Switching Notes

Note 22

June 1973

HUN Lecture No. 2

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Originally published as
SSWA/JCM/HUN5

x = Major Items

HIGH CURRENT DIELECTRIC BREAKDOWN SWITCHING

x Rise time of pulses from spark gaps:
- a Inductive;
- b Resistive phase.

e-fold rise times, the relation (or lack of it) to 10%-90% rise time.

MULTICHANNEL SWITCHING

x Two element gaps:

DC Breakdown)
Pulse Breakdown) sphere, rail and edge plane geometries

x Three element gaps:

Brief review of some gap types, concentrating on the field distribution gap.

Versions in a solid
b liquid
and c gases.

Typical performance of some gaps:
- Jitter
- Inductance

and Constructional techniques.

SF_6 as a gap medium.

EXTRA TOPICS POSSIBLY TO BE COVERED

Pulse sharpening gaps for generating rates of current rise of 10^{14} amps per second with a gas gap.

The Corona gap - a versatile low voltage gap for use in trigger and delay circuits.

LECTURE NO. 2

The NPT techniques should be consulted for an explanation of the rise time parameter used that is the e-fold rise time or maximum slope time and its relation or rather lack of it to the 10 to 90% rise time. It is entirely reasonable that no one parameter can adequately specify the full range of pulse rise fronts that nature can provide. You pays your money and takes your choice but the resistive phase time is a maximum slope parameter and has to be handled as such, it is not a 10 to 90% time, so confirmed 10 to 90%'ers had better get down to it and derive their own resistive phase relationship, good luck. The inductive component of the rise time is fairly easily calculated to 10% or so, the more novel expression is the resistive phase term. The original note quantifying this is given in reference 1 and was written some 8 years ago. Numerous experiments in many laboratories have since tended to confirm the relation and I know of no serious disagreement with experimental observations. Further discussion of the relation and possible variants of it are contained in the multichannel note reference 2 which should also be consulted. The NPT note gives typical examples of the rise time of the pulse derived from dielectric breakdown, for circuits with a range of parameters, showing the relative importance of the two terms under various typical conditions.

The multichannel switching note reference 2 was the final outcome of a long series of endeavours to obtain reliable multichannel operation in gas switches. Multichannel operation had been achieved with intrinsic breakdown solid dielectric switches almost as soon as they had been invented. Multichannel operation of triggered liquid gaps had been obtained fairly easily but gas switches had proved obstinate. However, eventually the conditions necessary to obtain multichannel operation had been specified (at least to the author's satisfaction) and reference 2 was the final outcome. Reference 3 contains some recent experimental results and calculations for two multichannel edge plane gaps which show excellent agreement with theory and also give pulse rise times in very good agreement with the rise time calculations. Some three years ago a DC multichannel switch was operated on a portion of a megajoule bank and switched currents of 4 million amps, the gap operating with a number of channels in agreement with theory. Since then Physics International have developed a pulse charged pressurised SF_6 multichannel gap working at 400 kV and switching a 1 ohm line, which works very nicely and whose operation agrees with theory.

It should be mentioned that the theory of reference 2 applies to the operation of multichannel light sources, again a case where stabilising resistors or transit time effects are not used to increase the isolation of the channels as they form.

TWO ELEMENT GAPS

The DC breakdown of conditioned gaps in pressurised air can be calculated to a couple of per cent or so using the treatment given in reference 4. This treatment is useful up to ten atmospheres or more. But for high enough pressures the breakdown field becomes dependent on the material of which the electrodes are made (see for instance Craggs and Meeks "Electrical Breakdown of Gases"). Also, if large coulombs are carried by the gaps deconditioning can occur, and then the breakdown voltage of the gap will develop a significant jitter and also fall below that at which the same gap carrying much less charge will operate. However, high coulomb carrying gaps have been developed by Mr. T. James of Culham Laboratories which are now operating at up to 100 coulombs as start switches. In pressurised SF_6 gaps the electrode material dependency sets in at a few atmospheres (at fields comparable to those at which the effect appears in pressurised air). However, below this pressure the breakdown voltage is pretty linear with pressure and there is no significant gap length dependency in well designed gaps as there is inherently in air. DC operated pressurised SF_6 gaps both triggered and untriggered have been extensively studied at Physics International of San Leandro California for high coulomb operation. Also Maxwell Laboratory of San Diego have done much work in pressurised spark gaps with both pressurised air and SF_6.

For pulse charged gaps the mechanical strength of the electrodes does not have time to be very involved, so higher gradients can be achieved in two electrode gaps with both air pressurised and SF_6. Reference 5 summarises some experiments on pulse charged nearly uniform gaps. Gradients in pulse charged SF_6 at 6 atmosphere pressure can approach 1 mV/cm and represent one of the best switching media known under these conditions. Also covered in reference 5 is the external tracking problems of a rail two electrode gap, where a gap with a pressure body diameter of 2" with 4" long fins attached did not track at 800 kV. Reference 6 gives further details of this pulse charged gap and also shows that the velocity of light may contribute to the rise time of the pulse from such a gap when used in a relatively high impedance system. In lower impedance systems two electrode rail gaps can have low inductances. The single channel breakdown is arranged to happen in the central region of the rails and the rest of the electrodes act as pressurised gas insulated parallel-wire feeds to the spark channel. For few hundred KV operation inductances of less than 20 nH are obtainable with 30 cm wide gaps. With pulse charged two element gaps, edge plane arrangements can be used. Reference 3 describes the construction and performance of two such gaps. A modest extrapolation of the pulse sharpening gap data would give a less than 1 nano henry inductance for a meter wide gap under the operating conditions given in the reference.

THREE ELEMENT GAPS

Whilst the summary given in NPT notes is still an adequate summary of the situation, a few additional comments will be given of later work.

SOLID GAPS

Triggered solid multichannel gaps have been used in a low impedance water generator at voltages of up to 1 1/2 mV with no trouble. The slave triggered gaps were of the more advanced field distortion version where the edges of the trigger strap were sealed with unpolymerised araldite. The trigger pulse that fired these was provided by a master gap which was a version of the older stabbed polythene switch. The reason this switch is still used is that it is rather tolerant of odd tracking etc. effects which lead to pulses on it, the field distortion gap is rather sensitive to any small voltage excursions on the trigger strap. In addition, the stabbed polythene switch can have a wide range of breakdown voltages by simply changing the depth of stab and/or its polarity, thus the firing of the slave switches can be simply controlled by the stabbed master switch over a range of voltages.

LIQUID GAPS

Physics International now have multichannel triggered oil switches operating at 10 MV in transformer oil and also have extended the working voltage of multichannel water switching to 4 MV, both of these are of course pulse charged.

GAS SWITCHES

Maxwell Laboratories, Ion Physics of Burlington, Mass. and Sandia Corporation have all extended the use of pulse charged trigatrons to 3 MV or so, and operated several switches in very close proximity in what is essentially a multichannel mode of operation. Mr. I. D. Smith of Physics International has originated a version of the field distortion gap known as the V/n gap. This gap is pulse charged and uses pressurised SF_6 and the field distortion trigger electrode is very close to one electrode, typically at one tenth or one twentieth of the total gap spacing. Thus, a 2 MV gap needs only 100 kV or so of trigger volts to fire it.

Descending from the rarified levels of very high voltage pulse technology to the medium voltage level, the three element field distortion gap operates over a wide range DC charged. Versions have been used over the range 200 kV down to 10 kV with no difficulty. Working at 80% of the self break voltage the gaps can be triggered in ten nanoseconds or less with a jitter of fractions of a nanosecond. The breakdown time of such gaps can be calculated using point/edge plane breakdown relation given in Lecture No. 1. For the most rapid breakdown the offset or simultaneous mode of breakdown is best where the triggering electrode is spaced at roughly 2 : 1 in the gap and the two parts of the gap are brokwn at approximately the same time. A fast rising trigger pulse of amplitude roughly equal to the self break of the gap is needed, but as the capacity it is driving is low, this does not present serious problems. Recently, versions of a triggered rail gap with a self break voltage in air of 15 kV have been triggered down to 6 kV and it is hoped to extend the working range of these gaps downwards significantly further in the near future. Work in the States has shown that similar gaps pressurised can have jitters of ± 0.2 ns and it is considered that by using pressurised hydrogen, this could be reduced further, if it was ever necessary.

On the practical side pulse charged three electrode gaps need careful balancing, if capacitors are used to hold the trigger electrode at its proper potential so that the gap does not operate early because the potential division of this has been disturbed. This difficulty can be obviated by putting a small gap in between the trigger and the trigger pulse generator. Of course, this has to hold off the pulse charging waveform of the trigger electrode but this is not too difficult to arrange. When the trigger pulse arrives it breaks this isolating gap and operates the gap. The isolating gap can be used to pulse sharpen the trigger pulse as well if this is desirable. Some form of auxiliary surface discharge u.v. irradiator may be necessary to break the isolating gap at reasonable voltages and so avoid having to provide an unnecessarily large trigger pulse. The spacing of the isolating gap can also be halved by back biasing it with a half voltage DC supply of the appropriate polarity.

Three element field distortion gaps can also be used as clamp gaps ie. ones that fire at nearly zero voltage but this application is a wide area where much work has been done in the plasma physics research establishments and the reports of these should be consulted.

As an example of the triggering range and fast firing possible with field distortion gaps, figure 1 shows the self breakdown voltage of a gap with spherical 1" diameter ball bearing electrodes operated with a 0.5 cm gap for a range of SF_6 pressures. The figure gives the breakdown voltage and also the voltage at which the gap closes after a delay of 40 ns. The curve labelled amplitude of trigger pulse is the value at which triggering starts in the gap. In a real system a trigger pulse more than this voltage would be needed, especially as it is desirable to fire on a fairly rapidly rising portion of the trigger waveform.

A mention should be made that with atmospheric SF_6 in a gap with fairly small spacing, breakdown voltages above that deduced from the values in the literature can be observed. These occur after fairly frequent low energy shots and are believed to be due to the formation of insulating layers (possibly sulphur) on the surface of the electrodes. These layers, if they exist, can hold up to ten kV or so in extreme cases. Filling with air and sparking removes most of the effect until the layer reforms. Also shown in Figure 1 are the calculated curves as well as the observed data and the agreement is quite reasonable. The calculations are made using the edge plane breakdown relations. Figure 2 shows the triggering delay for the gap at 3 atmospheres, the calculated values are not shown in this case but have the general form of the observed curve.

The optimum trigger spacing ratio in the case was 0.3 : 0.7 and essentially independent of pressure over the pressure range investigated. Jitter measurements were not made for this gap (they are quite tricky in the sub ns range) but would be expected to be ~ ± 5% of triggering time.

If a 20 cm wide rail version of this gap were made and operated in a single channel mode it would have an inductance of a little under 10 nanohenries.

With a sufficiently fast trigger pulse (possibly involving a pulse sharpening gap) and a good feed system to apply the pulse to both electrodes, multichannel operation should be possible, but to date we have not had the time or the necessity to do this with a pulse charged gap.

INDUCTANCE

As a rough guide sphere gaps can have inductances around 50 nH without going to great lengths to reduce this, rail gaps (single channel) around 20 nH and edge plane pulse charged multichannel gaps a few nH. With multichannel operation rail gaps can get down to the same range but have the advantage of a considerably smaller resistive phase, and the disadvantage that it is significantly harder to make a uniform field gap multichannel, than it is a pulse charged edge plane gap. The above rough guides apply for voltages between about 10 kV and 200 kV. Above this limit low inductances can still be achieved but multichannel operation becomes more desirable. Liquid gaps (triggered multichannel) have inductances in the 20 to 30 nH range up to several megavolts while solids can have 10 nH or less fairly easily up to a couple of megavolts. For DC use at 30 kV solid gaps, such as are used in the high current banks at AWRE, have inductances of a few hundredths of a nanohenry when used in total widths of twenty feet or so.

QUICK CONSTRUCTIONAL TECHNIQUES

Using ball bearings (mounted on OBA screws if about 1 mm pitch per turn is required) and perspex plates simplexed together as spacers, an unpressurised air triggered gap can be made up in about 1 hour. Such a gap can be used up to 70 kV. Using perspex tube and simplexing semipermanently on end plates, a pressurised gap can be knocked up in about 2 hours. If access to the gap is required an end plate can be sawn off and resimplexed after the alterations have been made. To make unpressurised triggerable rail gaps takes a little longer as the brass rods have to be contoured at their ends (see reference 3 for details). Pressurised triggerable rail gaps with anti tracking guards take longer again, the time being of the order of 4 to 5 hours for gaps working up to 150 kV DC. Much of this time is in the pressure sealing of the several feed through points along the length of the rail electrodes. This requires fairly accurate drilling of the holes, something I cannot usually manage and I finish up using a file invariably. These seals can be demountable but as it is rarely necessary to remove the main electrodes, simplex over the feed throughs, suitably applied, can provide a quick final seal.

Up to 3 inch OD perspex tubing of 1/2 cm wall thickness is regularly tested to 100 psig (wrapped in rags in case it blows up) and used up to 60 psig. We have never had any gap disintegrate in this pressure range but the possibility should be borne in mind. The only occasion a gap did physically break was in a 2 MV pulse charged system working under oil at 300 psig or thereabouts.

A flashover occurred (probably across the outside of the gap in the oil) the shock from this cracked the perspex pressure vessel and the expanding SF_6 gas took out a face of the perspex oil filled box, with the obvious results.

Care is always taken in simplexing up pressurised gap bodies to clean and roughen the mating surfaces and to provide an adequate length of joint. The vapour from setting simplex can cause vapour crazing of some versions of perspex tube which have not been completely stress relieved. Either a flow of air or moistening the surfaces near the joint can alleviate this surface crazing. The ultimate solution is to stress relieve the tube by warming to about 80°C for an hour or two. Quite bad surface crazing has not been observed to reduce greatly the strength of perspex tube, but it seems desirable to avoid it.

SF_6 AS A GAP MEDIUM

Examples have been given of the very desirable properties of pressurised SF_6. For large coulomb operation brass electrodes are as good as more exotic materials, as far as data exists, and are much more easily worked. The SF_6 should be dried and the gas charged every few shots, if full the DC hold off voltage is required. As the hot decomposed gas rises, the gas should preferably be introduced at the bottom of the gap and extracted at the top. We have never experienced any trouble with the nasty decomposition products of SF_6 the volume produced per shot is minute compared with that of the average lab. For high rep. rate and for large coulomb use, a hose pipe stuck out of the window might be necessary. For pulse charged gaps, the removal of the decomposition products is much less necessary and flow rates can be considerably lower. Pulse sharpening gaps are described in reference 3 which covers the issue pretty thoroughly from the point of view of achieving high di/dt outputs. They can also be used in other circuits, but where the pulse being sharpened is not of great amplitude a small sphere gap can be employed. Such a gap will work at large gradients on a fast rising pulse but will also display at jitter in its closure voltage. If this is undesirable the gap should be UV irradiated, this will remove the jitter in breakdown voltage at the cost of reducing this significantly. A very quick way to make a UV irradiator gap is by placing a sharp metal edge on a few thin mylar sheet which is in its turn stuck down to an earth plane. This sub gap is fed by a high resistance (~ 10 KΩ) and coronas across the mylar producing UV which irradiates the main gap. Another way is to include a small insulated pin drilled through one of the spherical electrodes. The trigger pulse is fed to this pin and causes an arc between this and the main electrode, irradiating the gap as it overvolts it.

THE CORONA GAP

These are extremely useful little gaps, which very few, apart from ourselves, have learned to love and appreciate. Basically they are gaps operating at low voltages (typically 5 to 10 kV) which can be triggered by a 300 volt pulse via a 50 ohm cable fed to the trigger strap via a step up transformer. They normally are not used to handle more than a few joules but can provide several hundred amps of input current rising in 20 to 30 ns.

Used with a reasonable trigger pulse they can have jitters of less than 2% and firing times of 40 ns or less. We have used them to provide pick up immune combined delay and output pulse units which can be quickly and cheaply constructed. For instance in one application a seven gap unit (size 1-1/2 feet x 1 foot x 1/4 foot) provided six delayed outputs (delay 0.1 to 100 μseconds) three of which were used to trigger surface discharge, light sources and three of which directly produced the 8 kV (via a double blumlein circuit) pulse to operate a 20 ns Kerr cell.

With this system reflected light 20 ns multiframe photographs were obtained, which is quite an achievement in view of the fact that the optics were operating at something like f 150. While the units themselves are pick up immune they may have to be boxed in order to prevent them firing other low level systems, but in fact all the normal functions of delay, trigger pulse production, and even the scopes themselves can be done using these gaps. They are simple, cheap, robust and reliable and can be made in a few minutes, if the components are stockpiled, or an hour a piece starting from scratch.

Unfortunately we do not have extensive write up of them and Tommy Storr has kindly produced a brief description of them as we make and use them (reference 7).

A very old write up of a system using an early version was excavated from the filing system (the early cambrian strata) and is included as reference 8. There is also a patent referred to in the NPT notes, but I could not understand it. A sealed off version has been produced at AWRE by another section (reference 9) and works well, but to my mind one of the great advantages of the gap is its ease of construction and this, of course, is lost once you start encapsulating in glass. There is a further write up in an AWRE report (reference 10). If [redacted] this report is obtained there is a statement on page 4 paragraph five with which I do not agree in general, although in the particular set up the author used, it could have applied because of the way the pulse transformer was wound.

Improved versions of this gap have recently been developed and it is hoped to make considerably better performance versions shortly. The SSWA group should be consulted if anyone [redacted] becomes seriously interested.

A further reference has been unearthed which deals with an early version of the Kerr cell, light source arrangement. A copy of this is included as reference 11.

LECTURE NO 2 REFERENCES

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3. "Pulse Charged Line for Laser Pumping" J. C. Martin Circuit and Electromagnetic System Design Note 15, February 1973.
4. "DC Breakdown Voltage of Non Uniform Gaps in Air" J. C. Martin Dielectric Strength Note 16, June 1970.
5. "High Speed Breakdown of Pressurised Sulphur Hexafluoride and Air in Nearly Uniform Gaps" J. C. Martin Switching Note 21, February 1973.
6. Notes for a Report on the Generator TOM J. C. Martin SSWA/JCM/735/407.
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8. "Brief outline of Operation of Trigger Unit" J. C. Martin HUN 1.
9. "Triggered Spark Gaps for Image Tube Pulsing" R. J. Rout Journal of Sci Instr 1969 Series 2, Vol. 2, Page 739.
10. "The Performance of the Miniature High Voltage Spark Gaps used in the E14 Camera" B. R. Thomas SPA2/E14/BRT/71-5 AWRE Report.
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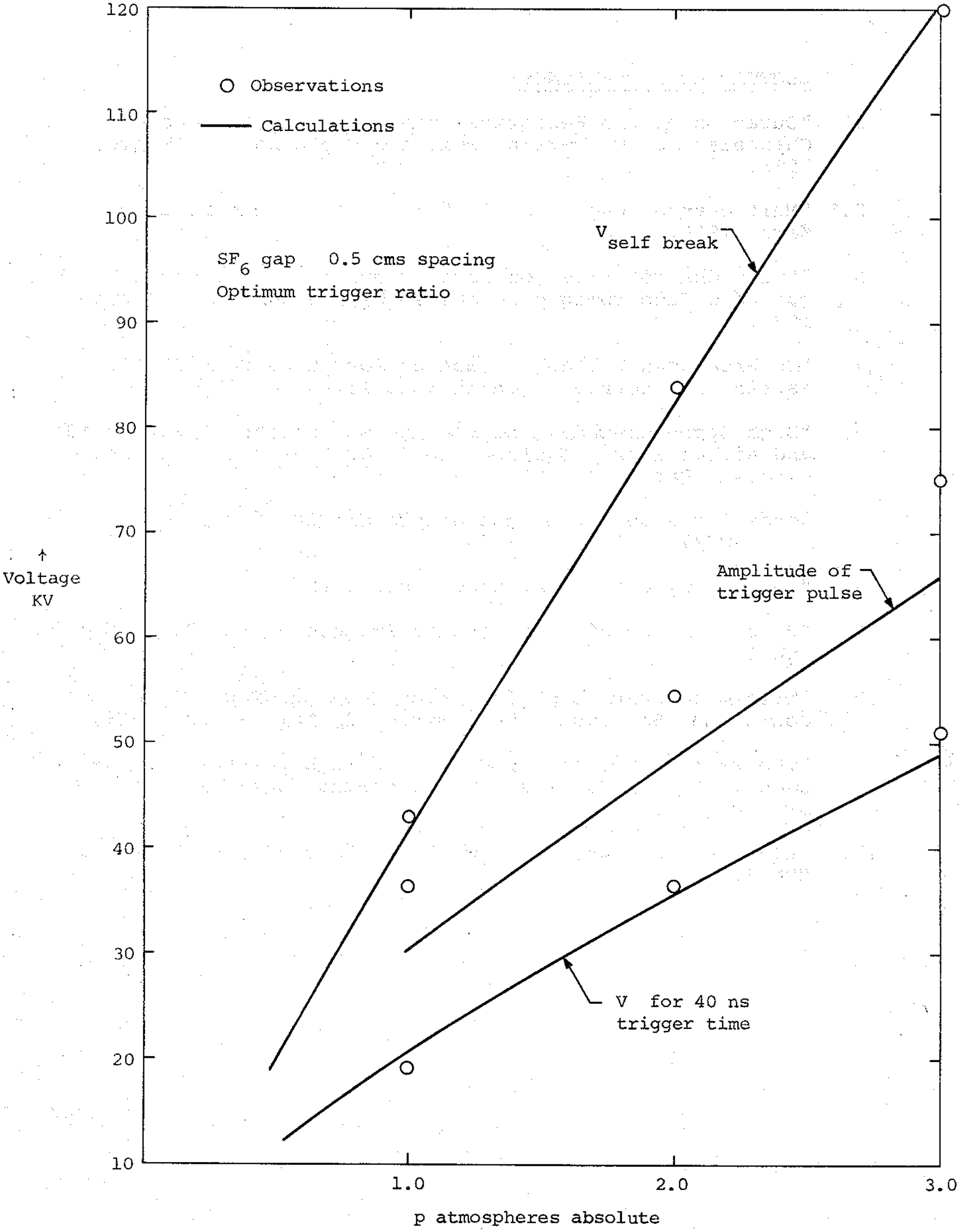

120
110
100
90
80
70
60
50
40
30
20
10
↑ Voltage KV
○ Observations
Calculations
SF_6 gap 0.5 cms spacing
Optimum trigger ratio
$V_{\text{self break}}$
Amplitude of trigger pulse
V for 40 ns trigger time
1.0
2.0
3.0
p atmospheres absolute

FIGURE 1

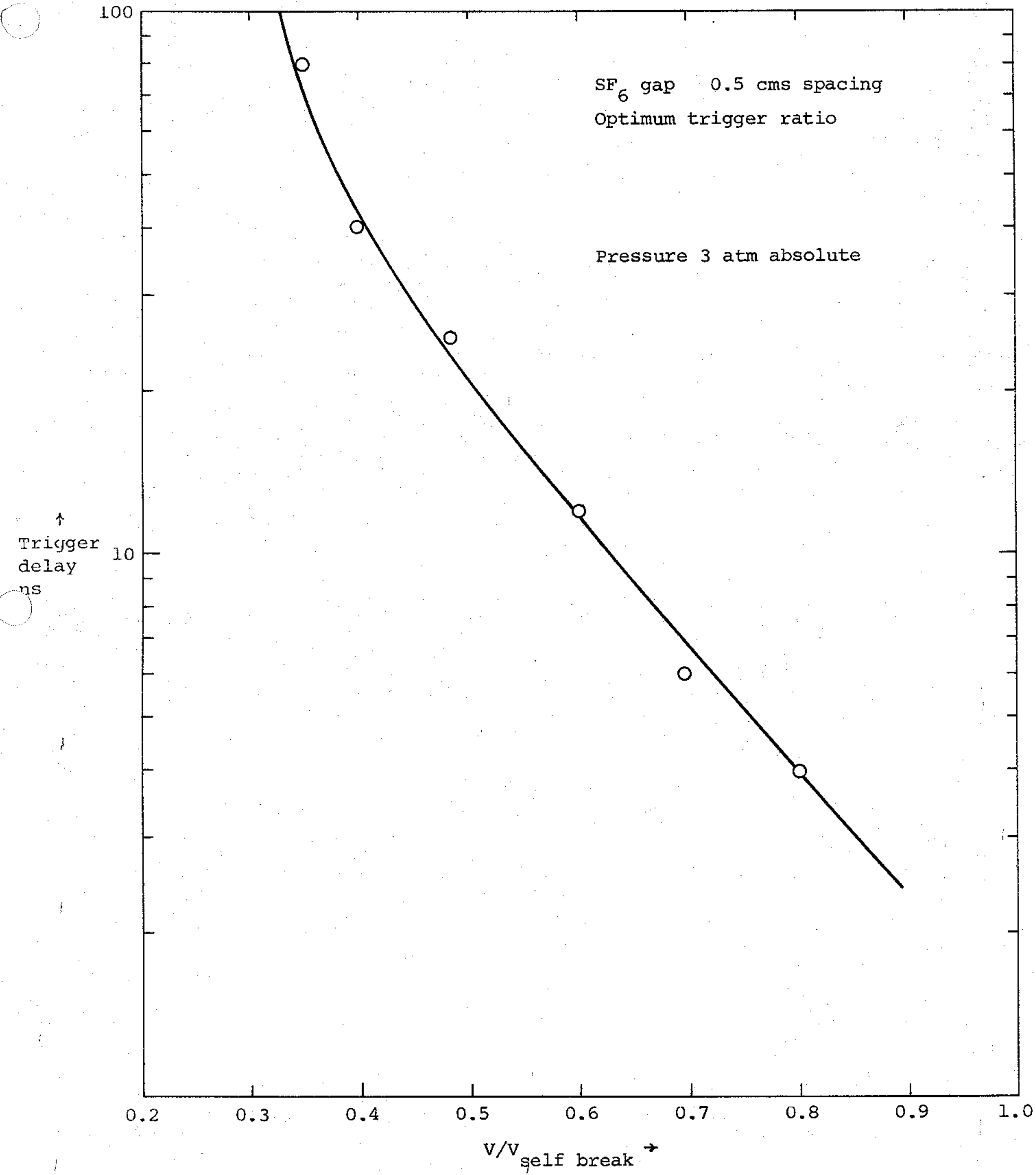
100
10
↑ Trigger delay ns
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
V/V self break →
SF6 gap 0.5 cms spacing
Optimum trigger ratio
Pressure 3 atm absolute

FIGURE 2