high speed section and to achieve breakdown in the switch, it is necessary to have theoretical relationships which enable the rise of the pulse to be estimated. It is also necessary to monitor the pulses at various parts of the system and as these systems can have rates of change of current up to 10^{15} amps/sec, pick-up is a serious problem. However, even in these conditions monitoring can still be fairly simple. It is also necessary to have additional components such as load resistors for test purposes, or deflector gaps and loads which will prevent the system ringing on until the time that it tracks somewhere. In addition to this, it is necessary to have dump resistors so that the system can be safely discharged in the event of a malfunction.

After briefly outlining the various items mentioned above, a few systems will be described, to give some idea of currently achievable items. In general, small systems store less than 1 kJ and provide test pulses for breakdown studies, to drive spark or streamer chambers, or to operate other low energy absorbing items. Such systems can go up to a few million volts and occupy 100 square feet of laboratory, or so. Systems involving, say, 100 kJ and above, will need a floor area ten times bigger and stand typically 10-15 feet high. These can give towards 10 million volts, but are obviously rather outside the scope of a general laboratory. However, they do not require the enormous hangar-like buildings that the slower, older systems needed, largely because they employ pulse charged dielectric media which can stand rather greater stresses.

2. Pulse Charging or Slow Systems

Air Cored Transformers

These are deceptively simple systems which can give up to 3 or more million volts. However, a surprising amount of expertise is required to make them properly and, in general, a small Marx, even though it contains many components, is more reliable. At the low voltage end - 200 or 300 kV, say, - they work well and are very simple to construct. However, for completeness, the more advanced type will be described as well, (Refs. (6) and (7)).

The high voltage dictates that in general no magnetic materials can be used in the core and consequently the primary inductance is low. It is therefore necessary to keep the leakage inductance very low so that gains approaching that of a lossless transformer may be achieved. As a consequence of this, it is also necessary to have a low inductance bank to feed the primary turns and care has to be exercised to use reasonably low inductance capacitors and low inductance switching. At low voltages an isolated primary can be employed but at high voltages even small transients can break the insulation between the primary and secondary turns, so that an auto transformer design is employed. Fig. 1 shows the basic circuit used, with a single condenser. Also shown is the preferred version which uses plus and minus charging. In general, in all the applications in this note plus and minus DC charging is greatly to be recommended. The first reason for this is that the DC flashover conditions are eased, since flashover distances go as a fairly high power of the voltage. Secondly, in any power pack the addition of a second set of rectifiers doubles the output voltage cheaply. Thirdly, pick-up is reduced in a balanced system.

Typically, high voltage pulsed transformers will have up to 70 : 1 turns ratio and into small loads have gains a little more than this. They have winding thicknesses which are of the order of 20 per cent of the mean radius and Fig. 1 shows a cross-section through the winding and also the form of the copper that makes up the winding. By tapering the winding, the transformer is reasonably well macroscopically graded, but in the absence of further palliatives there are very large fields developed at the edges of the winding, since the copper is only a few thou. thick. These high fields are avoided by impregnating the transformer with a dilute $CuSO_4$ solution, which forms thin resistive films at the edges of the copper. The resistivity of this solution is chosen so that the voltage pulse diffuses along the distributed resistor capacitor network so formed, a distance of a few mm. during the pulse. This technique of grading is effective but great care is needed so that the impregnation is complete. This is achieved by vacuum impregnating and by letting the solution into the transformer slowly so that the films of $CuSO_4$ solution can flow into all the windings. The output is of course $\pm$ V/2 and leads from the inside and outside of the transformer take the voltage to the test region.

For voltages in the region of 1 million to 3 million volts, the transformer sits in a cube of oil about 1 metre on a side, but for voltages up to about 1 million, a bench top model can be employed, with the working volume under oil or water. In the latter case, heavy capacity loading can be avoided by blocking most of the water volume out with perspex. Such a transformer should not be allowed to ring on at high voltages for long periods of time, as a track will eventually occur, and auxiliary water or oil gaps are used to dump the energy into a $CuSO_4$ resistor, after the pulse has gone over peak. The typical pulse rise time depends on the loading, but for a high voltage system is in the region of 1/2 μs. Such systems are particularly useful for doing scaled breakdown studies, tracking studies across interfaces, and experiments on switch design. In general, in pulsed voltage application, voltages scale, but some care and judgment has to be exercised. However, if the model tests show that tracking will occur, then higher voltage full-scale tests are obviously necessary.

A very elegant transformer design which uses the same volume as the DC capacitor has been invented by R. Fitch and V. Howell (Ref. (8)). This is known as the spiral generator and only needs a low inductance switch to generate high voltage pulses. Unfortunately, insulation flashover problems have limited it to voltages of under 1 MV or so.

In triggering gaps, fast and reliable pulses of 100 or 200 kV are very useful and these can be simply obtained by using much simpler pulse transformers. Typically, gains of 10 are all that is required and by using a one or two turn primary fed from a fractional μF capacity and spark gap, and by having a 10 to 20 turn secondary made out of the inner core of cable, this can be achieved. Additional insulation is placed between the secondary and the primary, but care is still taken to keep the leakage inductance low. Typically, such a transformer is 8" diameter and 8" high, and can work in air. The insulation is arranged to increase towards the high voltage end or ends of the secondary, which reduces the self capacity of the transformer as well, at a modest cost in self inductance. Such systems can have pulses rising in tens of ns when used into small loads.

Marx Generators

There has been a considerable development in the field of generators which charge capacities in parallel and then stack them in series by means of a number of switches. The prototype of such systems is the Marx generator, but the term has now been extended by usage to cover systems quite different from the original one, but still having the feature of stacking the charged condensers. Such generators are more complex than the auto transformer to make and involve many more components, but with care they can be made reliable and, using modern materials and techniques, can be constructed cheaply. Versions storing megajoules are being developed and systems giving up to 10 million volts and delivering their energy in a μs or two have also been made. (Ref. (9)). Many of the early Marx generators had an extremely limited triggering range and for large systems involving many gaps, care has to be taken that the mode of erection of the Marx is reasonably well defined and consistent. I personally would call a Marx healthy if it could erect satisfactorily at voltages down to 60 per cent of its self breakdown and under these circumstances there is a region, above 70 per cent, say, of the self breakdown voltage over which the erection time does not decrease much and is typically in the region of 1 μs or less. The reason for requiring a reasonable firing range is that small changes in gap performance, line voltages, etc. have little or no effect. In general, the Marx generators are built with fixed gaps and the operating range covered by changing the gas pressure and/or nature of the gas. At AWRE we have had satisfactory service using gaps charged up to ± 100 kV, these gaps being simply made out of 2" ball bearings inserted at intervals along a column of perspex tubing, 6" in diameter. To achieve a reasonable working range, the pressure can be changed from rather under one atmosphere to 2 1/2 atmospheres absolute of air and then the air replaced by dried SF6. SF_6

Figs. 2 and 3 show a plot of the best achieved output inductance and erection time for large Marx generators. These are ones storing 100+ kJ. The parameters are quoted per million volts of output and it must be repeated are the best that can be achieved at the approximate date quoted. However, such graphs may be of use in showing what has been achieved and what can reasonably be expected to be do-able in the near future, for systems where the inductance of the capacitors is low.

In addition to developing single Marxes, they can be paralleled, thereby achieving a further reduction in output inductance, but care has now to be taken that erection of these sub-Marxes is consistent and reliable, and consistency is usually achieved by making the erection fast.

Versions now exist which will trigger down to zero volts, such systems having essentially a triggered pulse generator in each switch. Others employ triggered gaps which are fed back across a number of switches by resistors, so that the trigger electrode stays roughly at constant potential while the gap erects past it. The additional complexity of putting trigger electrodes in the Marx gaps enables Marx generators to become more compact and still have reasonable triggering ranges. Where the capacitors do not have to be very closely packed, then the original approach of Marx modified to give increased triggering range can be employed, and apart from a few gaps at the bottom of the Marx, the gaps can be untriggered.

There is a novel version of the Marx due to Mr. R. Fitch which is called the "L.C. Marx". In this, a switch and inductance is placed across every other condenser and when these switches are closed simultaneously, every other condenser rings and reverses its polarity. This leads to very low inductance systems, but has quite a bit of additional complexity in getting all the switches to go reliably and has some interesting fault modes. Yet another novel Marx has been developed by Mr. Fitch and his associates at Maxwell Laboratories Inc., San Diego, where a small, lightly loaded Marx erects very fast and cross-connections from this fire up a number of parallel Marxes, again with triggered gaps, in between each condenser.

Most of the Marxes referred to here have particular virtues and these are, in general, of course bought at increased complexity. However, quite elementary Marx generators can be made healthy in quite simple ways. In the case of untriggered Marxes (that is, apart from the first few gaps), stray capacity built into the system can be made to link across every third gap. The magnitude of this capacity has to be considerably greater than the capacity across each gap and if two gaps have fired, nearly three times the stage voltage appears across the unfired third gap. These strays are usually built in by the capacity between the cases of the condensers, which are conveniently stacked in three columns. If it is not possible to do this, three sets of charging resistor chains can be employed, these chains coupling to every third capacitor. This discharges the unfavourable strays quickly for values of the resistors of a few kilohms. These can be made very conveniently and cheaply by using $CuSO_4$ resistors.

In the case of the triggered Marx, again the trigger electrodes are tied back by a resistor to the trigger of the switch 3 below.

These systems can of course be extended to couple across more than three switches but experience has suggested that, with care, coupling over three switches is adequate.

In the case of multimillion volt compact Marxes, they usually operate under oil, but Marx generators up to say 1 million volts can be built compactly in air, providing care is taken to prevent flashover. Such a Marx need not be more than 5 ft. high for a 1 MV output and can still have quite a low inductance.

The Marx generator can be a very reliable and consistent system, when properly made, and some versions can achieve a low enough inductance that they can feed a high speed pulse directly into the load. However, in general they are used to pulse charge a high speed section, some forms of which are mentioned in the next section of this note.

3. High Speed Sections

As the high speed section has to be treated as a transmission line, the impedance of the simplest form are given in Fig. 4. Since the local velocity of light is given by

$$\sqrt{LC} = \sqrt{\varepsilon} \times 3.3 \times 10^{-11} = \frac{1}{v}$$

and the impedance by

$$\sqrt{\frac{L}{C}} = Z$$

if the latter is known, the inductance and capacity per cm. length can be easily derived. The formula for the strip transmission line strictly only applies for thin lines but the impedance of fat lines can be obtained to about 10 per cent accuracy by calculating the impedance given by Z_{trans} in parallel with $200/\sqrt{\varepsilon}$ ohms. The extra impedance is roughly the energy flowing in the fringing fields. The impedance of a line of square cross-section in air is given as 200 ohms, which is correct. When the width of strip lines becomes very small compared with their separation, the impedance of parallel wires applies.

Two basic transmission line generators are also shown in Fig. 4. Firstly the case where a charged coaxial cable or transmission line (impedance Z_1) is switched into a load. This load can either be a resistance or another transmission line of impedance Z_2 . The gain of the system is given by

$$G = Z_2/(Z_1 + Z_2)$$

and is equal to 1/2 when the system is matched. This can be painful where great efforts have been expended in order to charge the original line to several million volts.

The second circuit shown in Fig. 4 was invented by A. D. Blumlein. The two transmission lines form the generator and these usually, but not necessarily, have the same impedance. For a duration equal to the two-way transit time the circuit acts like a generator of twice the charging voltage with an internal impedance of $Z_1 + Z_{1'}$. Thus the gain is

$$G = 2Z_2 / (Z_1 + Z_{1'} + Z_2)$$

which is equal to unity when the generator is matched.

For X-ray generation the optimum X-ray output is obtained when the load is about three times that of the generator, as the efficiency of X-ray production is a high power of the voltage. Under these conditions the gain of lossless Blumlein circuit is 1.5, so that 6 MV can be put on the X-ray tube from a system pulse charged to only 4 MV. If the high speed section is pulse charged from a Marx and the capacity of the Marx can be made twice as big as that of the Blumlein (considered now as a lumped circuit component), then in this case a further lossless ringing up gain of 4/3 occurs, so the Marx need only have an open circuit voltage of 3 MV. Various practical factors reduce the gains to be had at each stage, but approximately the calculations given above apply.

Both of the simple circuits mentioned above can be stacked to give voltage gain. Fig. 4 shows a four-stage generator using a simple transmission line to drive it. The generator only adds pulses for a duration equal to the two-way transit time of the stacked lines and hence the driving line is usually made the same electrical length. If the pulse rise time of the switch is comparable to this time, the pulse falls before it has finished rising and serious drops in gain may occur. Also, as is shown in Fig. 4, the volume between the stacked lines represents transmission lines going back to the switch. By making the impedance of the charged line very low compared with that of the stacked lines in parallel, a lossless open circuit gain of 4 is possible. However, real gains of 2 are more likely. In Fig. 4, the circuit of four stacked Blumleins is shown in the version where the simultaneously fired individual switches are replaced by a single switch. The lossless open circuit gain of the system is 8 and real gains of 6 may be achieved in practice. However, a very low inductance switch is needed to achieve an adequate fast pulse rise. A system of this form is described in Ref. (10).

In addition to the above circuits, tapered transmission lines, as described in Ref. (1) have been employed to obtain gain. However, such a system no longer produces square output pulses, even for ideal switching. Intrinsically the line produces a pulse which droops and such a shape is particularly susceptible to loss of gain with real life switches. A version of the tapered line which does not suffer from this disadvantage is a series of lines, each of which has an impedance twice that of the preceding one. In an ideal case a gain of 4/3 is obtained for each stage, with a small but acceptable energy reflection at each cable. However, real life small losses can reduce this gain substantially and in my experience this circuit is factually of not much interest.

In practical systems the coaxial version of the Blumlein circuit is particularly useful for generating high voltage pulses, an approach pioneered by Mr. D. F. Martin of Physics International, San Leandro. For smaller, laboratory bench top systems, stacked Blumlein cable systems can have open circuit gains approaching 10 when using careful construction and 8 or so stages. These use quite a lot of cable, but can have outputs of over 1/2 MV when employing reasonably sturdy coaxial cable. The impedance at the switch will be in the region of 2 or 3 ohms and a solid dielectric switch is usually the best way to get an adequate rise time, although advanced pressured gaps can be used. The system would of course be DC charged and can be simple and reliable. The size will be of the order of 1 metre cubed and hence is a bench top fast pulse system.

4. Breakdown Strength of Dielectric Media

Before starting to consider the individual media of use in high speed sections, it is worth making a general point about the degradation suffered in the breakdown field when the area or volume of the system is increased greatly. These are quite general considerations and refer to all media and indeed refer to other areas, such as strength of large structures, etc. The basic point is that if a major parameter, such as the breakdown field for a given volume of solid, has an intrinsic scatter, then there must be a degradation of the mean field as the volume is increased. This can be shown by considering an ideal experiment where the mean breakdown field of a large number of samples is known as well as the intrinsic standard deviation. Ten samples are then stacked or laid out and the question is asked what the mean breakdown voltage of this and other sets of ten units will be. Obviously in any large group the unit with the lowest strength will break as a rising voltage is applied and the new mean field will correspond to the voltage which broke only about 6.5 per cent of the samples when they were tested one at a time. This means that the mean breakdown field must decrease as the volume of the sample increases and that the local rate of decrease can be calculated from the standard deviation of the unit sample breakdowns. This, of course, assumes that there are no measurement errors involved. If the standard deviation is σ , then for a change of 10 the shift in mean field is just about 2σ . Thus for a σ of 12 per cent, which is typical of solid breakdown intrinsic scatter, an increase of volume of a factor of 10 will decrease the mean breakdown field to 80 per cent and the mean breakdown field will halve for an increase of volume of 1,000. In the case of solids, the breakdowns originate within the volumes for samples (other, possibly, than in thin films) and the effect is a volume one. However, for liquids and gases the breakdowns originate from the electrodes in general and hence the relevant parameter is the area of the electrodes. The reason the area is not quoted for, say, uniform field spark gaps is that, when conditioned, these have standard deviations of well under 1 per cent and an increase of 35 orders of magnitude would be needed to halve the measured breakdown field, so essentially the data is independent of electrode area in this case. However, for liquids and solids the standard deviations are frequently more than 10 per cent and the effect is quite important. Even for gases an area effect has been found in large high pressure DC systems, such as are made by High Voltage Corporation.

The distribution of breakdown voltages is not Gaussian but is a skew distribution which can be generated by replicating the Gaussian distribution a few times.

With regard to the way the breakdown data for media is presented, the point should be made that the designer only needs data to 10 or 20 per cent, since he will include a safety factor in general or be prepared to enlarge the size of the system slightly. In what follows several relationships are quoted and most of these are only approximately correct. However, in the absence of anything better they may be quite worth while, but they are not intended to have a high degree of accuracy. In any case, as there is an intrinsic scatter of solid and liquid breakdowns of the order of 10 per cent, accuracies much better than that are a bit meaningless.

In the next portion of this section the breakdown of gases, liquids and solids will be covered and in general one would like to be able to calculate the breakdown voltage of any of these for any area or volume of dielectric and for pulses of a given duration in any geometry. The pulse durations covered by the data are from a few μs to a few ns and in the case of the geometrical arrangement this is simplified to uniform, mildly diverging, or point geometries. In the case of gases and solids these are largely self-healing, although conditioning (both up and down) can occur. However, to the first approximation these materials do not have a life criterion, but for solids there is a definite life when operating at fields close to the intrinsic breakdown field and this, too, is covered briefly below.

Gases

As has been mentioned, Ion Physics have developed compressed gas insulated DC charged systems up to generator voltages of 12 MV. However, laboratory usage DC insulation in gases does not go much above 200 KV, but data in this range is useful for designing gas switches, etc., so some brief remarks on the DC breakdown of uniform and mildly non-uniform gases may be useful.

In uniform field gaps in air, the breakdown field can be expressed in the form

$$E = 24.6\ p + 6.7\ p^{1/2}/d^{1/2} \quad \text{kV/cm}$$

where p is in atmospheres and d in centimetres. For gaps in the region of 1 cm at 1 atmosphere, the field has the usually used rough value of 30 kV/cm, but this can rise substantially as the gap is decreased into the millimetre range. The expression also shows that the field does not go linearly with pressure when the gaps are small.

When spheres or rods are used as electrodes in gaps, unless these have radii large compared with the gap, the mean breakdown field can decrease considerably. The method of calculating the breakdown voltage, in the case of air, is to use the field enhancement factor (FEF) which is the ratio of the maximum field on the electrodes to the mean field. The FEF for spheres and parallel cylinders is given on page 6 of Alston's "High Voltage Technology". For instance, for spheres separated by their diameter, this factor is 1.8. It is now necessary to calculate the maximum breakdown field and this involves a length characteristic of the field fall off. Experiments show that this distance corresponds to the point at which the field is down to about 82 per cent of the maximum on the electrodes. This gives an effective distance:

$$d_{eff} = 0.115\ r \quad \text{(spheres)}$$

$$d_{eff} = 0.23\ r \quad \text{(cylinders)}$$

For example, for a 1 cm diameter sphere, $d_{eff} = 0.057$

and $E = 24.6 + 28.4 = 53$ kV/cm

and using the FEF of 1.8, the mean field $\bar{E}$ + 29 kV/cm.

As the gap is 1 cm in the example considered, the breakdown voltage is 29 kV at 1 atmosphere. However, at 3 atmospheres the breakdown voltage is 68 kV, significantly less than three times as great.

This treatment gives values within a few per cent of the observed conditioned breakdown voltages, except when the gap is small compared with the radius, when the uniform field approximation should be used.

In addition to the non-linear dependency mentioned above, an additional non-linearity sets in when the air pressure rises above 10 atmospheres or so.

Another effect which can change the breakdown voltage is if corona has set in, because the diameter of the electrodes is small compared with the gap. Then the field on the electrode changes and the breakdown voltages can be significantly affected.

When hard gases such as freon and SF_6 are used, the dependency of breakdown voltage with pressure is considerably nonlinear. From a practical point of view, freon is very much cheaper and is useful in flooding equipment to help to raise its breakdown. However, in gaps, dried SF_6 is much preferable but it must be changed reasonably frequently because the breakdowns cause its dielectric strength to degrade.

For pulse breakdown in gases in uniform or near uniform fields, there are two effects to consider. One is the statistical delays caused by waiting for an initiating electron to occur, to start the Townsend avalanche. However, for reasonable areas of rough electrodes, such as are used in pulse charged gas insulated lines, this effect only leads to increases of a few per cent. The second and more important effect is the fact that the avalanche process and the subsequent streamer takes time to occur and if the pulse is short enough, the breakdown field rises. Curves for various gases are given (Ref. (11)) which show for instance that for 1 atmosphere of air, the breakdown field has increased by a factor of 2.3 for a 10 ns pulse. The increase is only a few per cent for a 1 microsecond pulse and for high pressures the improvement decreases, so the effect is only useful for rather short pulses. However, for hard gases the fall-off of the DC breakdown field with moderate pressures mentioned above does not set in until much higher pressures are reached. Thus pulse charged SF_6 is fairly linear up to 10 atmospheres, at which pressure fields above 600 kV/cm can be obtained with the proper electrode materials.

For very divergent fields such as apply to points or edges, a rather approximate relation applies for gaps greater than 10 cms or so. This rough expression is

$$F_{\pm} \, (dt)^{1/6} = k_{\pm} \, p^{n}$$

where F is the mean field (V/d) in kV/cm, d is the distance in centimetres, t the time in microseconds and p is in atmospheres.

Table I gives the values of k and n for three gases.

TABLE I

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

The pressure dependency power only applies from 1 to 5 atmospheres or so. For air the time dependency disappears for times longer than of the order of 1 μsec for negative pulses and for several hundred μsec for the positive polarity. Thus for air at 1 atmosphere, a point will require about 1.5 MV to close across 100 cm in 100 ns.

For short pulses, mean fields comparable with 30 kV/cm can be achieved.

From the above integral relations differential velocity relations can be obtained but these are rather inaccurate and must be used with considerable discretion. However, lengths of incomplete streamers have been calculated which agree reasonably with experimental observations for high voltage, short pulses applied to wires.

Liquids

For liquids, the breakdowns originate from the electrodes and usually from the positive one. Thus an area dependency would be expected and is indeed observed. The smoothness of the electrodes is not critical, provided gross roughness is avoided. In addition, impurities and additives have little effect on the pulse breakdown field strength. For instance, several per cent of water or carbon introduced into transformer oil has less than 20 per cent effect on the breakdown fields, in complete distinction to their effect on DC breakdown.

For uniform fields the breakdown field is given approximately by

$$F t^{1/3} A^{1/10} = k$$

where F is in MV/cm, t in microseconds, and A is the electrode area in square centimetres. For transformer oil $k = 0.5$ and for water $k = 0.3$. However, experiments with diverging field geometries show that water has a considerable polarity effect, so that this k corresponds to positive breakdown streamers, while negative breakdown fields have the value $k- = 0.6$. The expression is not very accurate and it is not clear that other liquids obey exactly the same relation, but if they do, methyl and ethyl alcohol have about the same value of k as transformer oil, while glycerine and castor oil have values of k which are about 1.4 times as big as transformer oil.

In general, for pulse charged liquid lines, transformer oil and water have been the principal media used. Water is particularly useful because its dielectric constant is 80 and remains constant up to about 1 gigacycle. Water has to be deionised, not because impurities affect its pulse breakdown strength but just to prevent it providing an ohmic load on the generator. Resin deionisers give water with resistivities above 1 megohm centimetre when it is recycled through them and this is usually good enough, as the self-discharge time is then 8 microseconds. Thus for a microsecond charge time some 10 per cent of the pulse charge energy is lost by ionic conduction.

For mildly diverging fields, the breakdown field is applied to maximum field on the electrode (making allowance for any polarity effect) and using the area of the electrode which is stressed to within 90 per cent of the maximum field. A small correction can be applied to allow for the fact that the streamers are moving into a diverging field and this typically increases the breaking voltage by 20 per cent or less.

For point or edge plane breakdown conditions, the mean streamer velocity has been measured for a number of liquids for voltages from about 100 kV up to 1 MV and the mean velocity is given over this range by

$$\bar{U} \equiv d/t = kV^{n}$$

where $\bar{U}$ is in centimetres per microsecond and V is in MV. Table II gives the values of k and n for transformer oil and two other liquids.

TABLE II

	k+	n+	k-	n-
oil	90	1.75	31	1.28
carbon tetrachloride	168	1.63	166	1.71
glycerine	41	0.55	51	1.25

For water, the relationships are rather different, being best fitted over the range mentioned by

$$\bar{U}\, t^{1/2} = 8.8\, V^{0.6} \quad \text{positive}$$

and $\bar{U}\, t^{1/3} = 16\, V^{1.1}$ negative

Thus for oil, a negative point or edge will break down at 1 MV in 100 ns over a distance of about 3 centimetres. The fundamental mode of streamer propagation seems to be the negative one and for voltages in the region of 1 MV the slow positive streamers in water and transformer oil speed up and move with the velocity of the negative streamers.

For voltages from rather over 1 MV to 5 MV, both polarities in oil obey a relationship of the form

$$\overline{U} \pm d^{1/4} = 80\ V^{1.6}$$

A similar relation seems to apply to water, but with a lower value of k but data is lacking in this case.

Solids

For solids the streamer transit times are very short and down to a few nanoseconds the breakdown field is independent of the pulse duration. The breakdown field is given by the expression

$$E\ (\text{vol})^{1/10} = k$$

where the field is in MV/cm and the volume is in cc. Table III gives the values of k (which is the breakdown field for 1 cc) for various plastics.

TABLE III

	k
polythene	2.5
tedlar	2.5
polypropylethylene	2.9
perspex	3.3
mylar (thick)	3.6

For thin sheets, the standard deviation of the breakdown field decreases and the breakdown strength becomes almost independent of volume. For 1/4 thou. sheets this occurs at 5.5 MV/cm, for 2 thou. sheets at 4.0 MV/cm and for 10 thou. sheets at about 3.0 MV/cm.

For diverging fields, the maximum field on the electrode is calculated and the breakdown field used which corresponds to the volume which is stressed to about 90 per cent of the maximum field.

For solids, there is a reduction in breakdown field for repeated pulses. This life is given by the expression

$$\text{Life} = (E_{BD}/E_{op})^{8}$$

where E_{BD} is the breakdown field and E_{op} is the field at which the life is wanted. The power in the life relation seems to be related to the standard deviation and for thin films of mylar the power is 16 or higher.

As an example of the calculations applied to polythene, a volume of 104 cc has a mean pulse breakdown field of 1 MV/cm for a single pulse. However, this decreases to about 0.5 MV/cm if a life of 1,000 pulses is required. Thus a 1/16" sheet of polythene can be used in uniform field conditions at about 80 kV for a reasonable life.

For DC charged solids, several effects combine to alter the breakdown strength and usually, but not invariably, lower it. For instance, in some plastics conduction currents can heat the plastic and cause run away thermal degradation. Chemical corrosion from surface tracking can cause degradation of the breakdown fields, as can mechanical flow under electrostatic forces. All of these effects vanish in pulse charged systems, of course. In polythene, DC charging can give fields some 20 to 30 per cent higher than the pulse values. This is caused by enhanced conduction in the regions containing the defect that originates the breakdown. However, if the voltage is rapidly reversed, this "annealing" charge separation now adds to the field on the defect and polythene can be made to break with a pulse reversal of only 30 per cent when it has been DC charged. The time scale of this charge and annealing is of the order of milliseconds. Mylar and perspex show little or none of this effect and hence are to be preferred for DC charged strip transmission lines.

In addition to the above DC effect, both polythene and polypropylethylene show a polarity effect when pulse charged in diverging geometries. The negative point, or small sphere, is over twice as strong as the positive one.

Interfaces

This whole area is very complex and cannot be simply treated. In general, interfaces and legs can be designed to support fields as good as the main lines in which they are placed. In the case of diaphragms, the metal surfaces are recessed, so the field is reduced at the triple interfaces. In general, it is possible to avoid interface tracking in transformer oil, but in water, with its very big dielectric constant, the problem is much more difficult. However, acceptable solutions have been developed for pulse voltages up to 4 MV or so in a couple of systems. In this area more than any other, scaled experiments are of great help in developing promising solutions which can then be proved out at full voltage.

Edge Grading of Lines

When building strip transmission lines, if relatively thin copper sheets are employed, very large field enhancement occurs at the edges of the lines. This can be reduced to acceptable levels by using pseudo-Rogowski contours. These can be quickly made by using a file on thick plywood to solve Laplace's equation and then covering the thick rounded line with copper foil a few thou. thick. Another technique in pulse work is to use dilute copper sulphate films to resistively grade the edges during the pulse rise. A third technique of use for solid lines DC charged is to surround the edge of the metal foil with blotting paper, which helps to suppress surface flashover. Flashover voltages can be doubled, or more, by using this technique with care.

Vacuum Breakdown

This subject is rather beyond the scope of this note, but pulse fields can be very much greater than the DC ones, providing care is taken with the finish of the metal electrode surfaces. If there is no prepulse, oiling with transformer oil can raise these fields at which significant current flows to levels of the order of 1/2 MV/cm. In addition, self-magnetic fields can be used to suppress currents in vacuum insulated coaxial lines. As regards flashover across vacuum-insulated interfaces, Ref. (12) describes some work which has enabled X-ray tubes working at gradients of up to 2 MV per foot length to be made.

5. Switching

Before dealing with some aspects of switching, a general topic will be briefly covered. This relates to estimating the rise time of the pulse produced by a given switch. As was mentioned earlier, values good to 20 per cent are more than adequate and in order to be concise, various aspects which can occasionally be relevant will be omitted.

The rise time of the pulse, which is the same as the fall of voltage across the gap, of course, is largely controlled by two terms: the inductive term and the resistive phase term. The inductance of the gap is larger than that of the spark channel itself but in a well designed gap it is usually the major term. This inductance changes with time as the conducting channel expands and on occasions this can be important. However, in this note only a constant inductance will be considered. The second component of the rise time is the resistive phase. This is caused by the energy absorbed by the plasma channel as it heats and expands. In the case of channels working at reasonably high initial voltage gradients and driven by circuits of tolerably low impedance (i.e., less than 100 ohms or so), the plasma channel lowers its impedance mainly by expanding to become larger in cross section. The energy used up in doing this is obtained by the channel exhibiting a resistive impedance which falls with time. This expansion can be measured optically and correlated with the energy deposited in the plasma itself. A fairly wide range of experimental results have been collected and summarised in a semi-empirical relation which is easy to use.

The two terms in the rise time expressions both refer to e-folding times. For the case of a constant inductance L joined to a generator of impedance Z the voltage falls exponentially with a time constant $\tau_L = L/Z$.

The accurate calculation of the inductance of the channel is difficult and would require accurate knowledge of the channel radius. Fortunately it is not necessary to do this, because an adequate approximation is to use that of a wire of radius a fed by a disc of radius b in which case the inductance is

$$L = 2\, l \ln b/a \text{ nanohenries.}$$

In this expression $b >> a$ in practice and the value of L is only weakly dependent on a. The rate of expansion of the channel is of the order of 3×10^5 cms per sec. for air at one atmosphere and maybe half an order of magnitude greater for liquid and solid gaps, depending on the field along the channel when it forms. In the above expression l is the channel length and is in centimetres. For rise times of a few ns, the log term is of the order of 7.

Incidentally, when care is taken in selecting approximations to the various sections of an array of conductors, simple inductance relations can be used to obtain the total inductance to an accuracy of 20 per cent or so. The way of getting the inductance per centimetre of a chunk of an equivalent line was given at the beginning of section 3.

The relation for the resistive phase is given in two forms, for convenience. For gases, it is

$$\tau_R = \frac{88}{Z^{1/3}\, E^{4/3}} (\rho/\rho_o)^{1/2} \text{ ns}$$

where E is the field along the channel at its closure in units of 10 kV/cm, ρ/ρ_o is the ratio of the density of the gas to air at NTP, Z as before is the impedance of the generator driving the channel.

For solids with unit density

$$\tau_R = \frac{5}{Z^{1/3} E^{4/3}} \text{ ns},$$

where E is now in MV/cm.

To obtain the effective rise time of the pulse τ_{tot} the two times are added, i.e.

$$\tau_{tot} = \tau_L + \tau_R .$$

This time is the e-folding time, where the waveform is exponential and where the pulse rise is not, this parameter approximates to the time obtained when the maximum slope of the voltage waveform is extended to cut the 0 and 100 per cent values of the voltage, i.e.

$$\tau_{tot} \simeq V/(dV/dt)_{max}$$

Where the waveform is exponential, the e-folding time is multiplied by 2.2 in order to obtain the 10 to 90 per cent time. However, where a number of equal time constants are operated, one after the other, this factor falls rapidly and eventually tends to a little less than unity. Then there is no unique relation between the e-folding time and the 10-90 per cent rise time and I would suggest that for many applications, the one used here is of more use than the standard parameter. In particular, it gives the value of di/dt_{max} reasonably well and is the main parameter of use in calculating the energy deposited in the spark channel.

After the main voltage fall has occured, small voltages persist across the plasma channel as it cools, moves, bends, etc., as well as the more usual drops at the electrodes, but most of the energy is deposited in a time of the order of the resistive phase. In most gaps both terms are important, but for circuits with impedances of tens of ohms and higher, working at modest gradients, the resistive phase may be several times as large as the inductive one.

Various very approximate treatments exist to cover branching, non-uniform conditions down the channel, etc., but these are beyond the scope of this note.

Table IV gives an example of a calculation for a plasma channel or length 5 cms with a starting voltage across it of

100 kV, in air at one atmosphere pressure. The calculations are shown for three different values of Z .

TABLE IV

Z	τ_L	τ_R	τ_{tot}
100	1	6	7
10	10	14	24
1	100	30	130

Table V shows a representative approximate calculation for a solid switch with 200 kV across of 3 mm solid dielectric, such as polythene.

TABLE V

Z	τ_L	τ_R	τ_{tot}
100	0.04	1.6	1.6
10	0.4	3.6	4
1	4	8	12

All the times are in ns.

As can be seen, calculations based on the inductive term alone can be badly wrong. The combined effect rise time is also used below in some brief comments on multichannel switching.

General Comments on Switching

This field is very extensive, so here, even more than in the rest of these notes, the comments are of a personal nature and in particular the next few paragraphs are given purely as my views, views, however, that I am prepared to defend to the bitter end.

In order to reduce the vast field to more manageable proportions, I consider that, apart from mechanical closure gaps (which can be very useful - see below), the main kinds are:

trigatrons
cascade gaps
field distortion gaps
UV triggered gaps
laser triggered gaps.

Disposing of the last two versions first, the UV triggered gap has a very limited operating range and while the laser triggered gap can have an acceptable operating range, it cannot do anything that cannot be done in a tenth of the time and cost by one of the preceding gaps.

The trigatron gap has been extensively used and, properly designed, can be reliable. It tends to require a smaller trigger voltage (with, however, more drive) and was much favoured when 10 kV was a high voltage pulse. Nowadays this aspect is almost irrelevant. When used in a reliable mode, however, it needs about as large a trigger pulse as the other gaps and as the discharge goes to a limited area, erosion can be a serious problem.

When large capacitor banks had to be reliably triggered for plasma physics work, the cascade gap was extensively employed and for many applications it is still of considerable use. It can be triggered with jitters of tens of nanoseconds, but in most versions it needs a small irradiation gap in the trigger electrode and is also fairly bulky and expensive.

For most applications I prefer the field distortion gap which, because of the small radius on the trigger electrode, does not need any extra irradiation, as field emission from the rough trigger provides the necessary initiating electrons. In addition, the length of the gap, which is closely related to the inductance, is a minimum in this gap and it can be cheaply and quickly made. It can also lead to the spark channels being well distributed along or around the main electrodes, so erosion is a smaller problem where this is a factor of importance. Figure 5 shows a cross section of a field distortion gas gap (which also goes by the name mid plane gap). The gap can use either ball bearings as spherical electrodes or rods for a cylindrical electrode gap. The trigger electrode need not be in the middle of the gap and, indeed, in one mode of operation it should be offset. The field distortion or mid plane gap can be easily modified for use with liquids or solids and indeed for solids this form of construction is so simple as to be positively moronic.

Consideration will now be given to a few of the factors involved in gas, liquid, and solid gaps, concentrating mainly on the field distortion gap as a personally preferred type.

Gas Gaps

In general, gaps become easier to trigger and operate faster, the higher the voltage at which they work. The difficulty is usually to stop them working in unwanted ways such as tracking. In general, brass is an excellent material to make the electrodes out of and this material is equally good with air or SF_6. It can be easily worked and its erosion rate is as low as any other material in almost all circumstances. With regard to the gases to be employed, air and SF_6 can cover a wide range and in general are all that we use. The gas flow can be significant in the case of air at no cost and while SF_6 is quite expensive, a modest flow is necessary to obtain reliable operation. The gas employed should be dried, especially if the gap has a large coulomb usage. In the case of gaps using spheres as electrodes, these can be made out of steel or phosphor bronze ball bearings, with some very minor corrosion effects. The spark gap body can be made out of perspex, either in standard tube lengths or, for a high pressure gap, turned out of solid. Nylon has also been used with success, as well as other more exotic materials, but perspex has the advantage that it can be quickly joined with Simplex cement. This material is a powder monomer with a catalyst and is extremely useful in building high voltage systems cheaply and quickly.

The field distortion gap is usually employed in a cascade mode. In this, the trigger electrode is central and its potential (which is earth in a balanced system) is changed by the trigger pulse or by shorting it to one of the main electrodes via a small inductance. One half of the gap fires and the gap volts are then imposed on the second half. Such a gap will trigger fairly quickly down to something like 60 per cent of its self-breakdown voltage (i.e. it has a triggering range to 0.6). However, the gap can be easily used with a displaced electrode and then it can be made to trigger down to 0.4 or less. Such a gap, when used at 80 per cent of self-break, can trigger in a few ns and can have a jitter of a few tenths of an ns. These figures apply to gaps working at tens of kV and above. The trigger pulse needed is of the order of the self-break voltage of the gap, but as the capacity it is driving is small, this is easy to achieve. The gap with a displaced trigger electrode is arranged to break both portions of the gap simultaneously and the ratio of the gaps is of the order of 1:2, but depends a little on the gas and pressure.

In spherical electrode gaps the trigger electrode takes the form of a disc with a hole cut in it and this hole can be of the order of the gap separation, so that small errors in the DC potential of the trigger do not have any effect on the self-breakdown voltage. In general, the thickness of the trigger disc can be in the 1 mm range.

Such gaps work down to 15 to 20 kV well, but below this various factors contribute to making their operation more difficult. To bridge the gap between a few kV and these potentials, a cheap, simple gap exists (Refs. (13),(14)), which can be triggered quickly by a 300 volt pulse in a 70 ohm cable. This pulse is fed via a ferrite cored transformer and the resulting 1 1/2 kV trigger pulse applied to the gap. These gaps do not in general handle much energy and are best in the low voltage range, but versions working at 200 kV and handling 10 kilojoules have been built. Their main virtue is their cheapness and ease of construction. They can also have a jitter of firing on the trigger pulse of 1 or 2 per cent and have been used to make pick-up resistant trip, delay, and output circuits. In these, the internal pulses are all at the 10 kV level and the output pulses are of low impedance and have rise times of 50 ns or so. In conditions where electromagnetic pick-up is bad, they can be very useful.

As an example of a good low inductance gap, a rod or rail gap has been built with an outside diameter of a little over 3 inches. Strip line feeds to it were well insulated with doubled-over mylar and under freon it did not track at 210 kV. Its inductance, used as a single channel gap, was under 50 nanohenries and a triggered multichannel version was calculated to have an inductance of about 5 nanohenries. It took about three days to build and the materials cost a few tens of pounds.

Liquid Gaps

Figure 5 shows the general form that has been used for pulse charged liquid gaps. Water gaps have been operated up to 3 MV and have shoen modest multichannel operation at these levels. They have also been operated with oil by Mr. I. D. Smith of Physics International, San Leandro, at levels up to 5 MV, where again they have performed well. Mr. Smith has contributed greatly to many aspects of pulsed high voltage technology and it is a pleasure to record this.

In the version shown, the trigger pulse is simply derived from the energy stored within the gap, but better multichannel performance would be obtained by using an external pulse to operate the gap. In the case of water, the gap ratio is more like 7:1 but significant expertise is still required to operate liquid gaps at the multimegavolt level.

For simple, over-volted, untriggered gaps, both oil and water perform well and fast rising pulses can be simply produced. With care, jitters in the voltage breakdown can be 3 or 4 per cent and closure gradients of 400 kV/cm in oil and 300 kV/cm in water obtained for microsecond pulse charge times.

Liquid gaps represent an attractive approach for switching at the multimegavolt level and the only other type gap probably worth looking at is pressurised SF_6 or similar gas mixtures.

Solid Gaps

Mechanically operated solid gaps have been used for a long time and for many DC applications a slightly blunt tin tack and a hammer is by far the best approach. Indeed, this switch probably has the fastest rise time of any when used in a low impedance circuit. The reason is that both the thin copper or aluminium sheet top electrode and the insulating film flow and intrinsic breakdown eventually occurs in a very small volume at fields in excess of 8 MV/cm. The deformed electrodes also form a good feed to the very short plasma channel; all in all, it is quite a sophisticated gap. Several versions of mechanically broken gaps have been developed at Culham, as start and clamp gaps, and these are operated with modest jitters by means of exploding wires or foils to cause the mechanical deformation when required.

Two versions of intrinsic breakdown solid gaps (Refs. 15, 16) were developed at AWRE some eight years ago. The first type uses an array of 50 needles to stab holes in, say, a 60 thou. polythene sheet. By varying the depth of stab, the operating range could be changed from 40 to 150 kV with the stabs positive. As there is a strong polarity effect on polythene with the stabs negative, the range was from 120 to 250 kV or more. This switch could be stacked for higher voltages and a pair of them made a simple triggerable switch. The standard deviation of the breakdown voltage could be as low as 2 per cent and the switches had very similar characteristics when used from DC down to 10 ns charging times. In one quite old system, 40 such switches were regularly fired simultaneously at 200 kV, producing a 4 MA current rising in 8 ns or so, i.e. a di/dt of 5×10^{14} amps per second. Such switches are still in use in various systems and have been operated up to 1/2 MV pulse charged.

A second and even lower inductance solid dielectric switch was developed along the lines shown in Figure 5. Two mylar sheets of different thicknesses enclose a trigger foil whose edges are sealed with a thin film of transformer oil or silicon grease. Copper or aluminium mean electrodes are added to complete the switch. The inductance of a single channel switch of this kind is very low and the resistive phase is small as well. For DC charged high current banks a multichannel version of this switch is easily made and by injecting a pulse rising to, say, 40 kV in a few ns along the line formed by the trigger foil, hundreds of current carrying channels can be made to occur. Currents of tens of megamps can be switched by a couple of such switches and their inductance is extremely small. Pulse charged versions of this gap have been operated up to 1/2 MV.

Solid dielectric gaps have to be replaced each time, of course, but, in high performance banks with a relatively low rate of useage, they can be a very cheap substitute for tens or hundreds of more orthodox gaps.

Multichannel operation of Gaps

Single channel gaps transit time isolated have been operated in parallel for several years, but these do not come within the rather strict definition of multichannel operation that I use. For me, multichannel operation of a gap occurs when all the electrodes are continuous sheets of conductor. As such, while transit time isolation may play a small part, the main effect is that before the voltage across the first channel can fall very much, a number of other channels have closed. As such, it is the inductive and resistive phases which are important in allowing a very brief interval in which multichannel operation occurs. This time ΔT is given by

$$\Delta T = 0.1\, \tau_{tot} + 0.8\, \tau_{trans} .$$

τ_{tot} is as defined in the previous section and τ_{trans} is the distance between channels divided by the local velocity of light. Both of these terms are functions of n , the number of channels carrying currents comparable to the first one to form. ΔT is then placed equal to 2δ where δ is the standard deviation of the time of closure of the gap on a rising trigger pulse. This is related to the standard deviation of voltage breakdown of the gap by the relation

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

where dV/dt is evaluated at the point on the rising trigger waveform at which the gap fires.

Figure 6 gives the jitter of a negative point or edge plane gap as a function of the effective time of rise of the trigger pulse. For ordinary gaps (both gaseous and liquid) a good jitter is 2 per cent or so, but for edge plane gaps charged quickly the jitter can be down to a few tenths of a per cent. Typically ΔT is a fraction of a nanosecond - ordinary gaps require trigger pulses rising in 10 ns or so. However, for edge plane gaps, the trigger pulse can rise in 100 or more ns and still give multichannel operation. In one experiment 140 channels were obtained from a continuous edge plane gap.

The expression has also been checked for liquid gap operation and more approximately for solid gaps, and gives answers in agreement to some 20 per cent for ΔT . The way it is used is to define a rate of rise of trigger pulse and as such, this sort of accuracy is ample. Fast trigger pulse generators are required to obtain multichannel operation and these must have impedances of 100 ohms or less. Of course the pulse length produced by the trigger generator need not be very great and the generator can be physically quite small. Mr. T. James of Culham has done much work on high speed systems and gaps in general and Ref. (17) gives an example of a high current low inductance multichannel gap he has developed.

6. Monitoring and other General Items

Monitoring

The subject of monitoring is fairly intimately interwoven with the other problems of pick up and the oscilloscopes available to display the attenuated pulses. In general it seems little sense to me to attenuate a signal by a factor of a million and then display it on an oscilloscope with the sensitivity of a few volts per cm. Attenuation problems are extreme and the effort to reject unwanted signals considerable. Consequently, wherever possible, we have tended to attenuate the signal by a factor of a few hundred and to transmit it by cable at the level of 10 or 20 kV. When the signal is passed through the shielding around the oscilloscope, it may be reduced by attenuators using standard 1W resistors without loss of band width. However, even here we have followed a policy of using insensitive oscilloscopes whenever possible, a matter briefly dealt with below. In this section the main techniques for doing the initial attenuation will be briefly discussed.

In the case of voltage monitors, the stray capacity is the component which tends to limit the response of the attenuator and the inductance of the monitor is usually unimportant. For current shunts the reverse is the case. It is usually worth distinguishing between the two time scales, since high voltage monitors for the pulse charging system can have impedances of 10 kilohms or thereabouts, while the faster system can usually accept attenuator impedances of a kilohm or two. Reducing the attenuator impedance of course helps to reduce the integrating effect of any residual stray capacities. In high voltage dividers, the effects of stray capacity can be largely mitigated by placing them in an environment where they have essentially zero stray capacity, as is shown in Fig. (7). The ideal place is in the uniform field between, say, two parallel transmission lines. However, the gradients are so large here that flashover might well occur. If, however, the monitor is moved into the fringing fields and located along a line which approximates but is not the same as the field line, this stray capacity can be cancelled. By using $CuSO_4$ resistors in their simplest form, a tube of $CuSO_4$ will divide the potential along its length uniformly because of its resistance and also it will divide inductively in a uniform fashion. If now it is located so that it crosses the equipotentials uniformly as well, then to a first order its stray capacity is zero. This trick only applies for durations longer than a few times the transit of the signal across the gap and it does not apply to very high frequencies, when a complete theory would be very complicated. However, for lines 1 or 2 feet apart, these times are a nanosecond or two.

In the situation shown in Fig. 7, a plus and minus signal is taken out of the centre tap of the monitor. Using a balanced monitoring system helps to reject pick up but the approach works quite well where the tap off section is at one end of the resistor column or chain. Uniformly graded resistor columns are not essential and in diverging fields the cross-section of a $CuSO_4$ resistor can be changed, or indeed its concentration, but these are elaborations which are just not worth while.

Where the divider is made up of standard resistors, these can be zigzagged back and forth in a low inductive fashion and then the stack bent to conform with the required layout.

In general, 1W carbon resistors will stand pulse volts up to about 15 kV per resistor for short pulses and will absorb one or two joules with only a modest long term drift. At 5J per pulse per resistor this change becomes larger but can be cancelled to a first order by tapping off across a representative resistor. At the level of about 10J per resistor, they blow up with a satisfying bang!

An alternative approach to monitoring the high voltage pulse is to use capacitor dividers embodied in the walls of the transmission line. Several groups use this approach and, in particular, Mr. J. Shipman of the U.S. Naval Research Laboratory, Washington D.C., has developed internally damped high frequency capacitor dividers to a high level of perfection.

For monitoring currents flowing in the system, low inductance shunts can be employed, or integrating Rogowski loops. We have tended to use current shunts made from thin Nichrome, steel, or brass, and, once again, since tens or hundreds of kiloamps are flowing, output signals can easily be at the level of a few kV. The shunt is usually made fairly wide, rather short, and insulated with a few thou. of mylar.

Pick Up

While it is easy and indeed convenient to have most of the pulses monitoring the functions of the generator produced at the level of several kV, certain signals such as those from strain gauges cannot be made very big. In these conditions serious problems with pick up are likely to be encountered. These can be minimised by careful attention to each stage at which the signals are handled and it is possible to monitor few milliamp signals in the presence of low voltage banks generating 10 million amps.

In general, pick up occurs because of capacitive coupling or inductive coupling. Inductive coupling is much the most difficult one to cope with and my remarks will be restricted to this mode. A lot of work has gone on in the last few years to rationalise the rejection of unwanted signals. The field is a very large one and is eminently susceptible to rational analysis. The first message is that there is no 'black magic' in pick up: the laws of electromagnetism apply here just as anywhere else. Where many interacting metal loops have been allowed to occur, the situation may be too complex to analyse, but if care is taken from the beginning to simplify such loops, then the circuit can be analysed and answers to a factor of half an order of magnitude obtained. Such accuracies are entirely adequate because the aim is to reduce the pick up to very small levels. In general, there are three areas of importance in pick up - the system that is generating the unwanted electromagnetic signal, the monitor and its connections; and the oscilloscope, which is usually inside a screened room or box.

Every effort should be made to make sure that the bank or pulse generator is as low an inductance as possible. This is achieved by making sure that all return currents flow close to the outgoing current. Balanced strip line feeds radiate very little and, of course, help to speed up the pulse itself. Balanced charging and balanced output signals from attenuators can also reject common mode interference considerably.

With regard to the connectors between the attenuators and the monitoring oscilloscopes, two approaches are very useful. One is known as 'tree wiring' and in this every endeavour is made to reduce the area of the pick up loop. For instance, should it be necessary to join a monitor to an oscilloscope and the 'scope is joined to other 'scopes and units, all the wires flow along the trunks and branches, as in a tree, and are closely taped together. This means that the area in which pick up can occur has been made as small as possible.

The second general approach is to put a complete break or, if impossible, a high impedance in each loop. Under these circumstances only small currents flow in the outer braiding of the coaxial cables in which the monitoring signals are transmitted. This is not difficult to do in practice. For instance, pulses can be sent between oscilloscopes by small isolating ferrite cored transformers. The bank or high voltage system can frequently be isolated from earth by heavy duty $CuSO_4$

resistors of 10 or 20 ohms impedance. Since the bank will have a capacity to the rest of the laboratory, you can calculate the sort of impedance this represents and make this equal to the earth isolating resistor. From a safety point of view it is probably better to have three or four easily seen large $CuSO_4$ resistors than to vaporise a copper conductor inside its outer insulation cover because of the large circulating currents introduced by multiple earthing. Battery operated oscilloscopes can also be employed, but a much simpler solution is to wind 50 yards or so of mains cable on a cardboard drum to make an isolating inductor out of it. Small capacities of the order of 0.1 μF are needed between (live and neutral) and earth at both ends of the inductor, to avoid producing transient voltage pulses in the mains wiring and the mains transformer of the oscilloscope. The oscilloscopes can move away from earth by a few kV during the operation of the generator and while the shocks experienced by touching them would be small, the 'scopes should be isolated during the operation of the system. When proper care is taken, large fast banks can be fired without blowing plugs out of wall sockets and ringing telephone bells in adjacent buildings.

With regard to building a shielded monitoring room, or individual shields around the oscilloscopes, these techniques are fairly well reported and the only point probably worth making is that the boxes can be cheaply made out of wire mesh, providing good low impedance joints are made frequently along the edges of the mesh. This is because even a few tens of milliohms will cause surface currents to flow non-uniformly and allow signals to leak in through these high resistance joints. Phosphor bronze draught excluder strips make good seals for the necessary access door. Any further attenuation that the signal needs is done as it comes in through the wall of the oscilloscope box. The 'scope itself should sit off the deck and it is desirable to employ 'tree wiring' within the box.

The two concepts mentioned above of 'tree wiring' and placing impedances in each loop are not mutually incompatible and, in general, both should be employed. Where any one scheme is consistently carried out, a drop in interference of some 40 db is usually easily obtained.

Safety

It is not possible in this note to deal adequately with safety, but it is a matter which should be taken very seriously. In general, condensers storing more than a few tens of joules should be in a metal enclosure with limited access. In order to ensure safety before entry, it is desirable to have three complementary methods of making sure that, in normal operation, the bank is discharged. One useful method is a voltage meter that monitors the potential on the condensers. These have to work each time or else it is not known how much the bank has been charged and after the bank or system has been fired, they should be watched to make sure that they have fallen to zero or near-zero.

The second line of defence is a weight which is lowered onto the top of the charged system and which is coupled to two $CuSO_4$ resistors in parallel. These are designed so that they will not leak and are placed in a position where they are clearly visible.

The third, and last-ditch, shorting technique is a dropping weight which places a short circuit across the condenser system. This should be observed each time that it is operated and should, of course, never cause any spark on closure. In the event that it does, both of the preceding systems are malfunctioning and the matter should be investigated urgently. In the event of a bank blowing up, or some obviously unusual occurrence taking place, by far the safest thing is to sit down for ten minutes or a quarter of an hour and to think hard. Then re-entry with care and with a shorting-stick well to the fore can be attempted.

$CuSO_4$ Resistors

$CuSO_4$ resistors are of great use in nearly all high voltage applications. They are very much cheaper and simpler to make than soldering together 500 1W resistors. They can be flexible and disposed in elegant shapes. They can absorb vast amounts of energy, one cubic foot or so of solution taking, quietly and safely, the energy out of a 1 megajoule bank. As has been mentioned above, they are useful as voltage dividers and also act excellently as high energy terminators for transmission lines. They have a resistive response into the several hundred megacycles region and apart from the electrode-liquid interfaces obey a much better understood bit of physics than carbon resistors. The disadvantages are that it is quite easy to measure incorrectly their resistances. This is because insulating films form on the electrodes rather like electrolytic condensers and hence resistance measuring systems working at fractions of a volt see large capacitive components. However, these films can be easily stripped off with a DC current, or the voltage raised to the point at which the effect goes away. In use, of course, the fact that there is, say, a 5V drop at the electrode-liquid interface is irrelevant when a one million volt pulse is applied to the resistor.

In making $CuSO_4$ resistors, it is sensible to use deionised water and $CuSO_4$ only, and copper electrodes. The body can be either flexible PVC tubing or, if rigid resistors are required, perspex. The resistance of ionic conductors is a function of temperature and in long resistors temperature gradients can exist, but this is an easy matter to measure and should cause no problems, although it sometimes does. When large energy densities are dumped into $CuSO_4$ resistors the temperature rises and the resistance changes, but in addition a pressure wave develops because the liquid does not have time to expand. Consequently for dump resistors which may experience rapid rises of 10° or 20°C, flexible walled vessels should be employed.

In general, for low energy applications, resistors, or resistor chains, are quite adequate up to 50 or 100 kV but above this they become messy and for high energy absorbing applications and/or high voltages, $CuSO_4$ resistors are greatly to be preferred.

Low Sensitivity Oscilloscopes

One of the ancillary pieces of equipment developed at Aldermaston has been the low sensitivity oscilloscope, which has a deflection sensitivity of some 4 kV/cm on the film. It has a rise time in the region of 1 ns and apart from the rectifiers in the power pack, the only active element is a spark gap triggered off by a portion of the incoming signal. The oscilloscope is sufficiently immune to pick up to be used unshielded. The sweeps are exponential but this is an advantage since one is usually mainly interested in what happens to the front pulse, with a diminished interest in later reflections, etc. In one application where it was required to monitor the high speed pulse in a system pulse charged in about 1 μs, one of these 'scopes was floated up to 1 million volts and operated quite happily when the high speed pulse came along. The signal leads between the generator and the oscilloscope and the mains cable from the 'scope to earth were wound in the form of inductances and the 'scope located approximately in its proper potential place in the fringing field of the generator.

Power Packs

With modern plastics whose surface resistivities can be very high, modern power packs can be made light and compact. For instance, a ± 125 kV power pack need not occupy a volume much greater than 3 cu. ft. and can be easily carried. Air insulation is obviously used and to avoid having to make a large number of metal domes, the simple expedient is used of wrapping perspex sheets, or mylar, around and over the sharp edges of the power pack. A brief burst of corona charges up these insulating sheets in such a way as to grade the potentials correctly and, a small AC ripple apart, no further corona-ing will occur. For lower voltages, commercially made RF power packs work well and are reliable.

In general, either carbon resistor chains or $CuSO_4$ resistors should be included in the output leads of the power packs so as to limit the rate of discharge of these when the short occurs in the main generator, or if the generator is fired without switching the power pack off. This simple precaution can save quite a lot of money in replacement rectifiers, at the same time as isolating the power pack so that it does not radiate pick up.

7. Examples of Pulse Systems

As an example of a large system, Ref. (9) can be consulted. This machine is Hermes II and was built by Mr. T. Martin of Sandia Corporation, some three years ago. It works with up to 10 MV on the X-ray tube and the tube current is in excess of 100 kA. Physics International of San Leandro, California, Ion Physics of Burlington, Massachusetts, and Maxwell Laboratories of San Diego, all build a range of pulse power systems in the multimegavolt range and I am sure they will be pleased to supply literature on these. In the range 100 kV to 2 MV, Field Emission Corporation of McMinnville, Oregon, produce a wide range of systems. As a review of work at AWRE up to a few years ago, Ref. (10) lists some of the systems built and gives their characteristics.

In general, Marx generators of output voltages up to 10 MV and more are available and these can deliver energy at the rate of up to 1 GW (10^{12} watts). Fast systems have been built which provide

$$di/dt = 5 \times 10^{14} \text{ amps/sec}$$

$$dV/dt = 5 \times 10^{14} \text{ volts/sec}$$

and $dE/dt = 10^{13}$ watts.

However, such systems are large and expensive. In addition, their rate of operation is fairly limited, a matter of no great importance for their applications.

Turning to somewhat more modest systems, Table VI lists a series of slow and fast systems and gives very rough cost estimates when built by the persons wanting to use them.

In addition to these systems, fast and slow pulse generators with outputs up to 1 MV and storing a kilojoule or less can be built for a few hundred pounds in a few man weeks.

Systems giving a hundred kV or so can be knocked up in a week and at a very small cost, when the construction techniques we employ are used.

TABLE VI

Speed	Type	V (MV)	i (kA)	t_{pulse} (ns)	t_{rise} (ns)	Approximate Cost (£s)
Slow	Transformer	1	2	500	-	500
		2 1/2	5	1,000	-	2,000
	Marx	1	10	1,000	-	3,000
		5	100	2,000	-	30,000
Fast	WeeWOBL	0.4	20	45	5	1,000
	Plato	2	20	13	4	3,000
	MOGUL	5	60	48	14	10,000

Applications of the pulse generators include pulse X-ray generators, the generation of relativistic electron beams, various possible types of ion accelerators, spark chambers and, in particular, streamer chambers, dielectric breakdown studies and electromagnetic pulse generators of various kinds.

8. Concluding Comments

The field of high speed high voltage generators has seen a rapid development in the last seven years or so. This trend is likely to continue and systems an order of magnitude bigger than those mentioned above are within the range of real possibility. Approximate treatments have been developed that enable these systems to be designed with some confidence and relatively recent developments have enabled multichannel gaps to operate at such a level that the rate of rise of the pulse is essentially limited by the properties of the dielectrics available and not by the switches.

There is a rich field of interesting work waiting in the development of dielectrics with improved characteristics, particularly in the field of liquids. Understanding of the physics of pulse breakdown of media is also a fruitful area waiting to be exploited. The generators can be used to produce large relativistic beams of electrons and the study of the behaviour of these is both complicated and fascinating.

In concluding I would like to repeat my thanks to my colleagues at AWRE and the many other very able workers in the field in the United States and the UK.

These notes of necessity have had to be very compressed and I am only too well aware of the drastic simplifications that this has forced upon me. I am afraid I have had to leave out many aspects of all the subjects touched on in these notes, some of which may be of considerable importance in any particular application.

My sincerest thanks are again due to Mrs. V. Horne who has had to slave over a red hot typewriter, while disentangling my horrible syntax and impossible writing and spelling.

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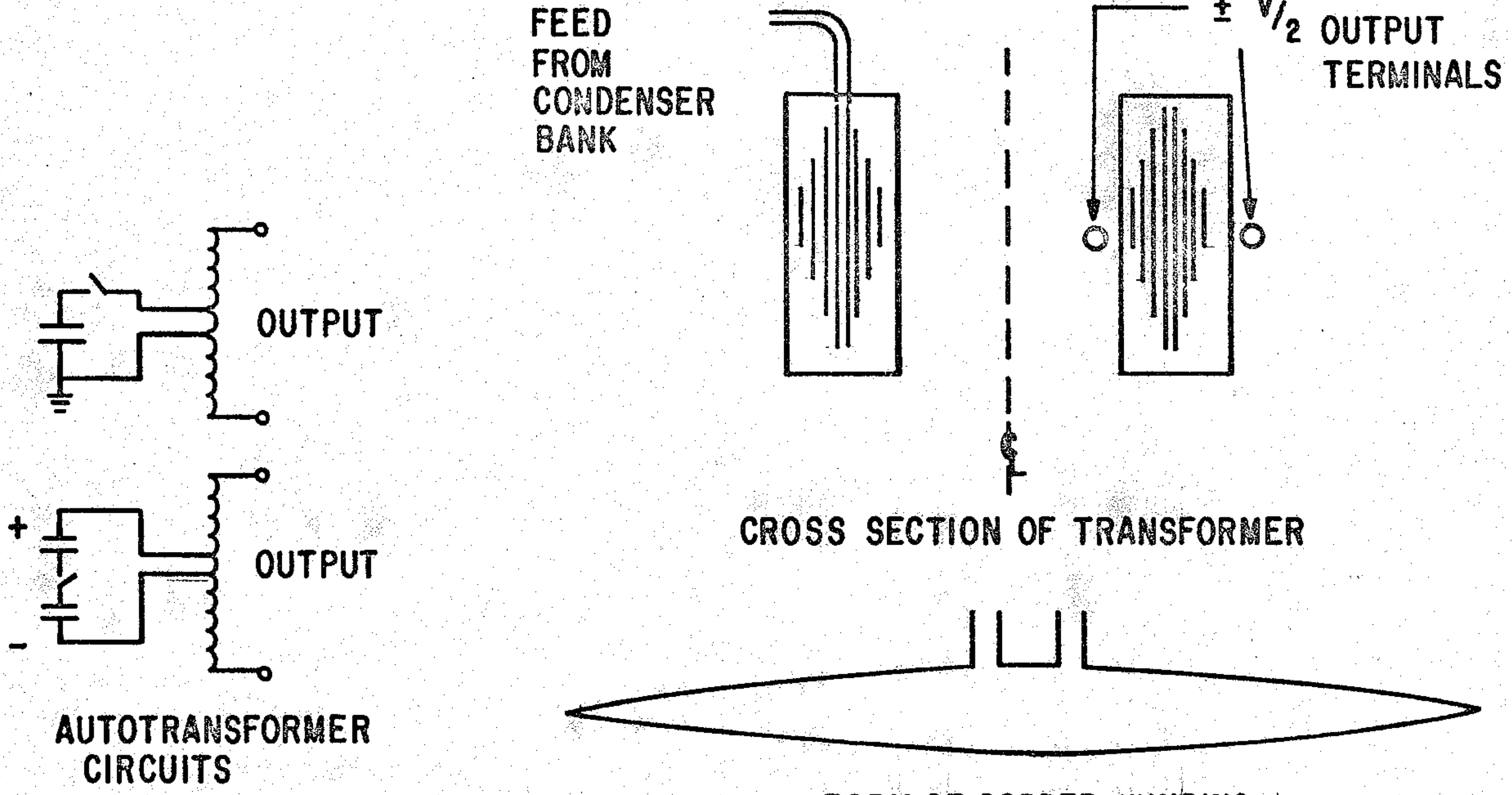
(16) J. C. Martin and I. D. Smith: "Electrical Switch having a Trigger Electrode whose Sharp Edges are sealed to suppress the Formation of Corona". Pat. No. 1,080,131.

(17) T. E. James: "A High Current 60 kV Multiple Arc Spark Gap Switch of 1.7 nH Inductance". CLM-P.212. Culham Laboratories, 1969.



CROSS SECTION OF TRANSFORMER

FORM OF COPPER WINDING

AUTOTRANSFORMER CIRCUITS

FIGURE 1 AIR CORED TRANSFORMER

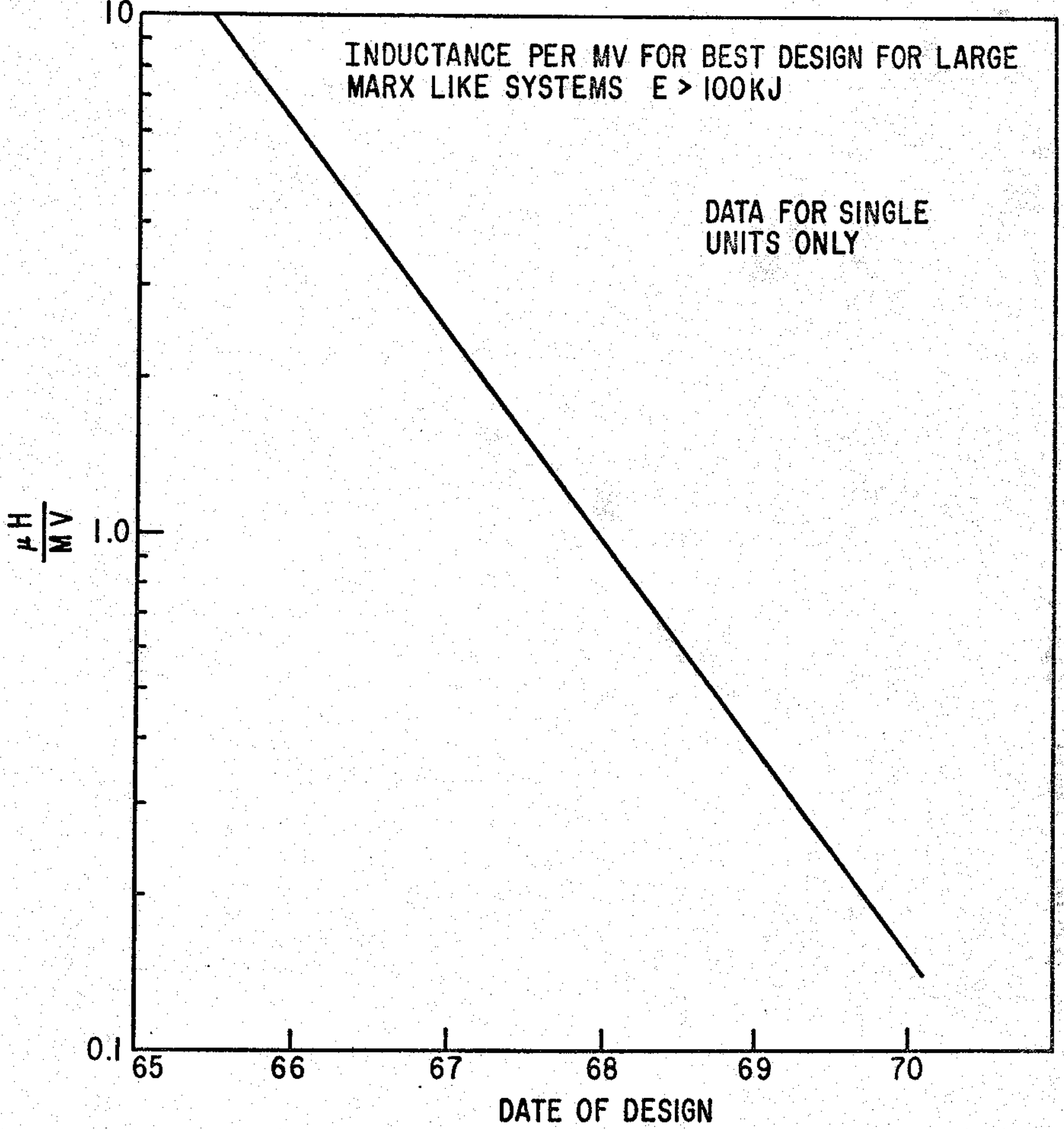

INDUCTANCE PER MV FOR BEST DESIGN FOR LARGE MARX LIKE SYSTEMS E > 100KJ
DATA FOR SINGLE UNITS ONLY
10
1.0
0.1
μH/MV
65
66
67
68
69
70
DATE OF DESIGN

FIGURE 2

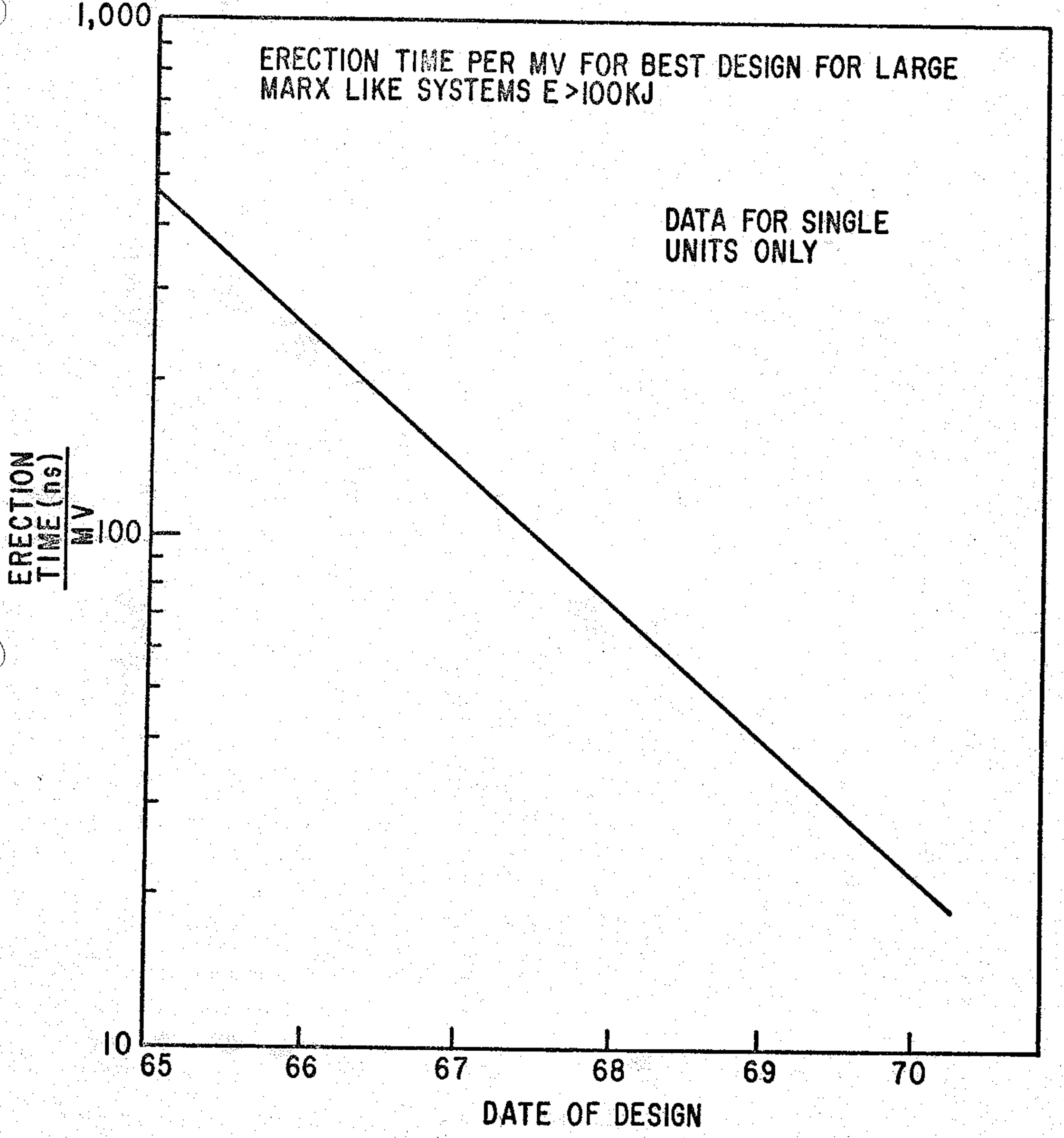

ERECTION TIME PER MV FOR BEST DESIGN FOR LARGE MARX LIKE SYSTEMS E >100KJ
DATA FOR SINGLE UNITS ONLY
ERECTION TIME (ns) / MV
1,000
100
10
65
66
67
68
69
70
DATE OF DESIGN

FIGURE 3

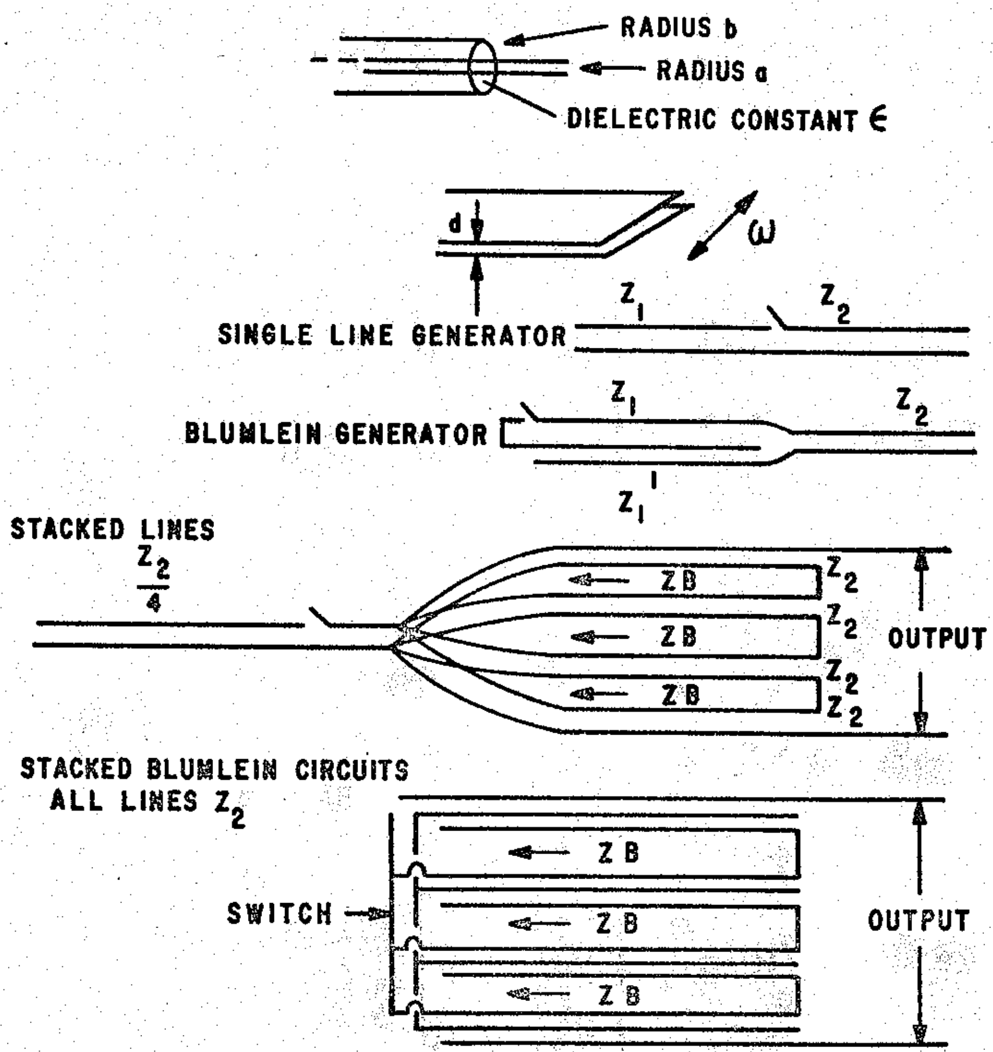
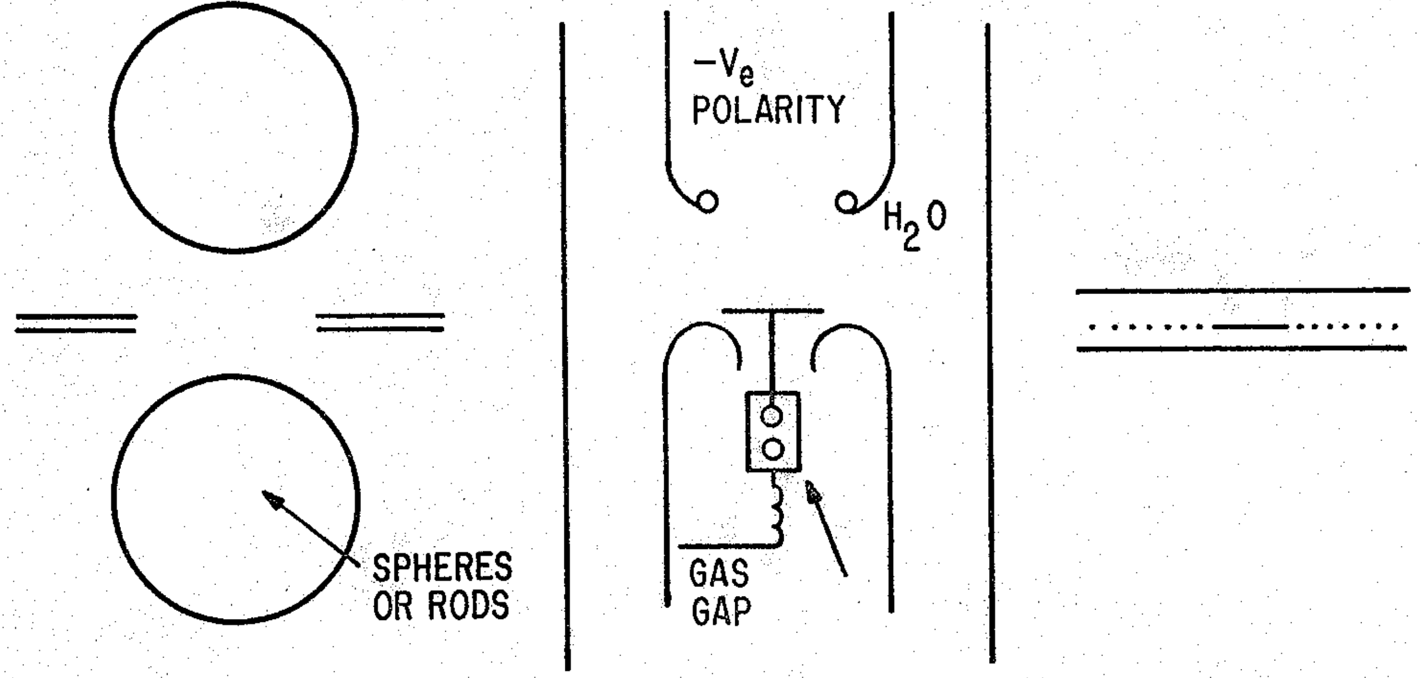


FIGURE 4 HIGH SPEED GENERATOR CIRCUITS



GAP RATIO ~ 2:1
GAS GAP

GAP RATIO ~ 7:1
LIQUID GAP

GAP RATIO ~ 2 1/2:1
SOLID GAP

FIGURE 5 FIELD DISTORTION GAPS

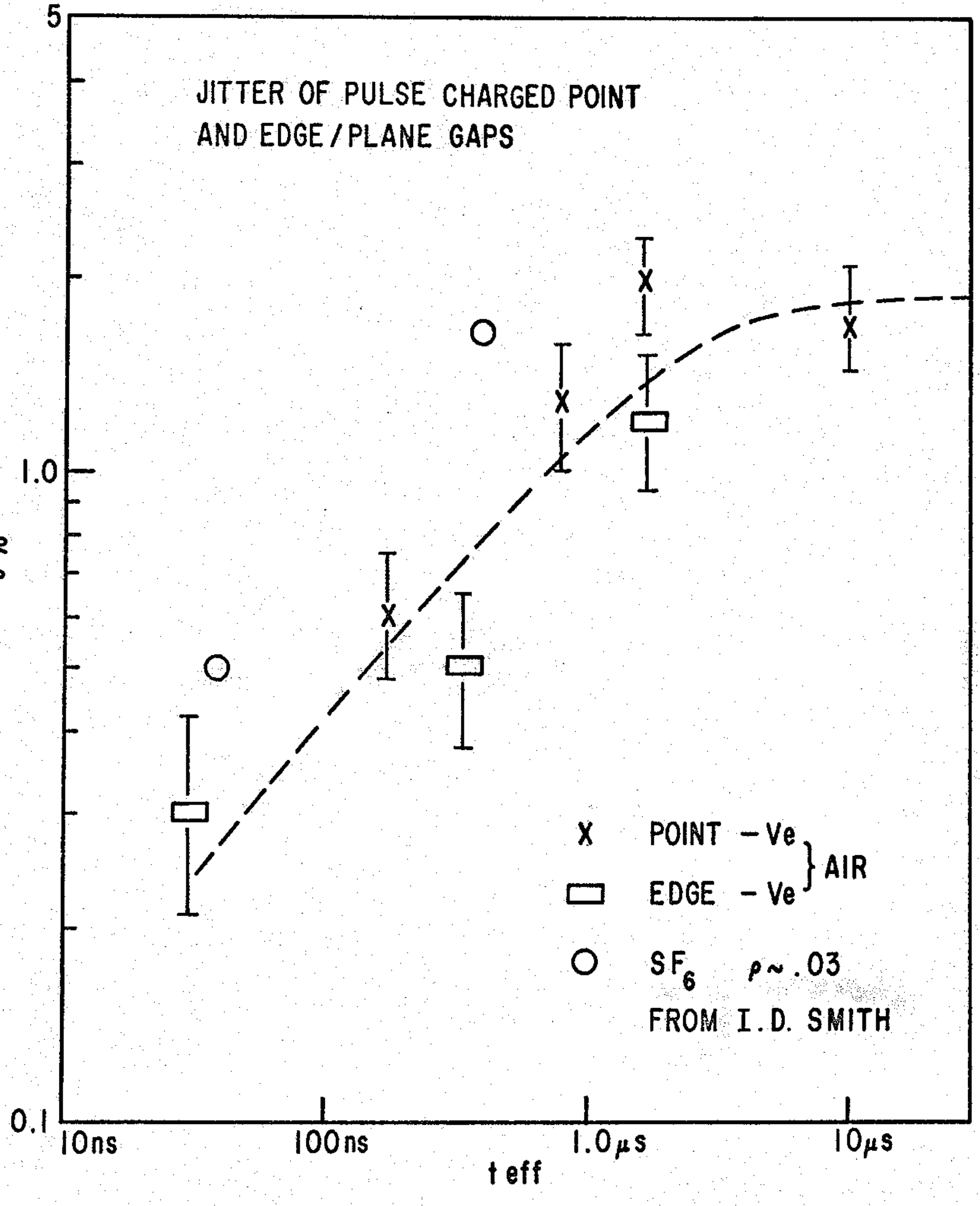

JITTER OF PULSE CHARGED POINT AND EDGE/PLANE GAPS
5
1.0
0.1
σ %
10ns
100ns
1.0μs
10μs
t eff
X POINT − Ve
EDGE − Ve
AIR
○ SF6 ρ ~ .03
FROM I.D. SMITH

FIGURE 6

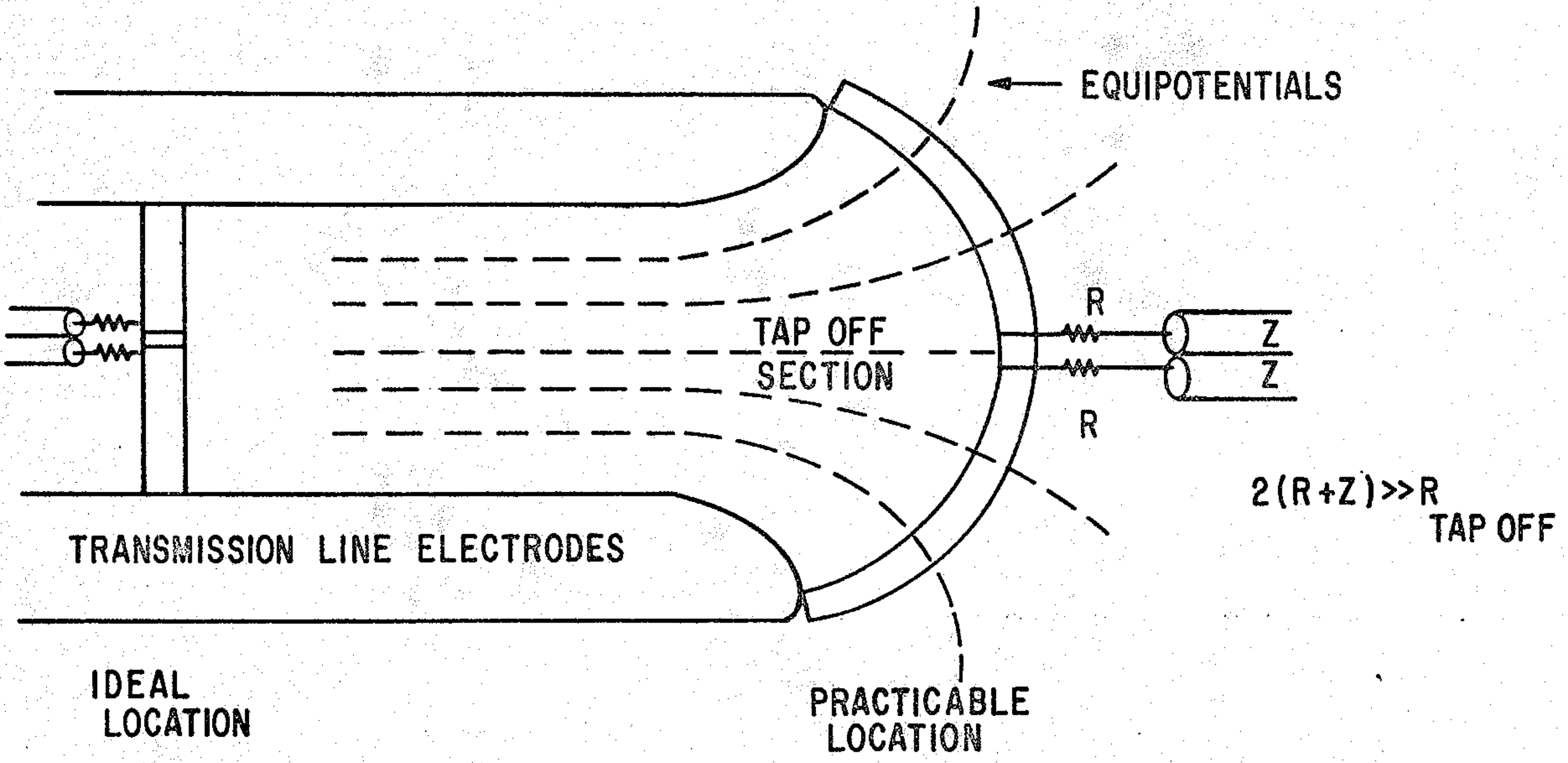


FIGURE 7 ATTENUATOR LOCATION