UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING

A METHOD FOR AN INVESTIGATION OF THE IMPULSE BREAKDOWN OF ELECTRICAL INSULATING OIL

A THESIS SUBMITTED FOR THE
DEGREE OF
MASTER OF PHILOSOPHY

by

R. J. Arnold

CONTENTS

ABSTRACT
FACULTY OF ENGINEERING
ELECTRICAL ENGINEERING

Master of Philosophy
A METHOD FOR AN INVESTIGATION OF THE IMPULSE BREAKDOWN OF ELECTRICAL INSULATING OIL
by Raymond James Arnold

A general introduction to liquid insulants is given with particular reference to mineral insulating oil. The composition of insulating oil is discussed with references to its uses as an insulant. A short review is included of previous work in the study of hydrocarbon liquid dielectrics in general and mineral oil in particular.

A detailed description is given of the design, construction and preparation of an oil filter system, a high voltage test cell including the electrodes, a high voltage impulse circuit and the control and recording apparatus required. Details are given of test procedures, sample preparation and results analysis.

Breakdown values are obtained for several oils of differing origins and characteristics, and these results compared with those of previous workers. A comparison is also made of the degree of preparation achieved by previous workers and the present work.

The design of the complete test system, the test procedures and the results are discussed in detail with a view to improving both design and procedure.

Some indication of further work which could be undertaken by the present equipment is given including modifications for future experiments. Possible experiments are outlined in view of some of the results obtained.

LIST OF FIGURES

ACKNOWLEDGEMENTS

I should like to thank the National Joint Advisory Council for the scholarship and the Southern Division of the Central Electricity Generating Board for granting me leave of absence.

My thanks are due to both the academic and technical staff at Southampton University and particularly to Mr. K. L. Morphew, my academic supervisor. I should also like to thank all those people who have helped in the preparation of this thesis.

LIST OF SYMBOLS

°A	(Length)	Ångstrom Unit
ASA	(Film Speed)	American Standards Association
°C	(Temperature)	Degree Centigrade
cms.		centimetre
"		inch
°K	(Temperature)	Degree Kelvin
KV		kilovolt
KΩ		kilohm
$^{\text{lb}}/\text{in.}^{2}$	(Pressure)	Pounds force per square inch
MV		Megavolt
MHz		Megahertz
MΩ		Megohm
mA		Milliamp
ml		Millilitre
mm.		Millimetre
mm.Hg	(Pressure)	Millimetre of Mercury
nS		Nanosecond
Ω		ohm
pF		picofarad
p.p.m.		parts per million
torr	(Pressure)	Millimetre of Mercury
μF		Microfarad
μH		Microhenry
μm		Micrometre

μs	Microsecond
V	Volt

A METHOD FOR AN INVESTIGATION OF THE IMPULSE BREAKDOWN OF ELECTRICAL INSULATING OIL

CHAPTER 1

INTRODUCTION

1.1 Liquid Insulants

Ever since the advent of high voltage engineering one of the greatest problems has been to supply adequate satisfactory insulation. In early days air was used together with porcelain and glass. It was found that a liquid often served the purpose better in that it was homogeneous, had a higher dielectric strength and kept moisture and dust away from the supporting structure.

Thus a need was created for a general purpose liquid insulant, this need being accentuated by the rapid growth of high voltage transmission systems, and high voltage technology generally.

A liquid readily takes up the shape of its containing vessel, and it is this fact which makes liquids desirable as electrical insulants. In taking up a shape the liquid provides a homogeneous insulating mass, which is in most cases the most useful form of insulation. There are normally no voids in which the local stress rises and causes small discharges which eventually cause complete failure, as happens in solid dielectrics. Hence complicated electrical equipment can be given homogeneous insulation very quickly and cheaply.

Insulation grading is achieved by using porous solids and impregnating them with a liquid insulant. Such a process allows the formation of homogeneous masses of different relative permittivities resistivities and dielectric strengths, depending upon the materials used.

Since a liquid will form an intimate contact with the walls of its containing vessel the heat transfer from any immersed equipment to the walls of its containing tank will be very good. This makes a liquid insulant even more useful since it can also be employed quite efficiently as a coolant.

1.2 Mineral Oil

A convenient general purpose insulant is pure mineral oil free from moisture and solid particles. This is reasonably plentiful and cheap to obtain and process, and although other liquids are used, mineral oil is the most popular at this time.

Mineral oil has a high dielectric strength which depends greatly on the amount and type of contamination in the oil. Very pure oil, as can be obtained in a laboratory, has been subjected to electrical stress of over 10^5 volts/mm without failure (1.1). The viscosity is only about 30 centi-poise making it easy to impregnate material with very small pore size.

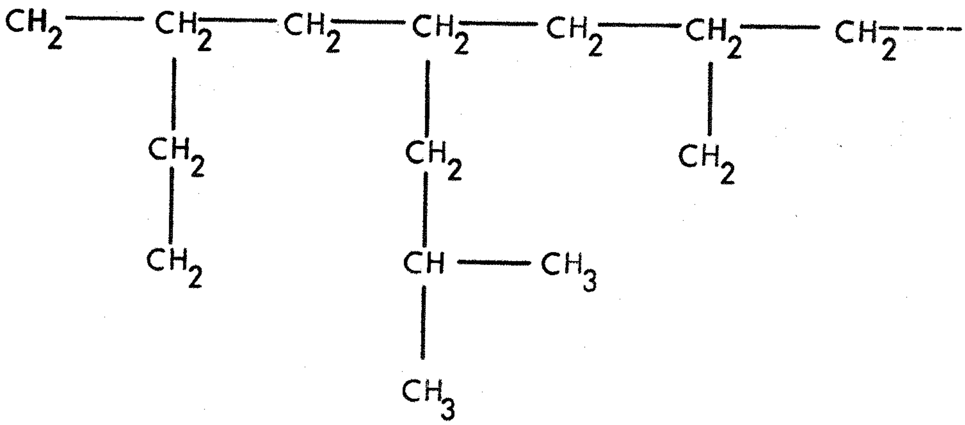
1.3 Composition of Mineral Oil

B.S. 148 describes an insulating oil as "pure hydrocarbon mineral oil, clean and free from matter likely to impair its properties and without additives". It also goes on to say that any oil to B.S. 148 may be mixed with any other whatever its origin.

The composition of crude oil will vary depending upon the geographical region from which it is obtained. A molecule of oil

$-CH_2-CH_2-CH_2-CH_2-$

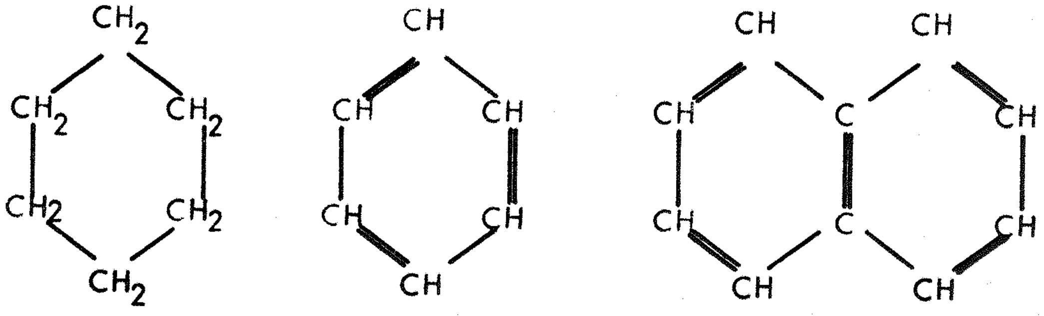
Paraffins



Iso - Paraffins

Naphthenes

Aromatics



Cyclohexane

Benzene

Naphthalene

FIGURE 1.1 TYPICAL HYDRO CARBONS EXISTING IN MINERAL OIL may contain one or all of any of the basic hydro-carbons shown in figure 1.1. Crude oil will contain substances which are either detrimental to the oil as an insulant or likely to damage equipment with which it has contact. These impurities, which include water, the ketones and esters, are removed from the oil during its initial refining.

An oil company marketing an insulating oil will wish to control quite closely the quality of its product, but the source of supply may vary from day to day; consequently blending is necessary.

The design of plant at high voltage calls for compact insulation to bring both size and cost down. It is therefore important to improve the breakdown strength of oil as much as possible. To do this it is necessary to understand the mechanism of electrical breakdown of liquids and in particular, mineral oil.

1.4 Statement of Problem

Much of the previous work on the electrical breakdown of insulating oil has been done with small electrode systems and electrode spacings of the order of 10^{-5} metres (1.1, 2.4, 2.13). Some work has been done with long gaps but in general very non-uniform fields have been used and the sample has been relatively impure (2.8,2.9).

The object of the present work is to establish a technique to enable the previous work on small gaps to be extended to gaps of the order of 10^{-3} metres.

The problem consists of the designing and construction of a uniform field electrode system for gaps up to 10^{-3} metres and to devise a means of purifying the oil to a high degree.

1.5 Approach to the Problem

A test cell was designed and constructed in such a way as to allow both impulse voltage breakdown measurements to be made and direct voltage and current readings to be obtained. A detailed explanation of the construction will be found in Chapter 4.

The electrodes were fabricated from stainless steel and shaped to give a uniform field as detailed in Chapter 5. To ensure that the oil sample reaching the test cell was as clean as possible the filter system described in Chapter 3 was constructed.

It was also necessary to design and construct a control system to enable the impulse generator to be used in conjunction with high speed recording equipment.

Tests were then conducted on the completed equipment to demonstrate correct operation of the system before any measurements were made on liquid samples.

Breakdown tests were then carried out on cleaned oil under very carefully controlled conditions and the results obtained are given in Chapter 11.

CHAPTER 2

PREVIOUS WORK

2.1 Mineral Oil

Although the dielectric properties of insulating oil have been under investigation for some time, see for instance Whitehead (2.1) most serious work has been during the last twenty years or so.

Hoover and Hixon (2.2) in 1949 investigated the variations in breakdown strength with both temperature and pressure. Their ideas were that the breakdown strength depended upon the size, number and position of small bubbles of gas or air in the dielectric. Hence they concluded that any temperature dependence was due to the variation in solubility of air in the oil and the pressure dependence was due to the variation in bubble size. Their experiments included degassing the oil in an attempt to show that a rise in strength was obtained when the possibility of bubble formation was removed.

Martin and Thompson (2.3) described in detail an apparatus for filtering, drying and degassing oil. They took the view that insulating oil however carefully prepared, was always contaminated to a greater or lesser degree and hence any serious work on the electrical properties of oil must be preceded by cleaning of the oil. Incorporating the test cell into a closed circuit filter system allowed many cycles of purification without risk of re-contamination.

Watson and Higham (2.4) using a system similar to that described in (2.3) above, carried out tests on insulating oil over a wide pressure range (a few mm Hg to 500 lb/in^2) using direct, alternating and impulse voltages and came to the conclusion that several breakdown mechanisms operate. During long periods of application of a high field there is time for any particle impurities to cause a breakdown. An impulse voltage breakdown however is probably similar to that seen in pure liquids. Between these two regions is a further transition region where the breakdown is initiated by cavitation and hence is pressure dependent.

P. G. Priaroggia and G. Palandri (2.5) showed that the breakdown is practically independent of the saturation pressure provided that a perfect equilibrium is reached between the gas dissolved in the oil and the free gas above the oil surface. It should be noted that Watson and Higham made no note of awaiting such equilibrium conditions. Their results, showing variation of breakdown strength with pressure would therefore probably not agree with those of Priaroggia and Palandri.

Hancox and Tropper (2.6) working on the impulse breakdown of oil found that the electrode material influenced the breakdown voltage. Also it was found that the method of testing and preparing the test cell affected the result. They put forward the theory of micro-bubbles on the electrode surface which locally raise the stress and cause a small discharge thus initiating a breakdown.

Darveniza (2.7) said that breakdown levels for oils were still well below those of pure liquids and evolved a method of distilling the oil in order to purify it. The objection previously raised to this method was one of oxidation. Darveniza however used a flash distillation process at very low pressure and successfully circumvented this problem. Using this method of purification and very small electrode spacings (75 - 125 micron) electric strengths of 132 kV/mm, were obtained in small samples of oil. The rate at which distillation could proceed was very slow, being of the order of 50 - 100 millilitres per hour.

At C.I.G.R.E. in 1962, J. I. Skowronski(2.8) described how the differences in breakdown strength between extremely pure insulants and those of technical purity may be due to particles. To cause breakdown such particles need not be conducting, but just of a higher permittivity. He also explained that different mechanisms were almost certainly responsible for breakdown in the pure and impure states. The effect of impurities causing breakdown will mask any molecular process. Particles of water were also observed to play an important part in the breakdown of impure liquids.

Sletten and Dakin (2.9) studied the effect of varying the amount of purification of the oil and used a long gap. The conclusion, that even with the purest oil obtainable the impurities still caused the breakdown, was based on the fact that no transition was noticed in the breakdown strengths as the oil was purified. They suggested that a small gas bubble is formed by electrolysis of a contaminant or by evaporation of a water droplet, and breakdown is propagated within this gaseous inclusion.

An important observation that may be made about these researches is that what each worker has meant by purified oil differs considerably, hence it is difficult to compare results. For example, the oil Darveniza used was very pure compared with the purest obtained by Sletten and Dakin who used an open test cell.

Hancox and Tropper and more recently Zaky et al (2.10) have shown how the preparation of the electrodes and the cell, the material of the electrodes and the test procedure can alter the results greatly. Skowronski also demonstrated how the shape of the electrode system will influence the breakdown voltage of a particle contaminated liquid.

The breakdown of insulating oil is a very complicated and not well understood process. It is for this reason that many workers use simple liquids of known purity in an effort to investigate some of the basic processes leading to breakdown. Efforts to correlate such results with those obtained with complex liquids however are being made with some degree of success.

2.2 Simple Liquids

Work on the breakdown of simple[≠] liquids has been carried out for a very long time, see for instance Hirobe (2.11) or Güntherschulze (2.12). Much of the earlier work was concerned with problems of purification and the removal of contaminants.

Lewis (2.13) studied breakdown in hydrocarbons with direct voltage under carefully controlled conditions. The now familiar closed circuit purification system was adopted and careful preparation of the electrodes was mentioned.

[≠] i.e. liquids which consist of only one sort of molecule and not a mixture of many substances.

A system of rapidly removing the test voltage on breakdown was employed to prevent excessive damage to the electrodes or liquid sample. This took the form of a thyratron clamp switch which shorted the test gap within 0.7 μS of breakdown.

The voltage used for these experiments was of the order of 25 kV with gaps of 10^{-2} to 10^{-1} mm.

Very clean liquid systems ; meticulous electrode preparation ; limited discharge energy ; low voltages and small gaps has been a feature of many of the studies since this time.

Lewis reported very little dependence on electrode material but noted that metals with stable oxides or no oxides, e.g. Al and Cr, gave the least scatter in results. A marked dependence on gap length was noted; the breakdown stress being higher at very small gaps. It was also reported that an increase in breakdown stress was obtained with hydrocarbons having a longer chain length.

To explain the lack of dependence on electrode material, Lewis considered that two conditions were necessary for breakdown;

(a) electron emission from the cathode, and

(b) electron multiplication in the liquid.

The values of electric stress for these two mechanisms are similar but if the field required for multiplication is reached before that required for electron emission then an electrode dependence would be noted. If the field required for electron emission is reached before overstressing of the liquid occurs, then the final breakdown will depend only on the field required for multiplication, and hence there will be no cathode dependence.

In order to support this theory of a Townsend type electron avalanche, Lewis suggested a form of energy barrier. Electrons with low energies will lose their energy to the molecules by exciting the bond vibrations. The now slow electrons are then trapped, forming negative ions of low mobility.

Higher energy electrons will accelerate and ionize the liquid and electron multiplication will take place. The fields required for multiplication will not be directly related to the ionization potential, because the vibrational energy barrier will cause the effective mean free path between ionizing collisions to be longer.

If the gap is small, then a very high stress is required to develop the avalanche and hence for very small gaps (10^{-3} mm), there should be a minimum voltage below which no breakdown can occur.

An electron avalanche from the cathode may not always cause a breakdown, a further model is suggested of a positive space charge growing towards the cathode (thus enhancing the field) into which the electrons fall. This positive space charge will form a streamer and thus breakdown will occur.

Bragg et al(2.14) were able to demonstrate some of the effects that the cathode has on the breakdown strength by using a liquid cathode whose ion emission was reproducible and calculable from the concentration of the electrolyte used.

A current in the gap will depend on the cathode emission and the properties of the dielectric. At low field strengths all the charge emitted by the cathode is transferred to the anode. At high fields the emission is much greater and the current depends only upon the dielectric properties.

A cathode which emits strongly at low fields will take the system into 'space charge limited' conditions producing non-uniform fields, and low breakdown strengths. If a cathode has no appreciable emission however, until fields approaching the breakdown field, then no distortion occurs and breakdown occurs at this value.

It is pointed out that in the case of metallic cathodes this theory may not be appropriate; the experiment was limited to the use of ion emitting cathodes.

Crowe (2.15), by investigating the formative time lag to breakdown attempted to show that breakdown depended upon some charge species crossing the gap; he considered positive ions and electrons.

By showing that the time to breakdown was independent of hydrocarbon chain length it was demonstrated that positive ions do not contribute to the breakdown. The ion transit time is much greater than the measured time lag and will increase with chain length.

It was considered that the breakdown was propagated by an electron avalanche, the apparent velocity of which gave electron mobilities an order of magnitude down on those expected.

It is likely that electrons in a liquid spend part of the time trapped or attached to neutral hydrocarbon molecules, and only occasionally break away as free electrons under the influence of an intense electric field. The measured mobility therefore would be somewhat smaller than that of a free electron and yet insensitive to variations of molecular size.

Ward and Lewis (2.16) interpret Crowe's results in a different manner by proposing a statistical time lag. The role of the cathode was demonstrated by showing how the statistical time lag varied with cathode conditions. A roughened cathode which should give better emission also gave low and consistent time lags, whereas a polished cathode gave long and erratic time lags.

Estimation of a formative time lag gave results for the avalanche velocity an order of magnitude faster than those of Crowe; this is more compatible with the anticipated mobility of electrons in such a liquid.

Swan and Lewis attempted to show how the measured electric strength of liquid gases depended upon electrode conditions (2.17). Different electrode materials were used with various thicknesses of oxide and two possible mechanisms were suggested, both depending on the formation of negative ions.

First it was suggested that electrons from the cathode formed negative oxygen ions; the oxygen being present as an impurity. As such an ion approaches the anode, a strong field will appear across any oxide layer present. This field may ionize any adsorbed molecules or extract positive metal ions from beneath the oxide layer. These ions then travel to the cathode and produce more electrons and hence lead to breakdown. Alternatively, the negative oxygen ions may be neutralized at the anode thus forming a layer of oxygen at the surface. This oxygen layer will affect the production of positive ions which may lead to an avalanche and breakdown.

Since this work was done at 90°K, Schottky emission from the cathode was not considered, electrons present are those produced by the positive ions as 'secondary electrons'.

Chadband and Wright (2.18) carried out optical studies of a gap prior to breakdown and found a region of changed refractive index. This region is propagated from the point cathode of the gap and grows to bridge the gap, whereupon an arc is formed.

It was suggested that this region represented the increase in thermal energy of the liquid molecules, which is brought about by electrons emitted from the cathode colliding with the molecules and exciting their bond vibrations. The thermal expansion of this region would cause a density change which could be observed as a change in refractive index.

This observed region represents an electron cloud moving towards the anode, and will be a weak plasma with a high field at its boundaries able to produce high energy electrons.

By increasing the gap voltage the rate of propagation of this region was greatly increased. This suggests that at high field strengths electron mobilities are increasing rapidly with increasing field strength.

Although most breakdown and conduction studies have been carried out using hydrocarbons, Brière (2.19) has recently shown that polar liquids and weakly ionic liquids may be studied. By using an ion exchange membrane, such liquids may be deionized, and resistivities of the order of 10^{12} ohm cms. have been achieved. For water, after deionization, breakdown strengths of up to 1 MV per cm, have been obtained. This work demonstrates how pure polar liquids may be obtained.

Kok in his book (2.20) attributes breakdown of liquid insulators to the impurities contained in them. These impurities are in the form of particles, having a diameter from 15°A to 500°A, which form a colloid with the liquid. Kok examines in great detail the behaviour of such colloids under electric stress. Eventual breakdown is ascribed to the formation of complete particle bridges between the electrodes, relationships are derived showing electric strength as a function of particle size.

Krasucki in two recent reports explains many results obtained by other workers in terms of small conducting particles present in the liquid (2.21), (2.22). Particles of the size 200°A to 300°A are considered and both breakdown phenomena and conduction currents are explained.

In the case of breakdown, a series of very elegant experiments demonstrate the dependence on viscosity and hence some form of instability in the liquid. This instability is shown to be a bubble of vapour in which a discharge takes place leading to total breakdown. A bubble would be formed at a point of zero pressure in the liquid which could be formed in one of two ways. A microscropic particle on an electrode will gain charge from the electrode until the force acting on it reaches a value at which it tends to leave thus generating a point of zero pressure. The other method suggested is from a consideration of the liquid-particle interface. Any charge at this surface will tend to lift the liquid from the particle, and when this force is equal to that due to surface tension and the hydrostatic pressure, a vacuous cavity will be formed.

Conduction currents were explained by the action of small conducting particles moving between the electrodes. It was shown that such a theory can explain most of the observed phenomena to date.

2.3 Summary of Breakdown Processes

There is no single theory of the electrical breakdown of liquid dielectrics, which satisfies all the known experimental facts. It is clear that any one of several mechanisms could cause breakdown. It is useful therefore to summarise the possible explanations currently considered.

There are possibly three main groups of mechanisms with the second group having a large number of causes :-

(1) Conducting or high permittivity particles as an impurity.

(2) Some form of inhomogenity leading to instability.

  (a) Ionic impurities.

  (b) Liquid globules.

  (c) Gas bubbles.

  (d) Small particles.

(3) An electron collision process.

(1) Conducting or High Permittivity Particles

Any conducting particle or one of high permittivity, (i.e. higher than the liquid), will be attracted to the point of maximum stress. Such particles include metal dust (either from previous breakdowns or as a result of polishing) and moist fibres (often cellulose). If there are enough of these particles present they will eventually line up to form a bridge across the gap in a region of high stress. This bridge will draw a large current resulting in local heating and complete breakdown.

The presence of such gross impurities will cause early breakdown of a liquid dielectric by the above method and any other breakdown mechanism will be completely masked.

(2a) Ionic Impurities

Although there is always a small current in the liquid due to field aided dissociation of the liquid molecules, this is insufficient to cause breakdown. If there are present large concentrations of ionic impurities, then the liquid will behave as a weak electrolyte.

The resulting increased current flow will lead to local heating and vapourization of the liquid. Such vapour bubbles rapidly promote partial or complete breakdown.

(2b) Liquid Globules

A small globule of a foreign liquid held in suspension within the bulk of the insulating liquid will be acted upon by any externally applied electric field.

The globule, normally spherical, will become a prolate spheroid. It can be shown that if the permittivity of the globule is more than twenty times that of the main liquid, then the globule is in fact unstable above a certain value of applied field (2.23).

At this field the globule rapidly elongates until it bridges (or nearly so) the gap and breakdown occurs.

The distorted globule will cause the insulating liquid to experience a much enhanced field. In this region of enhanced field some other mechanism then completes the breakdown process.

(2c) Gas Bubbles

Micro-bubbles present in the liquid will remain in suspension for long periods. The application of an electric field will, at some critical value, cause ionization of the gas in the bubbles. Ions thus formed may now be accelerated within the gas bubble and cause bombardment of the bubble wall. This energetic bombardment will cause local vapourization of the liquid, hence the gaseous cavity will grow until it bridges the gap and breakdown occurs.

If the field is sufficient, a discharge will take place within the bubble leading to local de-composition of the liquid. These de-composition products cause a lowering in strength which will lead to breakdown.

(2d) Small Particles

A small particle on the surface of an electrode will represent a protrusion of the electrode. This will produce a local enhancement of the electric field many times that of the main field. The enhanced field will promote more electron emission if the electrode is a cathode, this emission causing localised heating of the liquid. The liquid is vapourized and a bubble formed. Now a discharge may take place within this bubble leading to breakdown.

Alternatively, the particle will become charged, by virtue of being in contact with the electrode, at the same polarity as the electrode. A force is exerted between the particle and the electrode, tending to part them.

At some critical field they part, leaving a void of zero pressure between them, which is filled with liquid vapour, a bubble is formed. Breakdown will follow as above, since a discharge within the bubble will produce de-composition products, local heating and rapid bubble growth.

Small particles will remain in suspension and drift around depending upon convection currents, applied fields, etc. Charge at the liquid-particle interface will cause the liquid to lift off the particle in the same way as the particle lifted off the electrode surface. The electrostatic force must be equal to the sum of the liquid and surface tension pressure for this to occur. At such a critical field, a point of zero pressure will be generated at the liquid-particle interface and hence form a vapour bubble.

(3) Electron Collision Process

At the values of breakdown field being currently investigated (10^5 to 10^6 volts per centimetre) electron emission can take place. Such field aided emissions are explained by Schottky and Fowler-Nordheim type mechanisms.

Enhanced electron emission from localized sites on the cathode could be ascribed to one of several causes :-

1. Micro- projections left after cleaning and polishing,

causing a greatly enhanced field.

2. Small insulating particles on the surface may have a forbidden energy band at the fermi level of the surface, with an occupied state above it. The applied field will tilt this band thus allowing electrons to tunnel through the lowered potential barriers.

3. Positive ions arriving at the surface will not be discharged immediately, thus high extraction fields will exist which will enhance electron emission.

Electrons moving through the liquid will be involved in collisions with the liquid molecules. If an electron possesses a high energy (10ev), then ionization of the molecule can take place; however very few electrons will be this energetic. Most of the electrons will give up their energy by exciting the molecular bond vibrations. The rate of energy loss will therefore depend upon the nature of the molecular bonds and the liquid density.

An increase in bond vibration can be regarded as a rise in temperature of the liquid. Thus a cloud of electrons will move across the gap. Some electrons reach ionization energy and produce positive and negative ions and the region of raised temperature becomes a weak plasma. No field will exist within this region and electrons will be accelerated only at the boundaries. The region is however propagating towards the anode, and so the field available for electron acceleration is increasing.

This cumulative process rapidly leads to the ionized region bridging the gap and breakdown occurring.

If a liquid insulant is required with a high value of breakdown field then several general requirements may be noted.

The liquid should be as free as possible from solid particles of all types. Krasucki, it should be noted, considers particles of 170°A in diameter to be important.

Dissolved gasses in general should be reduced to the minimum. Any micro-bubbles of gas forming in the stressed liquid will lead to breakdown.

Water will moisten any solid particles present and also lead to an instability due to its high permittivity (80).

Ionic impurities or molecules with a high dissociation rate must be removed. It is shown that an insulating liquid will behave as a weak electrolyte if only a few free ions are present, (2.24).

These requirements only consider the condition of the chosen liquid and do not attempt to specify the physical or chemical properties of the liquid.

CHAPTER 3

PREPARATION OF THE OIL SAMPLE

3.1 Requirements

The filter system was designed to satisfy the following requirements, which were considered necessary to clean and purify the sample.

1. To be capable of filtering solid particles from the oil whose size exceeded 1 micron diam.
2. To be capable of subjecting an oil foam, at a temperature of 60°C, to a vacuum of 10^{-2} torr.
3. To include the test cell and a pump in a closed circuit to allow repeated processing.
4. To contain enough oil to conduct a series of tests without the necessity of allowing air into the system.

3.2 Description of Filter System

The filter system, shown in figures 3.1 and 3.2, consists largely of standard glass components with minor modifications where necessary.

The sample entered the system via a porosity No. 3 sintered glass disc mounted in the funnel at the top right hand side of figure 3.1. The oil then entered a 2 litre reservoir, in which it could be stored under vacuum or allowed to reach atmospheric pressure through a desicant breather. From this reservoir the oil passed through a demountable sintered glass filter and its two associated isolating valves. The oil was then allowed to foam

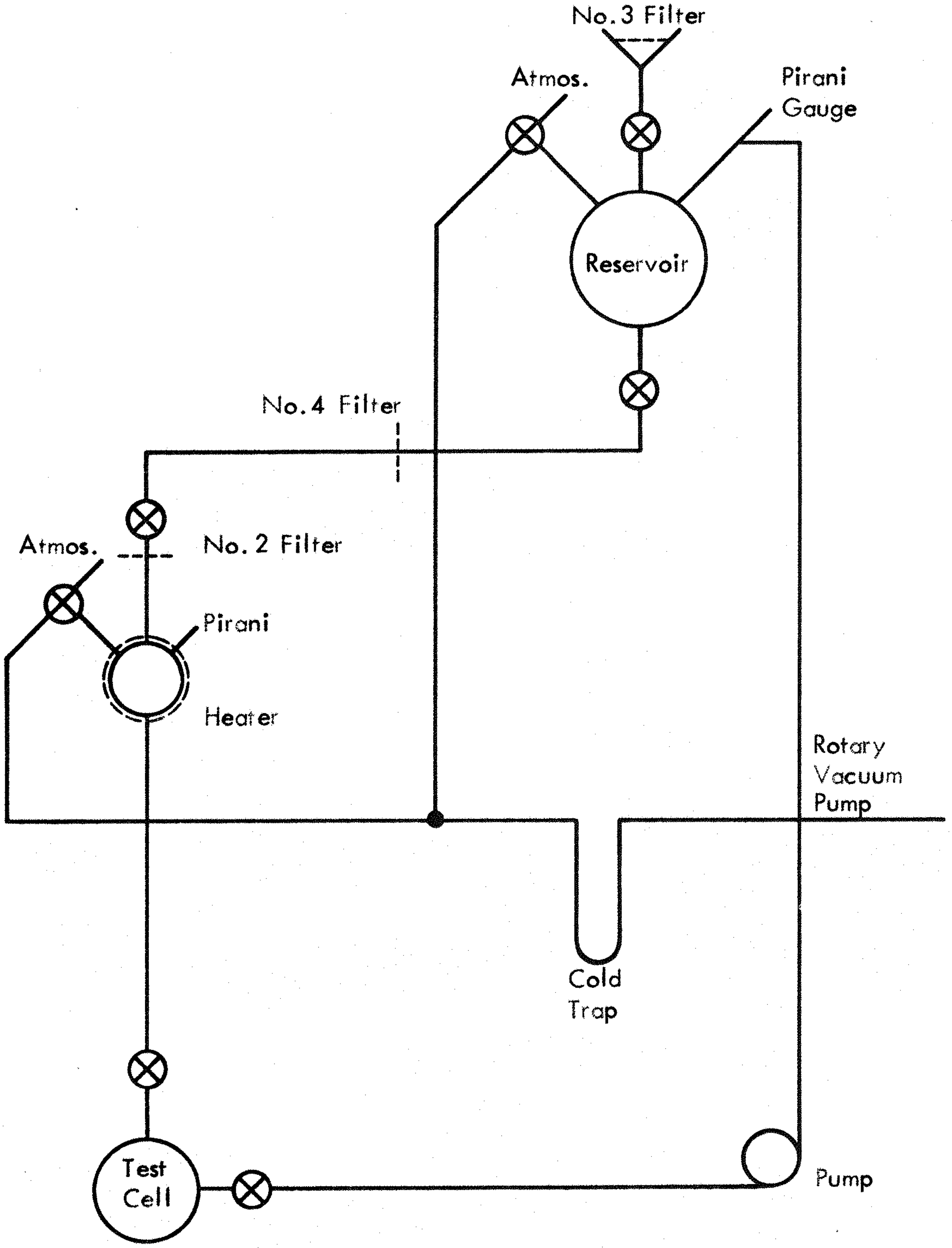


FIGURE 3.1 SCHEMATIC LAYOUT OF FILTER SYSTEM

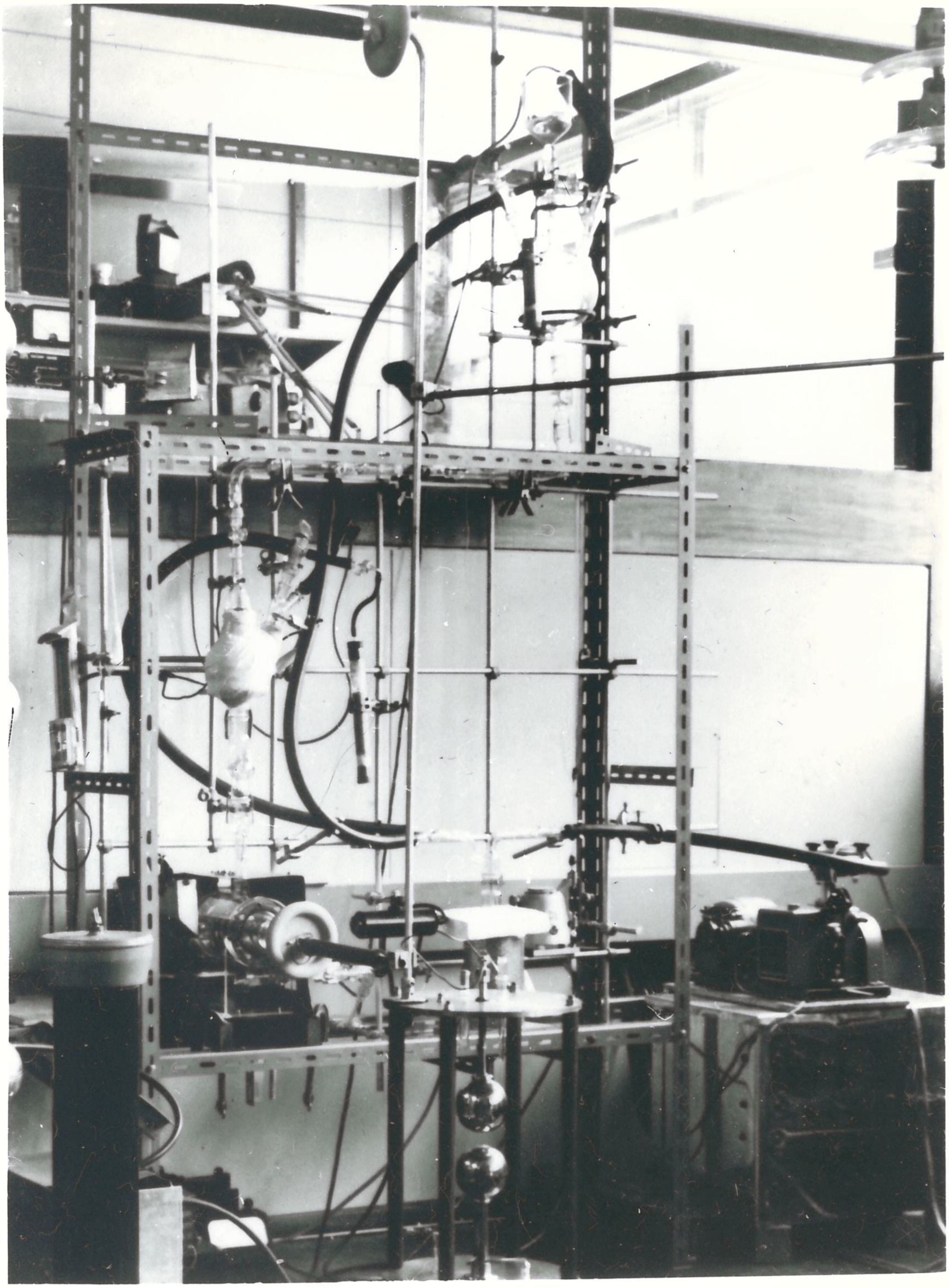


FIGURE 3.2 GENERAL VIEW OF FILTER SYSTEM

through a No. 2 porosity sinter into a 500 ml. reservoir. The valve above the sinter had only to be cracked to allow the foam to form but not fill the reservoir. At this point the system was capable of being connected either to atmosphere (via a desicant breather) or to the vacuum line. This vacuum line was connected to an Edwards rotary pump via a liquid nitrogen cold trap, the purpose of which was to condense out any vapour in the vacuum line. Pirani gauges were inserted into the system at two points so that the pressure across the filter could be accurately set and maintained. The surface of the lower reservoir was maintained at 60°C, the temperature being measured by a thermo couple on the surface. The object was to encourage the breakdown of the foam into a thin film on the surface of the reservoir. The oil then flowed into the test cell, the design and construction of which is discussed in chapter 4. After leaving the test cell the oil was pumped to the upper reservoir by a perestelsis pump.

Each component in the system was joined to the next by a cone and socket joint which meant that the whole system had to be held rigid to ensure that it did not leak. Oil could not be used as a joint lubricant, since its low viscosity allows rapid migration into the system. A high quality silicone grease was used, care being taken that none was allowed to contaminate the system.

The circulation pump consisted of stainless steel valve boxes and a silicone rubber chamber. Investigation over a period of six months showed no degradation of either rubber or oil.

The filter was built as a demountable unit to facilitate cleaning and changing. It is also possible to substitute alternative filters of different types for future work.

3.3 Operation of Filter System

Initially all components of the system were washed in a hot solution of detergent, rinsed with dust-free distilled and deionised water and then oven dried for 12 hours at 120°C. The system was then assembled without delay in an attempt to minimise re-contamination of the glass, it was then evacuated (before introduction of oil) to check that no leaks were present and also to pump away as much moisture as possible. On filling the system for the first time, and at each subsequent change of sample the following flushing procedure was adopted to ensure a pure clean sample was tested.

A small quantity of the oil was introduced into the system and circulated three times. This oil was then drained from the system and a further flushing quantity introduced and circulated. After disposal of the second flushing charge the sample was introduced into the system. This flushing procedure was adopted to avoid dismantling the system each time a new sample was required. The oil was introduced to the cleaning system by allowing it to be drawn through the funnel and porosity No. 3 glass filter. Valves were then closed and the complete system evacuated, the oil passed through the main demountable filter and to the degassing section. The oil was allowed to foam through the glass filter onto the heated surface ($60^{\circ}C$) of the vacuum receiver where the foam was broken down. From this receiver the oil fell under gravity into the test cell.

Before any breakdown tests were carried out the sample was allowed to reach atmospheric pressure.

After testing, or if it was required to recirculate the sample, it was pumped back to the reservoir by the pump.

Regular cleaning of the filters in the system (the funnel and the demountable type) was essential to ensure clean samples and fast filtering. Cleaning was undertaken whenever the oil sample was changed and anyway after about thirty breakdown measurements. Cleaning was required more frequently during the initial testing.

The small particles filtered from the oil, eventually clogged the very fine porosity filter so that the filtering rate became very slow. There did not appear to be any lowering of the quality of the oil but it was expedient to clean the filter to ensure reasonable flow rates.

The filter was washed in hot detergent to remove most of the oil, soaked in tri-chlorethylene and dried in an oven at $50^{\circ}C$. Chromo-sulphuric acid was then allowed to drip through the filter overnight thus removing all the solid particles. The filter was then washed thoroughly in distilled water and oven dried for several hours at $100^{\circ}C$. After reassembly into the system, about one litre of oil was introduced as a flushing charge.

CHAPTER 4

THE TEST CELL

4.1 Design and Construction

The cell, figures 4.1 and 4.2, was constructed of Perspex with glass cone and socket fittings. In order to retain the strength of the Perspex, the temperature was limited to 70°C. This also allowed the use of epoxy resin for the Perspex-glass joint, since the differential expansion is small at 70°C.

Viewing and illumination ports, with flat windows were provided, through which the electrode sparking area could be observed. A small lamp was placed such that the gap could be observed and measured by means of a travelling microscrope.

The high voltage end of the cell consisted of a plate with a small bushing on one side and a cone bushing on the other. Through this assembly passed a brass conductor which was threaded at its inner end to take the electrode. The whole assembly was secured to the cell body with eight 1/4 inch nylon screws.

The low voltage end of the cell had no bushing; in its place being a sliding seal, which allowed the brass conductor to move backwards and forwards without oil leakage. This seal was a modification of the Wilson type of seal. Movement of the electrode was achieved by means of the micrometer screw thread and thrust bearing assembly shown in figure 4.3, and could be set to within 0.01 mm.

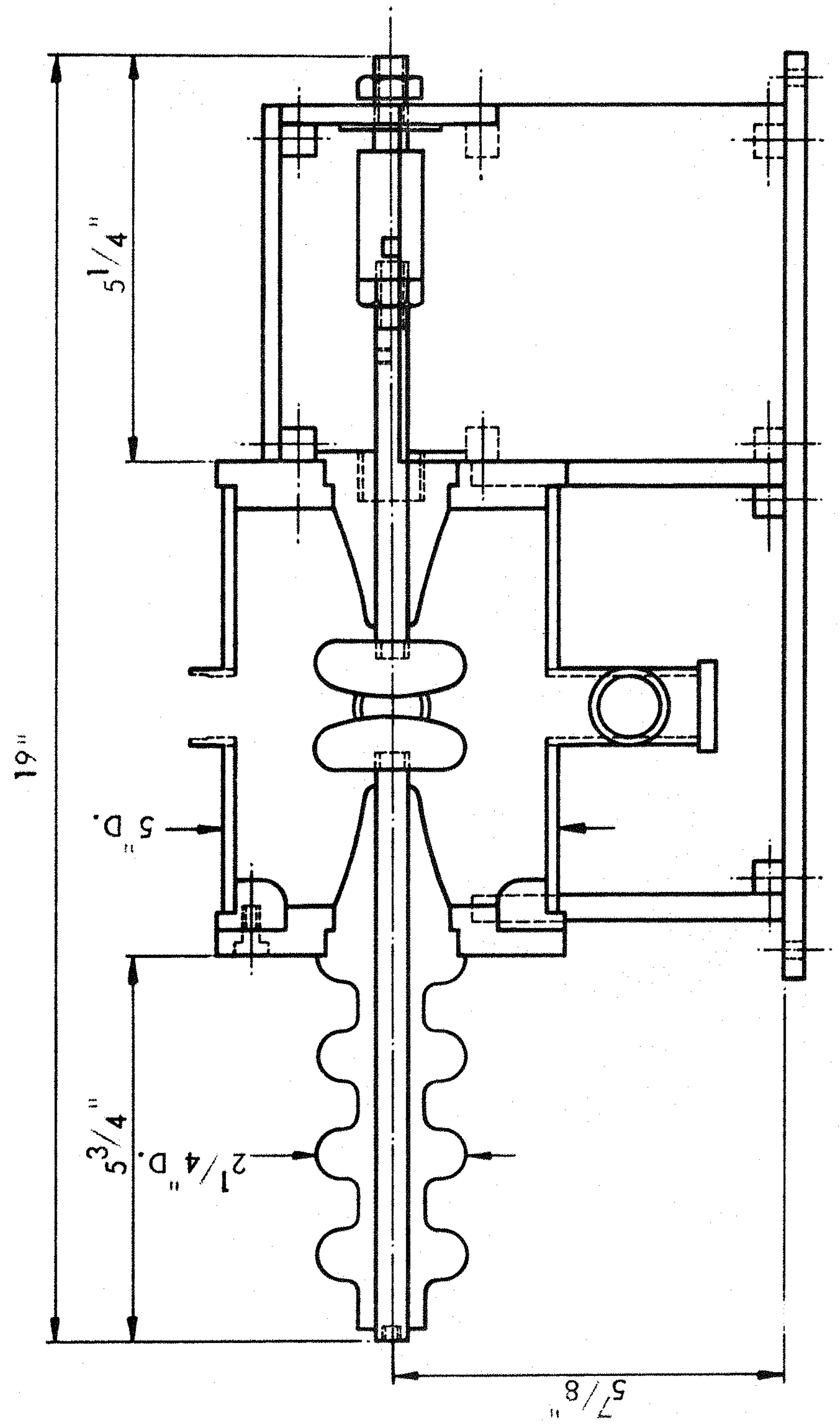


FIGURE 4.1 CONSTRUCTION OF TEST CELL

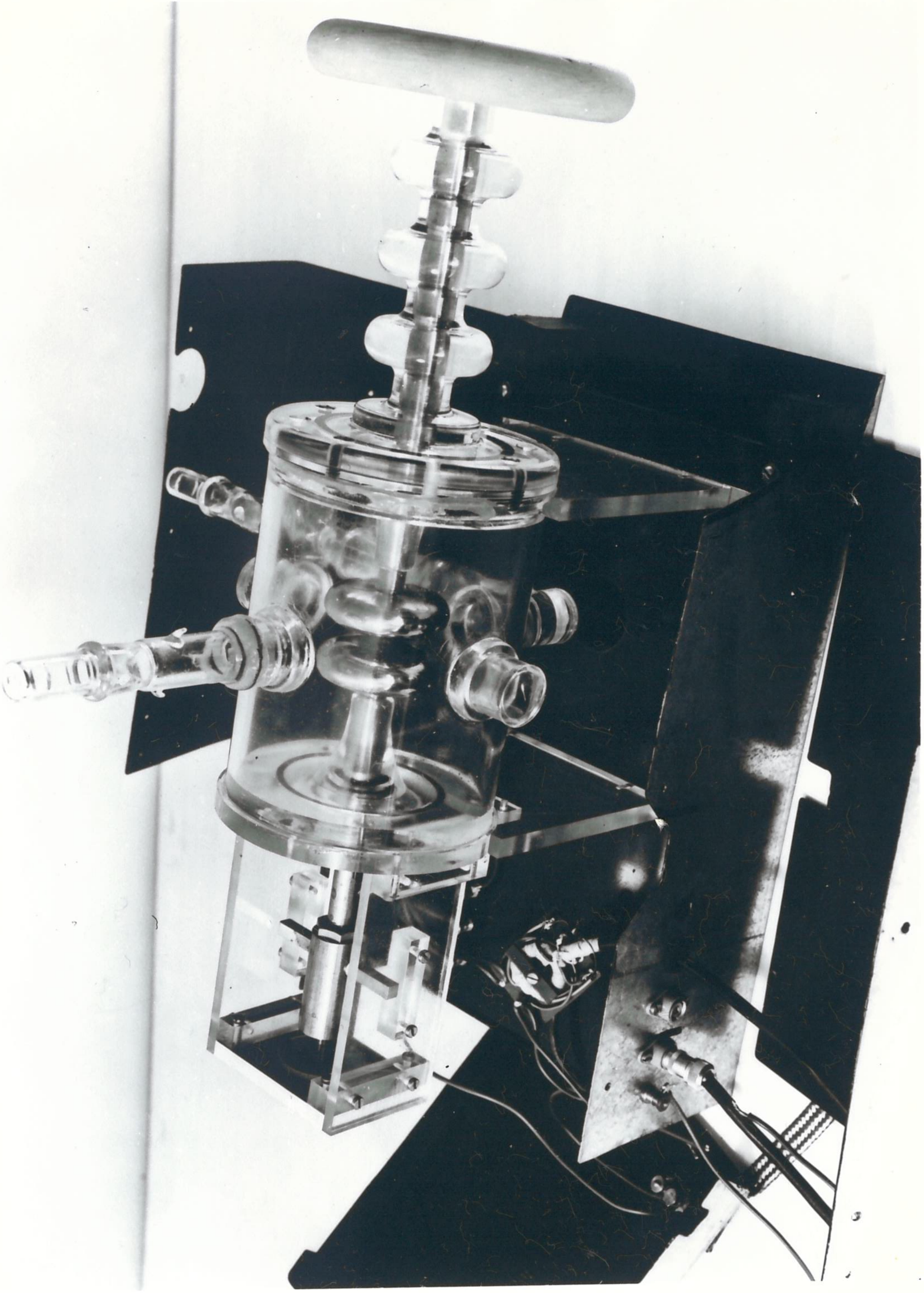


FIGURE 4.2 GENERAL VIEW OF ASSEMBLED TEST CELL

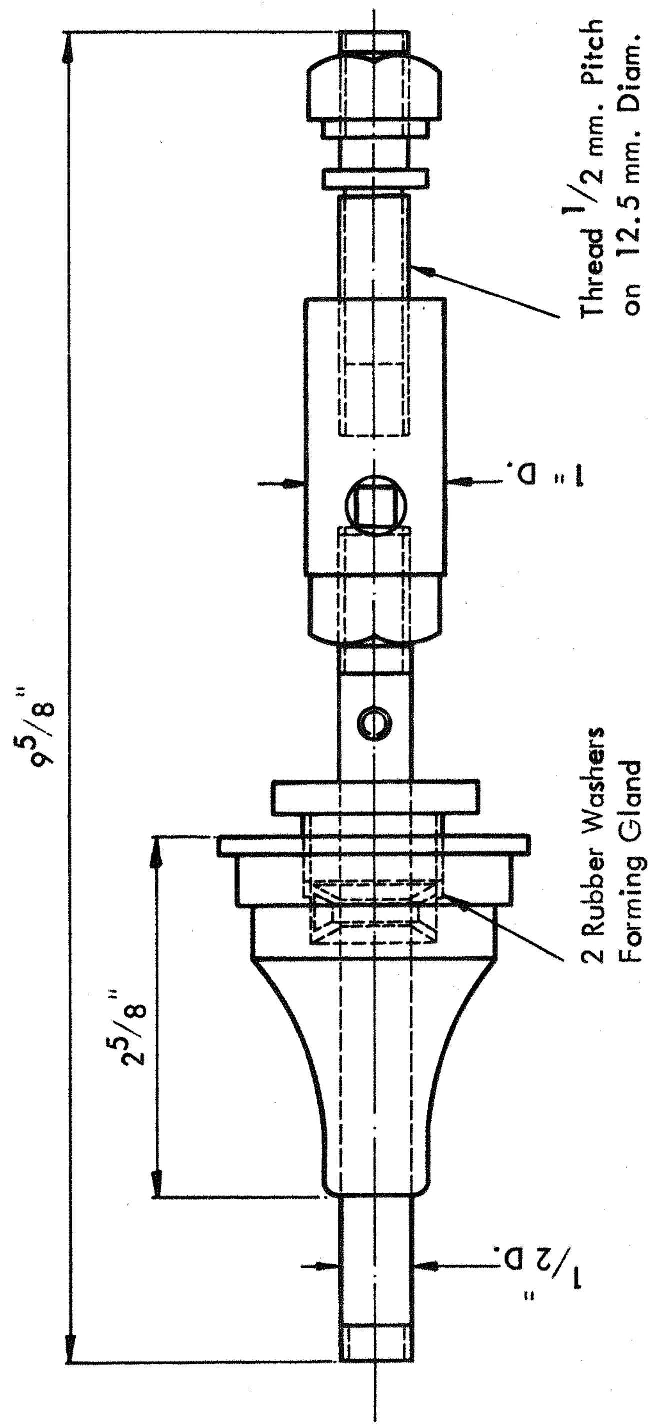


FIGURE 4.3 DETAILS OF SLIDING SEAL AND MICROMETER ADJUSTER

4.2 Screening and Corona Reduction

Guard electrodes were incorporated into both the inner and outer walls of the low voltage end plate. The insulated stand on which the cell was supported was also provided with such electrodes.

These guard connections were taken to the surrounding metal box which was intended to reduce the light entering the cell as well as to reduce the effect of any external electric or magnetic fields. Within this screening box was the Rogowski type coil for the generation of discrimination signals.

A corona reducing toroid was mounted on the high voltage electrode. This was constructed to dimensions given by Hylten-Cavallius et al (4.1) and painted to give an electrically conducting finish.

4.3 Cell Preparation

Many degreasing agents cause surface crazing of Perspex which affects its strength and produces cavities which harbour dust and other contaminants. Petroleum Ether 100-120 was used to degrease the cell at 20°C, this solvent having no degrading effect on Perspex.

Fibres were observed in the gap after assembly, these were removed and cleaning continued. As the cleaning and flushing procedure progressed small spots of light were observed in the gap. With the filter of smallest pore size no such spots of light were observed and it was assumed that the cleaning process was complete. These observations were guidance for all subsequent cleaning and flushing operations.

The minimum pore size was 1 μm, and it is hoped that no particles larger than this were present in the bulk of the liquid. Krasucki (4.2) has said that even after such stringent precautions large particles (50 μm) have been observed attached to cell walls or electrodes. The only known method of removing these is by dispersing them into the bulk of the liquid by means of ultrasonically vibrating the system.

The resistance of the cell was measured by means of a direct reading electrometer and found to be greater than 2 x 10^{14} ohms, between the high voltage electrode and the low voltage electrode with the guards earthed.

If the guard electrodes were effective then the resistance should be calculable from an estimation of the leakage path.

The manufacturer (4.3) gives the volume resistivity of Perspex as 10^{14} ohm. cm; estimation of the total resistance by consideration of the leakage path gives a value of 0.89 x 10^{14} ohms.

CHAPTER 5

THE ELECTRODES

5.1 Construction

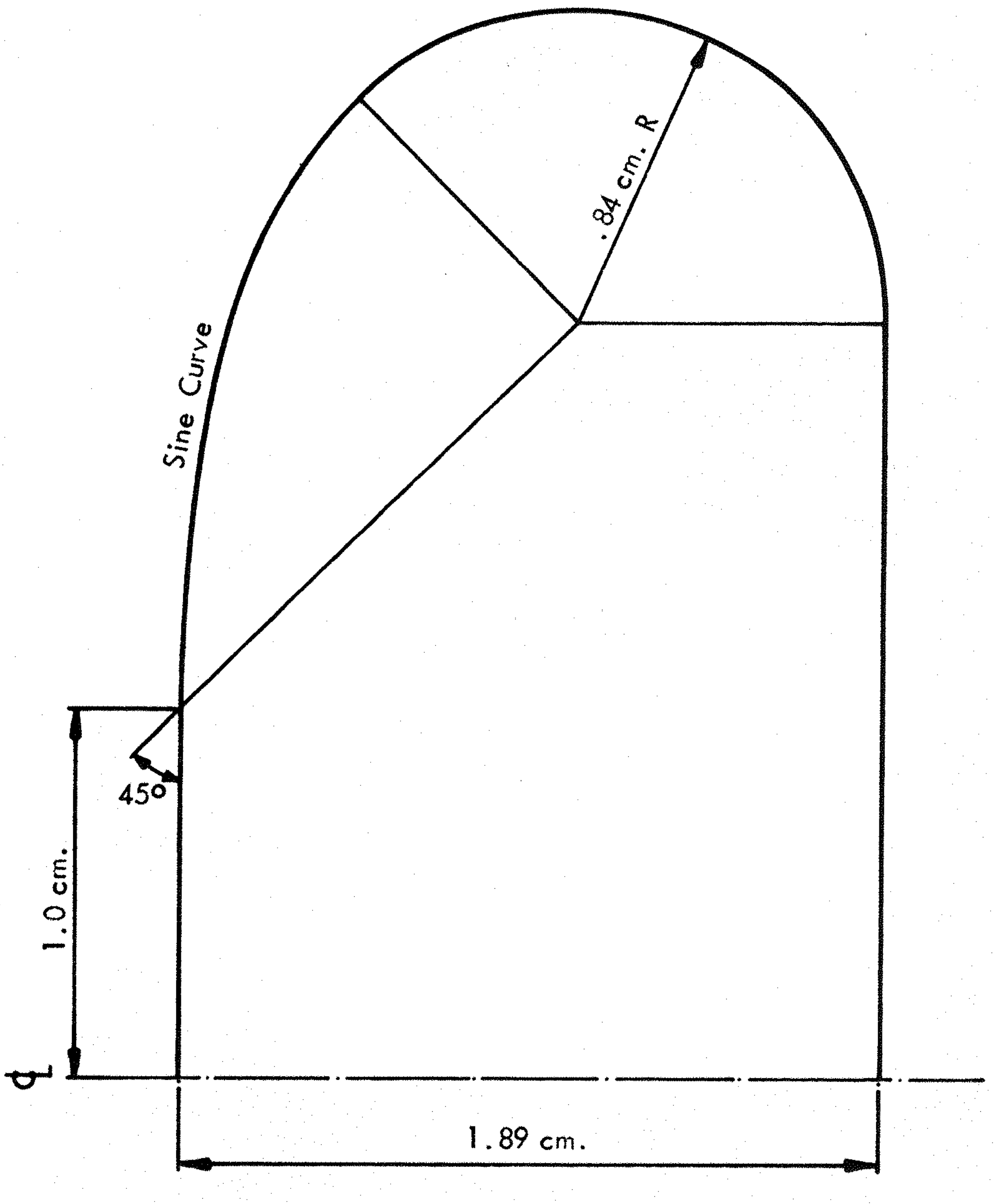
The electrodes, which have a plane sparking area were constructed to a profile developed by Bruce (5.1) to ensure a uniform field in the gap, figure 5.1. The nominal diameter of the electrodes was 2.0 cms, and at a gap of 1 mm. this ensured a large area of uniform field. They were constructed of EN58E stainless steel in two parts; a body and a removable face as shown in figure 5.2.

The two parts were secured together by means of five screws before any profiling was undertaken to ensure smooth curves over the electrode surface. The removable face facilitated the changing of pitted electrodes and the use of different metals as sparking surfaces.

5.2 Preparation

The initial profiling, smoothing and rough polishing with coarse (14/5 Dialap) diamond paste, was done with the electrode mounted in a lathe. Final polishing, ending with 1/ $^{1}/4$ diamond paste was done very slowly on a polishing machine. The machine used was housed in a polythene tent to ensure that dust, which could scratch the surface, was kept to a minimum.

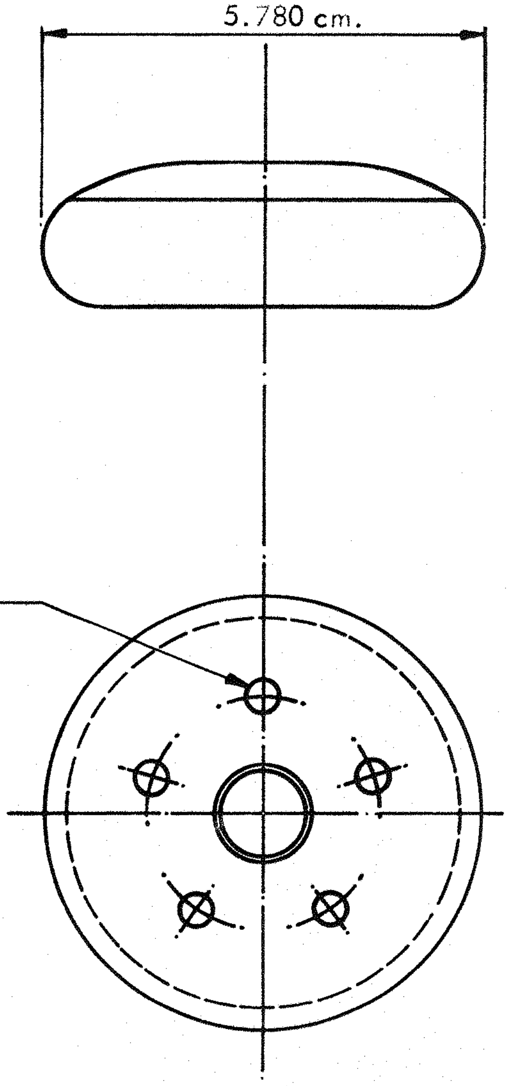
The final surface was then examined with an incident light microscope, figure 5.3. The surface was flat but rippled with a



Half Section Shown

FIGURE 5.1 ELECTRODE PROFILE

Electrodes:- Two off
Scale:- Full size
Material EN58E S/S



5 No. screws, 2 B.A. C'sk
2 B.A. clear in body. Tapped
2 B.A. in face x 2.5 mm. deep
on 1.5 Ø cm P.C.D.
Screws of stainless steel with
two grooves, 45° angle, to
thread roots, & bored 1/32"
Grooves on diametrically
opposite sides.

FIGURE 5.2 ELECTRODE CONSTRUCTION

FIGURE 5.3 MICROGRAPH OF POLISHED SURFACE

number of scratches across it. These scratches were of the order of one micron wide and hence represent the largest size of diamond dust present in the final polishing paste.

After polishing the electrodes were degreased in ether and dried, washed in distilled water and oven dried at 100°C, care being taken to avoid re-contamination by dust or grease. They were then assembled onto the appropriate conductors and rinsed in clean insulating oil. The electrodes were then assembled into the cell without delay, and the cell sealed.

5.3 Cell Capacitance

With the cell filled with oil and with a gap of 1 mm. the capacitance was measured using a Wayne Kerr B112 bridge. The value of this capacitance was found to be 35.4 pF.

In order to calculate the capacitance of the system a method was used which involves the sketching of the equipotential lines as shown in figure 5.4. This method will normally give an answer to within ± 5% which is adequate for the estimation of the impulse wave shape.

Now the capacitance of any plane system is given by :-

$$C = {}^{\varepsilon A}/d$$

where ε is the permittivity
A is the area
d is the distance apart

Consider now an elemental ring of dielectric dr whose centroid is radius r and let the gap at this point be t.

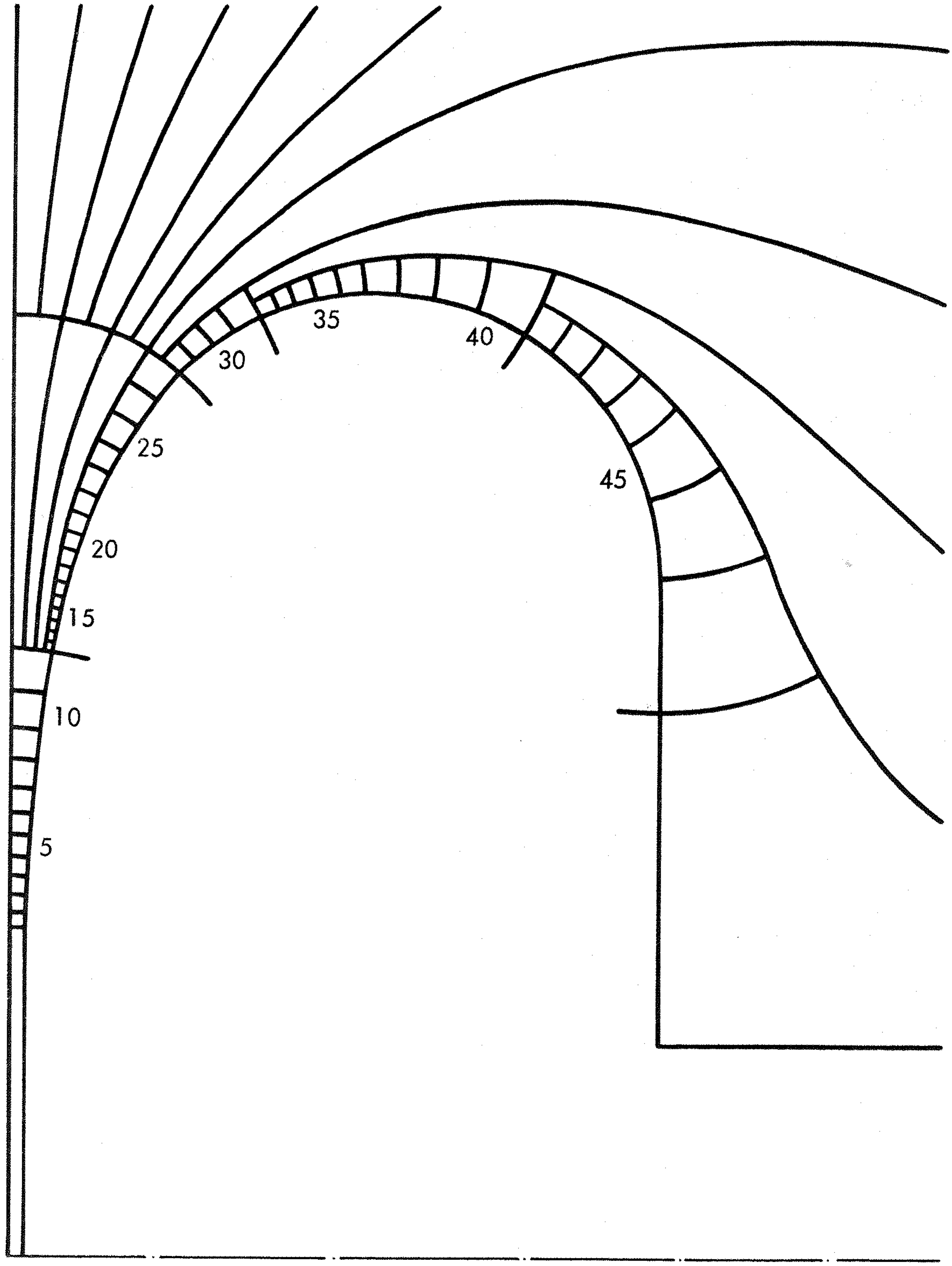


FIGURE 5.4 EQUIPOTENTIALS FOR ELECTRODE SYSTEM

For convenience consider r and t to be measured in millimetres and C in picofarads.

$$\therefore \quad C = \frac{\varepsilon \times 2\pi \times r \times 10^{-3} \times dr \times 10^{-3} \times 10^{12}}{36\pi \times 10^{9} \times t \times 10^{-3}} \ \text{pF}$$

Now let ${}^{dr}/t$ be a square of 1 millimetre.

Hence the capacitance of an annulus whose cross section is 1 millimetre is :-

$$\underline{\underline{{}^{r}/18 \ \text{pF}}}$$

If now, as shown in figure 5.4, the half section is divided into squares then it can be seen that the total capacitance is obtained by the summation of all the capacitances of such 'squares'.

In the case of the flat portion however it is simpler to express :-

$$C = \int_{R=0}^{R=10} {}^{r}/18 \ dr \ \text{pF}$$

$$\underline{\underline{\simeq 2.8 \ \text{pF}}}$$

Such a summation gives the result 17.7 pF.

Now the relative permittivity of transformer insulating oil is given in the literature as 2.18 thus giving 38.5 picofarads which is very close to the measured value of 35 picofarads.

CHAPTER 6

THE HIGH VOLTAGE SYSTEM

6.1 The Impulse Generator

The high voltage impulse generator used in this work was the Foster equipment installed in the University of Southampton. The generator is a three stage Marx type circuit incorporating Goodlet's later modification (6.1). The capacitance per stage is 0.1μF and with the maximum charging voltage of 100 kV, the nominal output is 300 kV with a discharge energy of 1.5 Kilojoules.

The front control resistor is situated outside of the generator in series with the output. Variation of this resistor is undertaken by substitution of another resistor of a different value. The fixed value tail resistors serve both as charging resistors and structural braces between the capacitor columns.

The generator is tripped by means of a triggered spark gap, the lowest stage being in the form of a trigatron; the trigger voltage pulse required is 8 kV and is derived from a pulse thyratron as described in chapter 8.3.

Regular re-alignment and cleaning of the stage sphere gaps was necessary to ensure a smooth rise of voltage and a minimum of premature breakdowns or misfires.

Curves were plotted of the sphere gap breakdown voltages for both negative and positive charging voltages. These curves, figure 6.1, defined a zone in which the stage sphere gaps did not break down before the application of a trigger pulse but

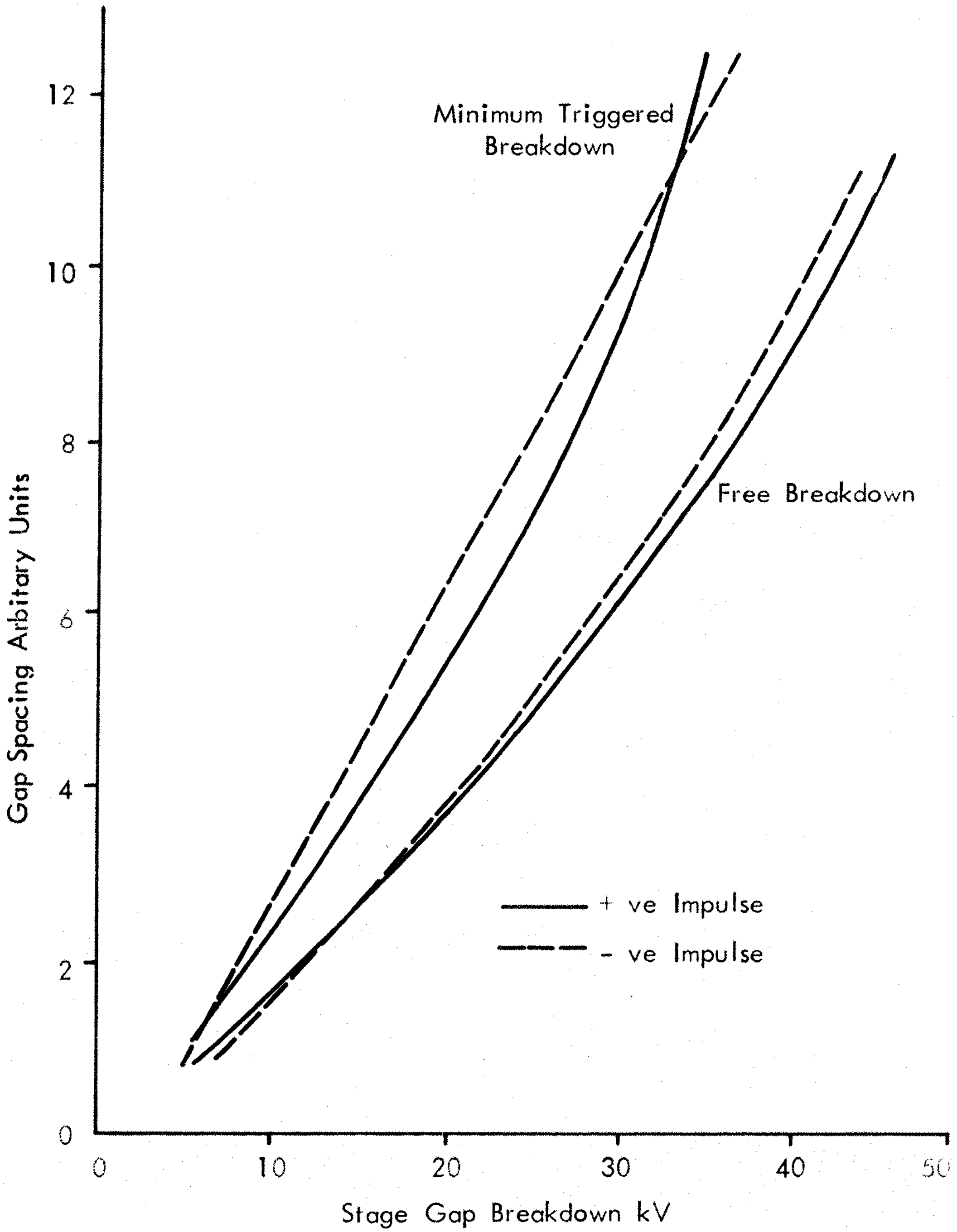


FIGURE 6.1 BREAKDOWN CHARACTERISTICS FOR STAGE GAPS

always broke down on application of this pulse.

In addition, the output voltage of the generator was plotted against charge voltage for each mode of operation used, figure 6.2.

6.2 The Impulse Voltage Divider

A resistive potential divider was used in conjunction with the transient recorder (chapter 9.1) to monitor the voltage applied to the test cell. The high voltage arm of this divider consisted of a length of 'Schroeber' resistance ribbon mounted on an insulating tube and immersed in insulating oil.

A large grading cone was fixed to the top of the divider to assist the potential grading. The device was very delicate since the weight of the grading ring on top of the slender oil filled Perspex tube made it prone to mechanical damage.

The low voltage arm consisted of three interchangeable units to give ratios of 100, 250 and 500:1. These units also consisted of resistance ribbon mounted in a convenient place for removal.

6.3 The High Voltage Circuit

The complete circuit is shown in figure 6.3 with a general view in figure 3.2. The capacitance of the chop gap is a calculated figure; the inductances have been estimated by a method described by Grover (6.2) or obtained from data on 'Schroeber' resistance ribbon.

The low capacitance of the test cell ensured that the energy dissipated in the sample at breakdown was kept to a minimum. Normally a generator with an output capacitance of 0.003 μF would

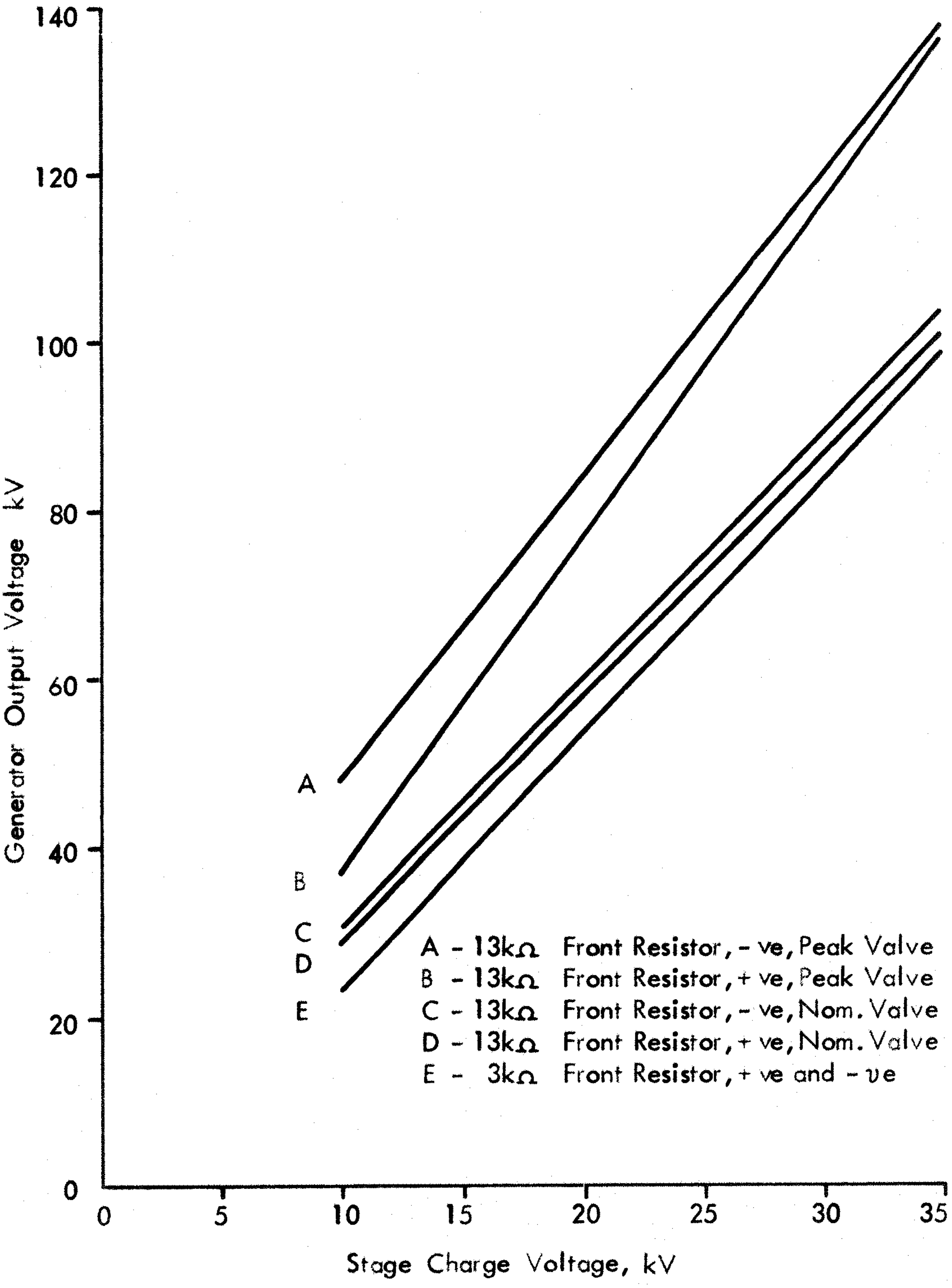


FIGURE 6.2 GENERATOR OUTPUT VOLTAGE

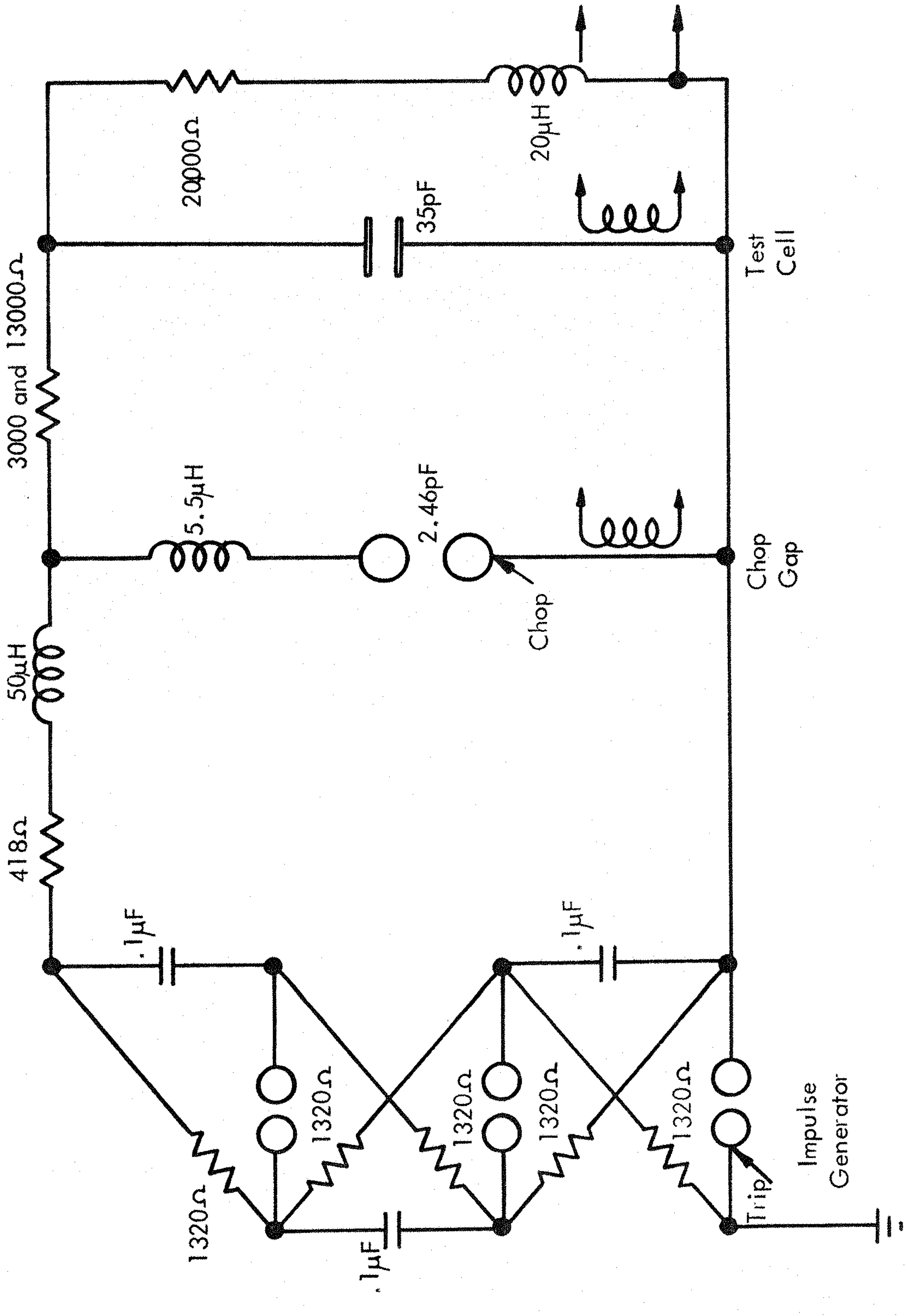


FIGURE 6.3 HIGH VOLTAGE CIRCUIT DIAGRAM

require a front control capacitor with such a small test cell capacitance. The energy stored in such a capacitor would have to be dissipated in the sample on breakdown. In order to avoid this situation a large resistor in series with the output was used to control the wave front. This resistor limited the discharge current into the sample at breakdown but also lowered the voltage efficiency of the system. This situation was tolerable because the generator voltages were much larger than required to break down the sample.

Two special front control resistors were constructed to give the rise times required, the slower being a nominal 1 μsec. wave front (6.3). To keep the inductance low, these resistors were constructed in the form of a series/parallel arrangement of 2 watt carbon resistors mounted in an oil filled bakelised paper tube, figure 6.4.

6.4 Impulse Voltage Waveforms

Several methods for the calculation of impulse waveforms are available which avoid the tedium of solving the differential equations which describe the network response.

The present circuit however does not lend itself to such methods due to the large impedance differences between components. Figure 6.5 shows the simplified network. Approximate solutions, such as those suggested by Hawley (6.4) are not accurate enough since they assume a well 'conditioned' network. A computer programme (6.5) was used to evaluate the transient response of the

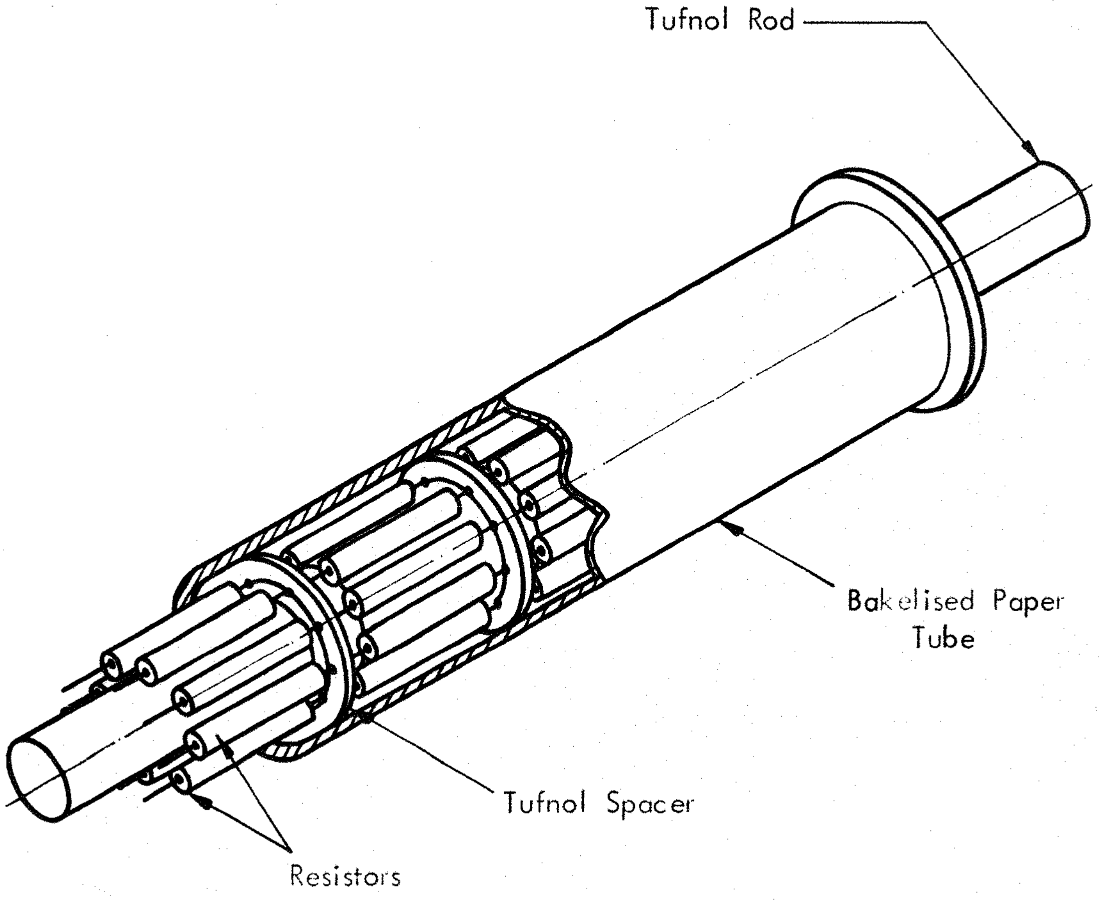


FIGURE 6.4 FRONT CONTROL RESISTORS

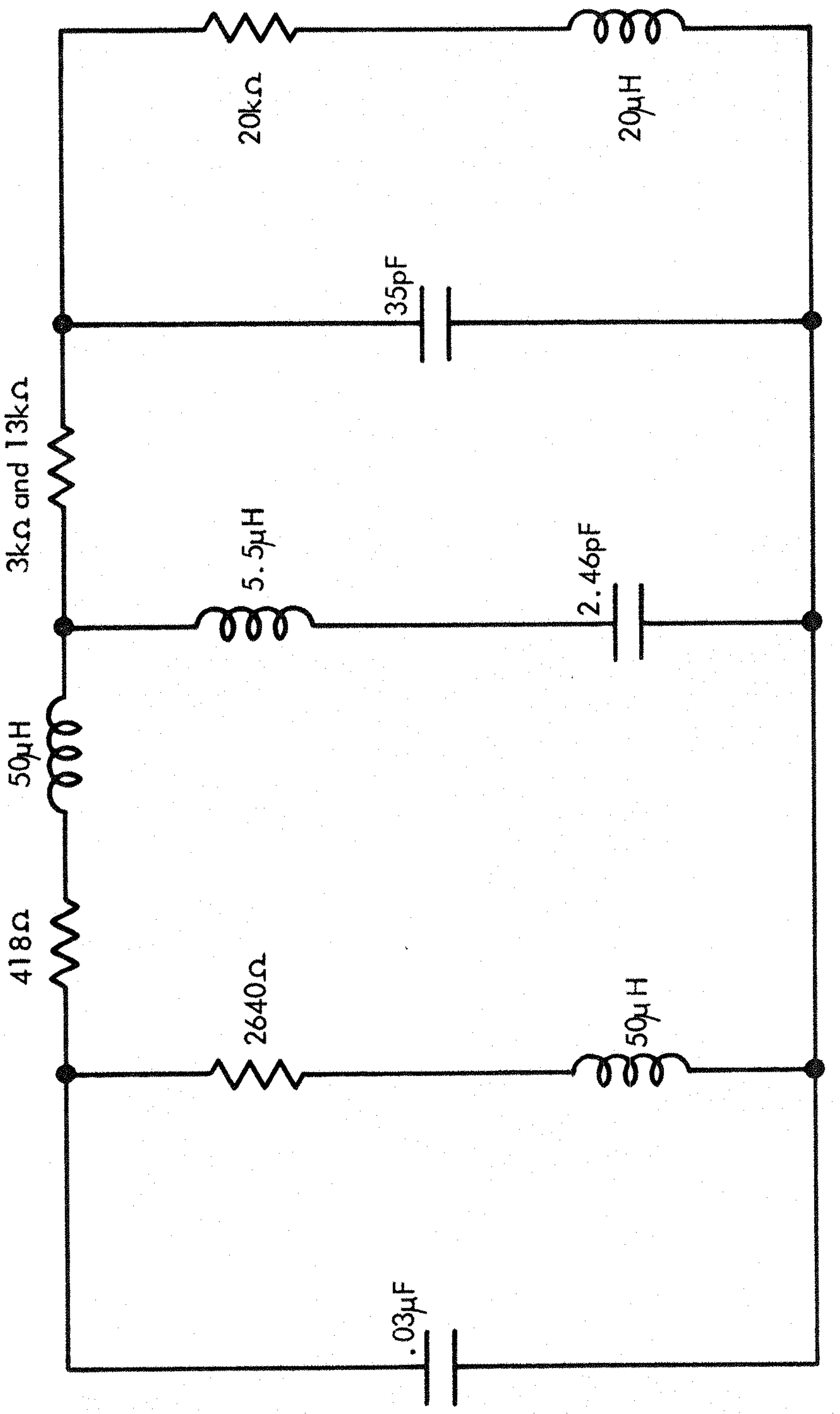


FIGURE 6.5 SIMPLIFIED EQUIVALENT NETWORK

network shown in figure 6.5 and the results are shown in figure 6.6.

The calculated waveforms are within the tolerances quoted in BS 358 where applicable.

Figures 6.7(a) and 6.7(b) show the waveforms produced by the network. These waveforms, when compared with those in figure 6.6. show that the predictions were of the correct order, and demonstrate the validity of using the generator in the rather unusual configuration.

The oscillations which appear on the crest of the faster rising impulse voltage are not oscillations of the main circuit; examination shows it to be over damped. The frequency is of the order of 2.7 MHz; it is less than 10% of the crest voltage and decays in a few cycles showing that the oscillating circuit is near its critical condition.

Consider a loop consisting of the test cell, front resistor and chopping gap as shown in figure 6.8(a). It can be shown (6.6) that this circuit will oscillate near its critical condition; its natural damped frequency being 3.9 MHz, which is near the measured frequency, figure 6.8(b).

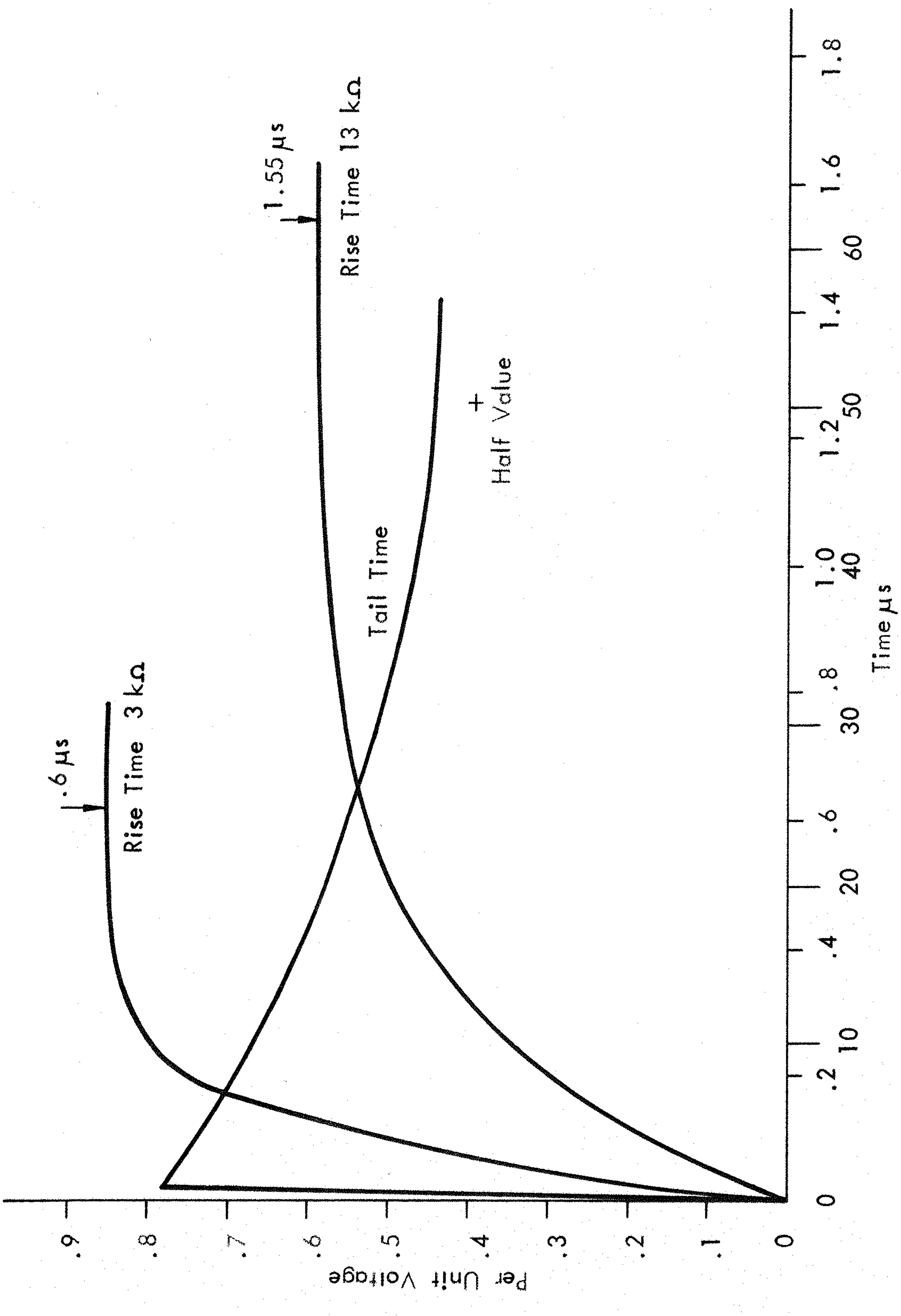
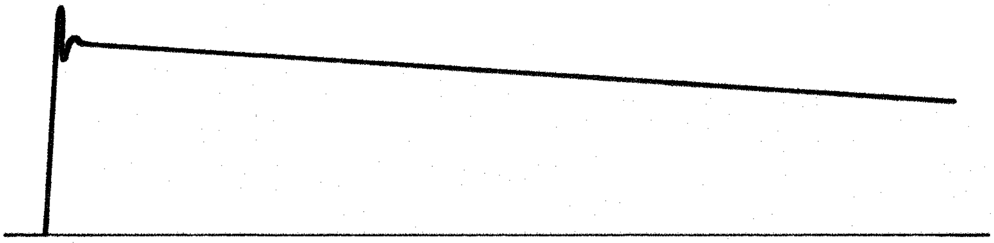
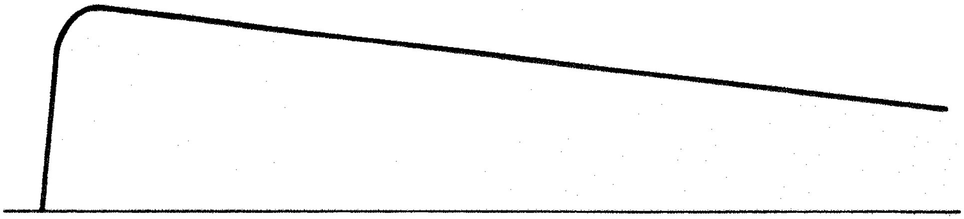


FIGURE 6.6 CALCULATED IMPULSE WAVEFORMS



Front Time .6μS
Half Time 48.5μS

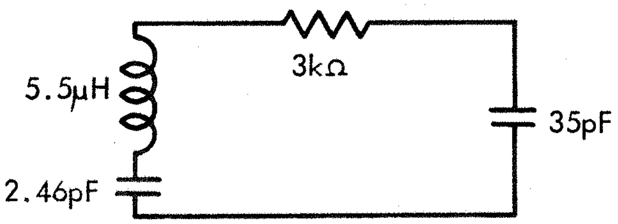
(a) 3.0 kΩ Front Resistor



Front Time 1.9μS
Half Time 55μS

(b) 13.0 kΩ Front Resistor

FIGURE 6.7 IMPULSE VOLTAGE WAVEFORMS



$C = 2.29$ pF

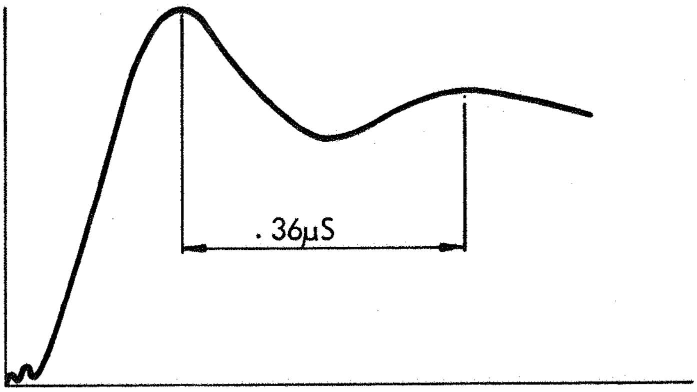
$R = 3.0$ kΩ

$L = 5.5\,\mu$H

$$W = \frac{1}{LC}\sqrt{1 - \frac{R^2}{4}\cdot\frac{C}{L}}$$

$\therefore$ f = 3.9 mHz

(a) Possible Oscillating Circuit



$f = {}^{1}/_{\lambda}$

$\therefore$ f = 2.75 mHz

(b) Crest Oscillation

FIGURE 6.8 OSCILLATION ON IMPULSE VOLTAGE CREST

CHAPTER 7

TRIGATRON

7.1 General

The development of triggered spark gaps or trigatrons has been described by J. D. Craggs, M. E. Haines, H. M. Meek (7.1) and since this date much has been done to improve their performance. Broadbent and Cooper (7.2) describe experiments in which single stage trigatrons were used successfully up to 1 Mv with a voltage range of 30%. J. D. Williamson (7.3) describes the design and construction of small (1 - 10 kv) spark gaps with voltage ratios of 50% and operation times of 100 n secs and less.

7.2 Construction

The present device was built from brass and paxolin, and is shown in figure 7.1. It consisted of 9 cm. diam. brass spheres mounted between two brass plates which were held apart by four paxolin rods. The upper sphere was mounted on a screwed brass rod so that the gap spacing could be varied. The lower sphere had a 7 mm. hole drilled at its sparking point, was fixed and mounted on a hollow copper tube. A steel rod was mounted in the lower sphere, and insulated from it; this formed the trigger electrode. The trigger gap was the annular gap formed by the trigger electrode in the 7 mm. hole, as shown in figure 7.2.

The sphere spacing was measured by means of a travelling microscope to within ± 0.1 mm.

FIGURE 7.1 THE TRIGATRON CHOP GAP

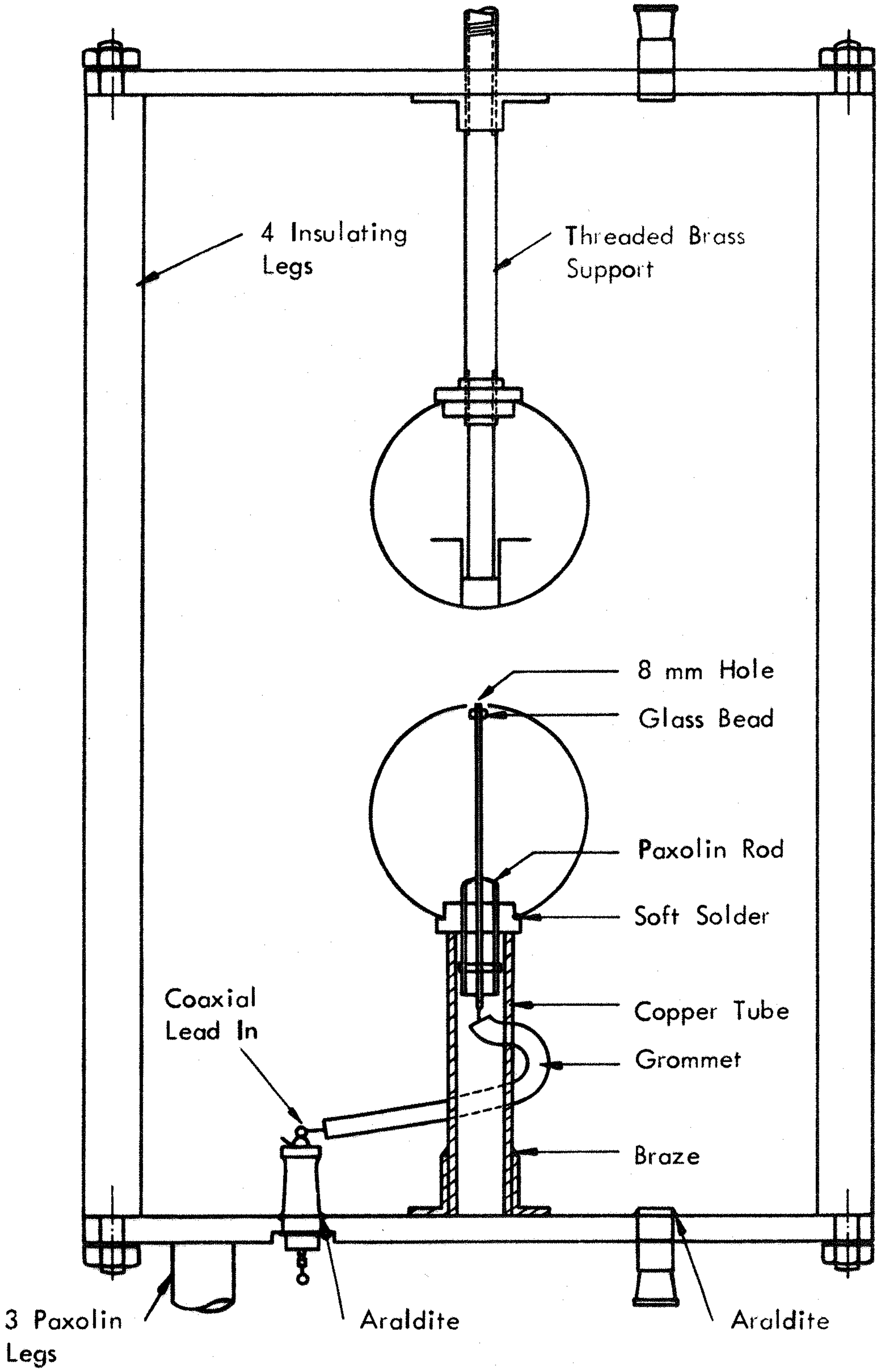


FIGURE 7.2 CONSTRUCTION OF TRIGATRON

7.3 Performance as a Two Electrode Gap

Figure 7.3 shows the results of using the trigatron with a glass shield around it, as a two electrode device. The results are erratic and have a large scatter, thus making it impractical for use as a triggered spark gap. The results obtained without the shield are much less erratic and exhibit less scatter, figure 7.4.

It was noted that as the spheres became dirty and pitted through use, premature breakdowns at the higher levels occurred. This phenomena was compared with the results obtained when the gap was irradiated with an ultra-violet lamp. The effect of the ultra-violet lamp is shown in figure 7.4.

These premature breakdowns can be attributed in both cases to increased electron emission from the cathode during the voltage hold-off period. The pitted surface will decrease the work function at the surface thus allowing electrons to be more easily ejected into the gap. The ultra-violet radiation will also cause emission of electrons in the same way. The result of these tests was that the trigatron was operated without a glass shield and without ultra-violet irradiation. In addition regular cleaning was necessary to ensure consistent results.

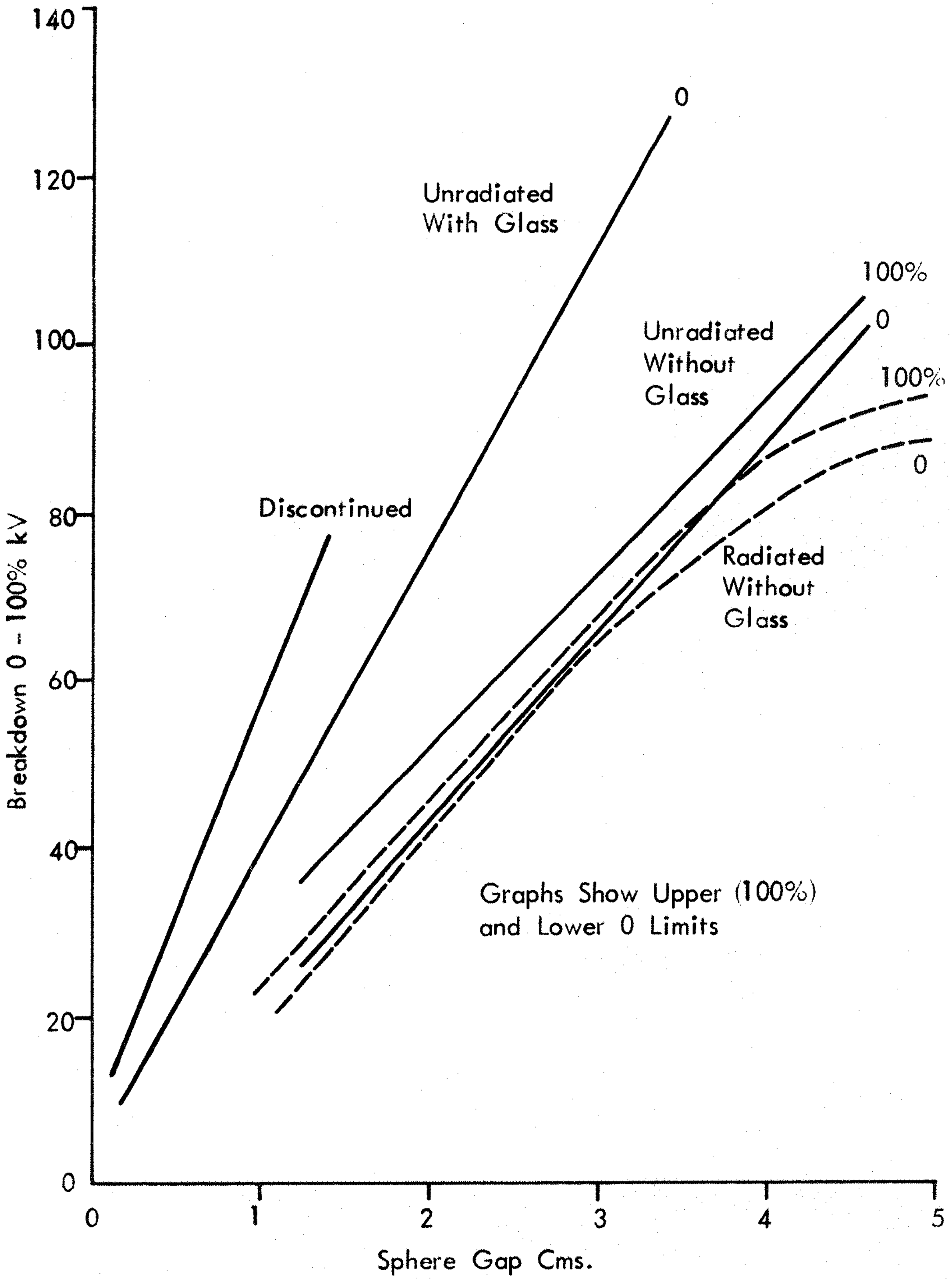


FIGURE 7.3 ERRATIC RESULTS WITH GLASS ENVELOPE

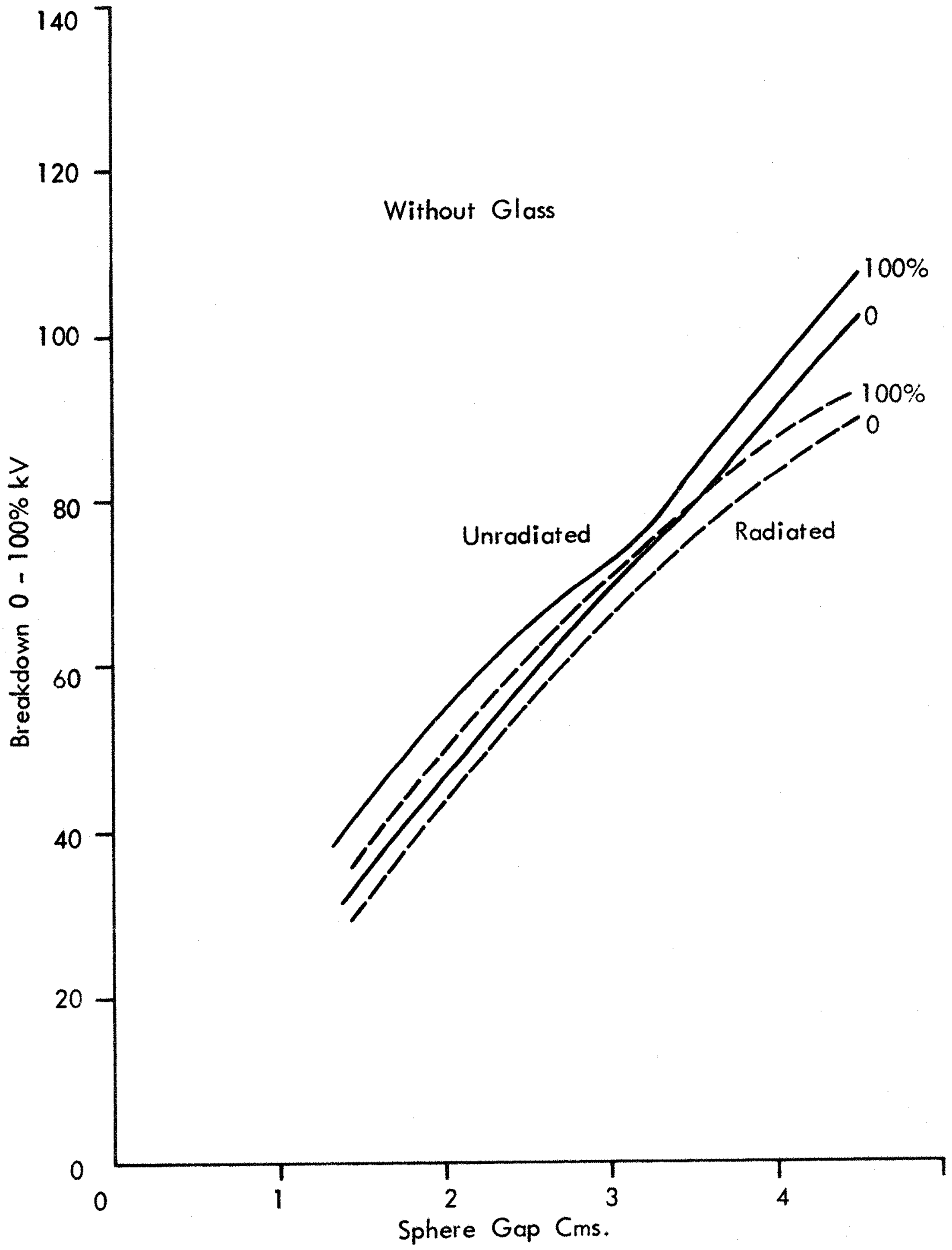


FIGURE 7.4 RADIATION OF TRIGATRON AS TWO ELECTRODE GAP

7.4 Performance as a Three Electrode Gap

Figure 7.5 shows the final operating curves for the trigatron which were used throughout the tests. Examination shows that the working range is greater when the high voltage electrode is negative. Since the trigger electrode is always positive with respect to the 'earthy' sphere, this is in agreement with Williamson (7.3) whose results showed that such a configuration gave the best possible operating range.

It was also shown that the next best configuration was, a positive high voltage electrode and a negative trigger electrode. The present design could be improved by the addition of a facility for providing a negative trigger voltage.

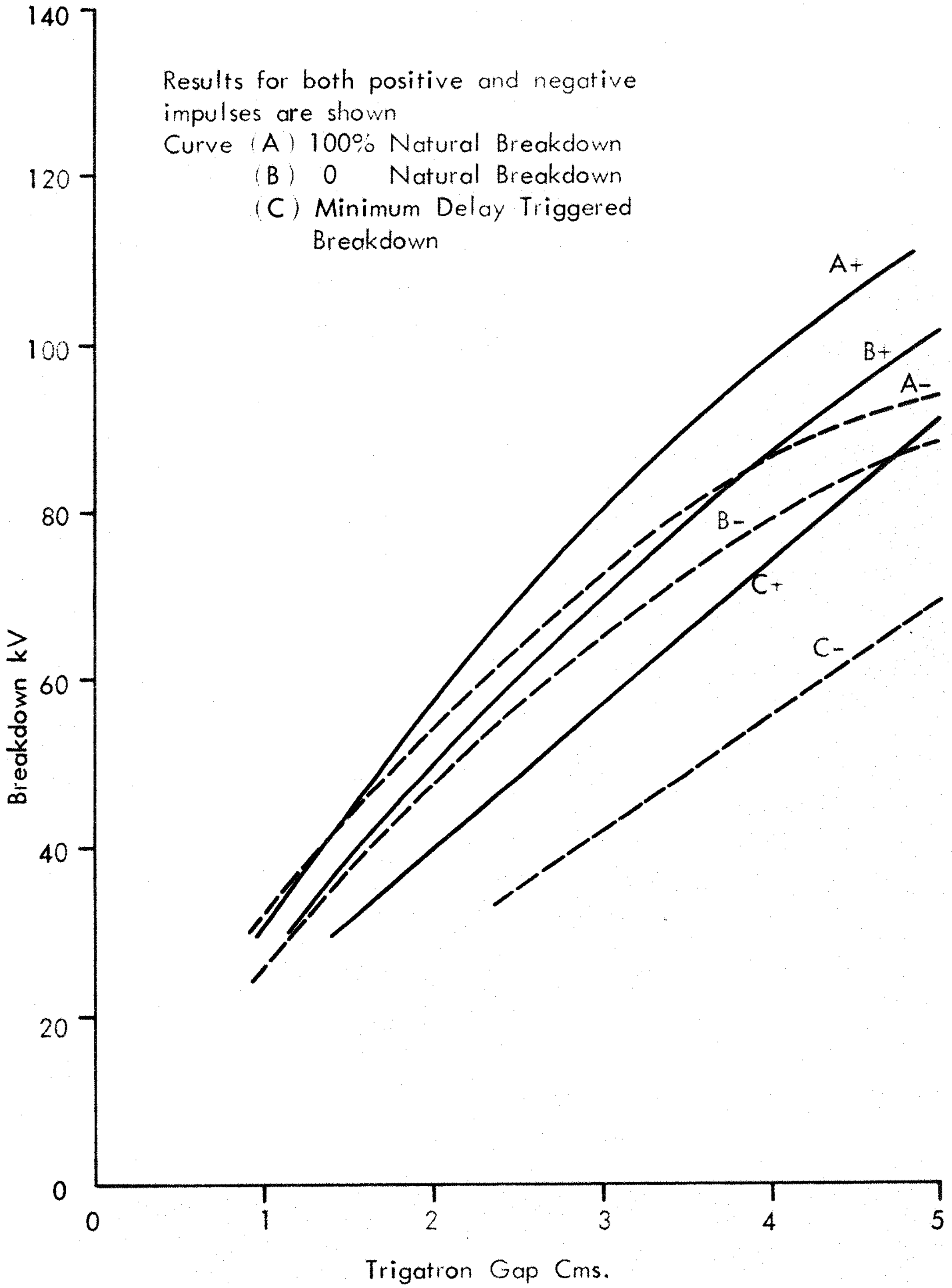


FIGURE 7.5 BREAKDOWN CHARACTERISTICS OF TRIGATRON (FINAL FORM)

CHAPTER 8

CONTROL CIRCUITS

8.1 Requirements

To control the impulse generator and the oscillograph, it was necessary to construct a comprehensive control system. The requirements of the system can be summarised as follows :-

1. Supply a pulse to start the oscillograph.
2. Supply a pulse to trip the impulse generator after a predictable and variable delay.
3. Supply a pulse, after a further delay to trip the 'chop gap'.
4. Supply the above (3) pulse with minimum delay if the test sample breaks down at any time during the time of the applied voltage.
5. Indicate whether the test sample broke down, or whether the chop gap was tripped afters its pre-determined delay.

The unit was based on a design by Stark and Higham (8.1) which satisfied requirements 1 to 4; the present unit also satisfying requirement 5. The function of the unit is shown in figure 8.1.

The operation of an impulse generator causes a lot of interference pulses to be generated which can cause the control equipment to malfunction. Great care was taken during the design and construction of the control equipment to reduce the effects of such pulses. Earth loops were eliminated, and cables

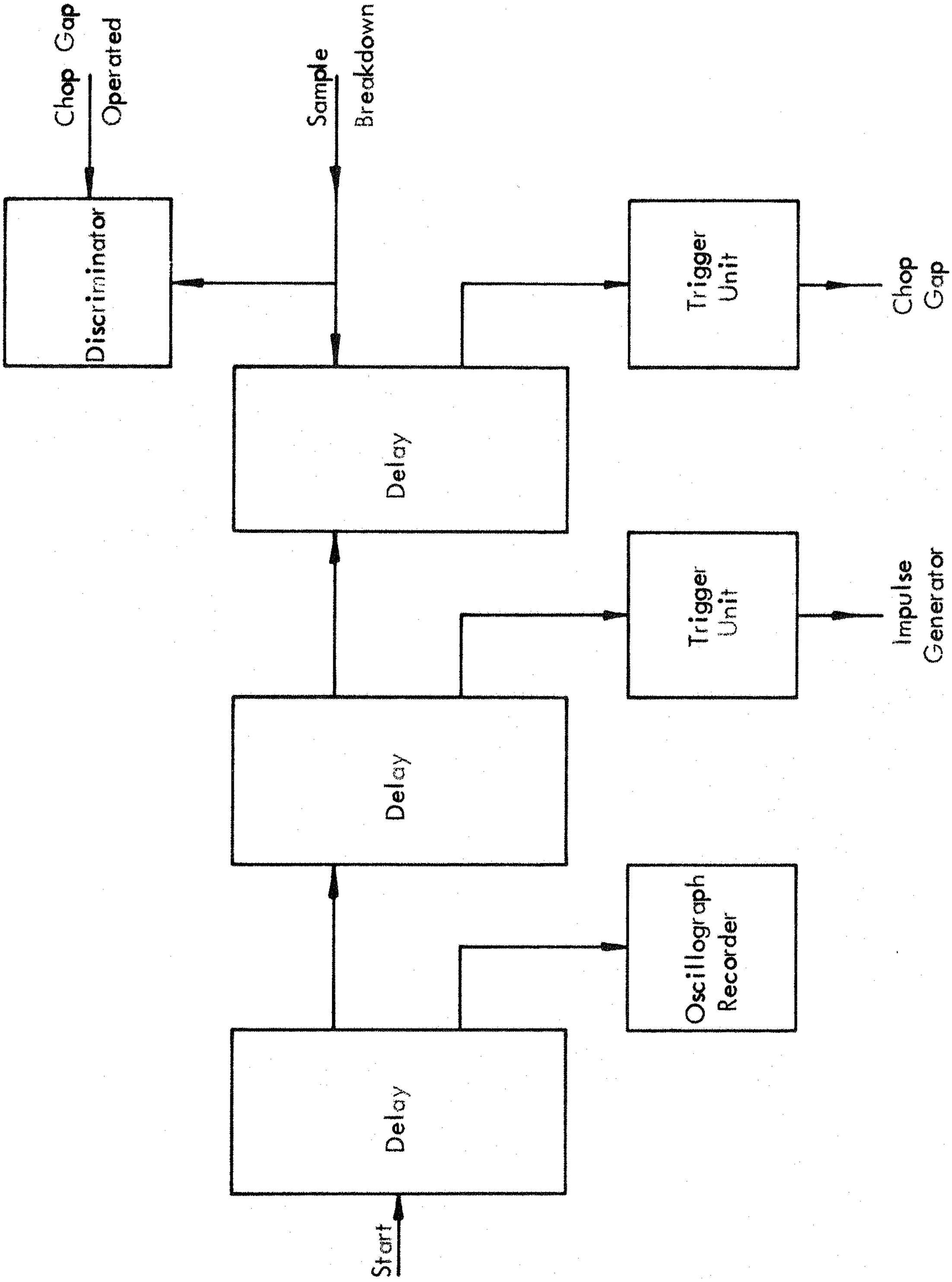


FIGURE 8.1 BLOCK DIAGRAM OF CONTROL CIRCUITS

and components sited to reduce capacitive shunting or induced voltage effects.

Most of the circuits used thermionic values; the larger signals giving better signal to noise ratios. Where solid state circuits were used complete isolation of power supplies, signal leads and earth connections was provided.

Ferrite cored pulse transformers were used to couple signals to the control equipment, this eliminated earth loop problems, allowed trigger amplitude adjustments, and the addition of damping to avoid unwanted interference voltages and also isolated the control equipment from the generator earth. The generator trigger thyratron caused the subsequent stages of the unit to maloperate; it was therefore placed on the bottom stage of the generator. In this way interference was kept at an acceptable level.

8.2 The Delay Unit

Referring to figure 8.2, the thyratron V1 is fired by closing S1, the output being taken to V2 and V3 via a potentiometer. The delay times of these two thyratrons will depend upon the potentiometer and their grid to cathode capacitance, this being variable in the case of V3. The output of V2 starts the oscillograph, whilst V3 starts the impulse generator via its cathode follower (V4) and trigger unit.

The delay time of V7 is selected either by the value of the resistance capacitance network in its grid circuit or the

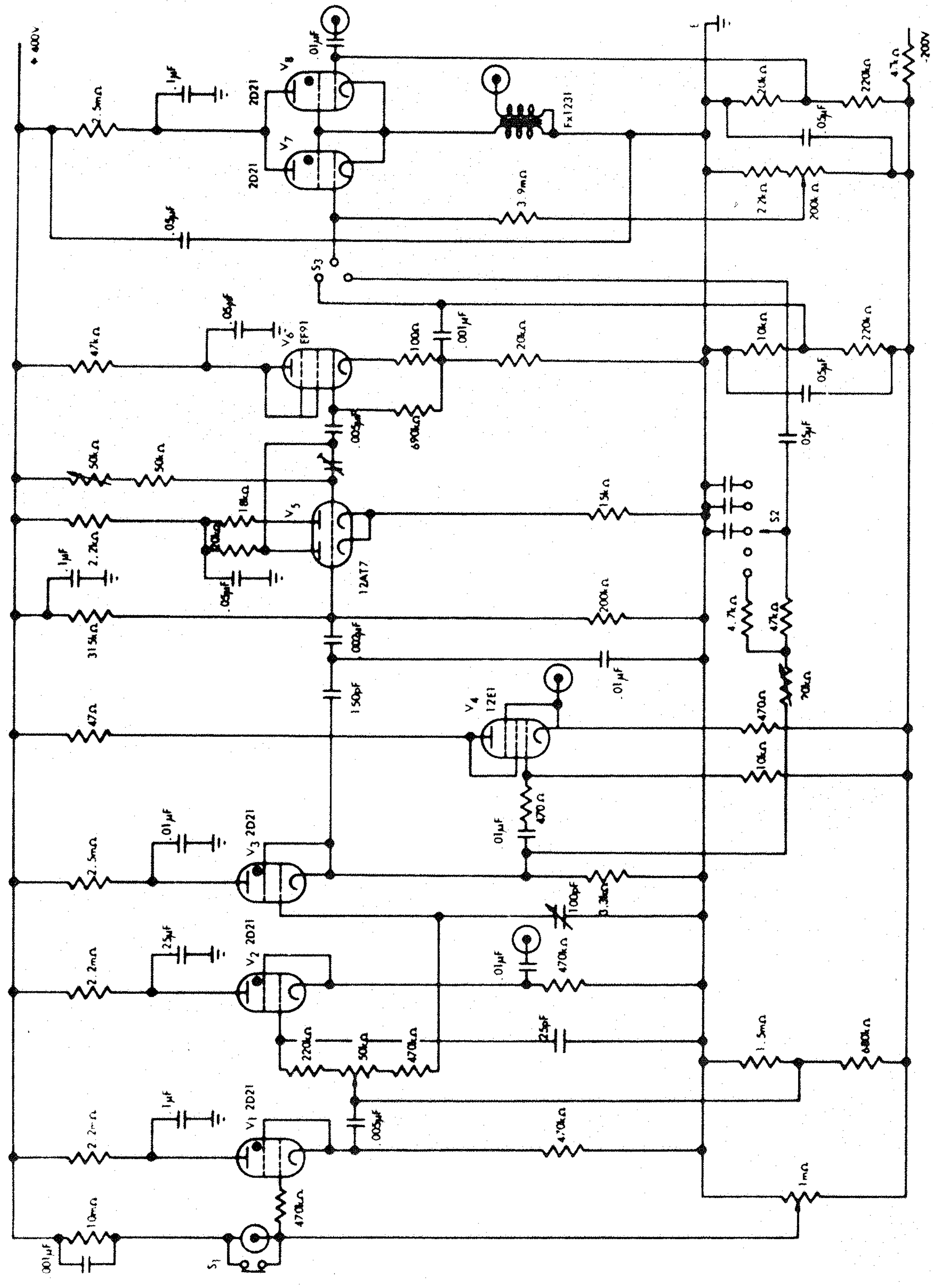


FIGURE 8.2 CIRCUIT DIAGRAM OF DELAY UNIT

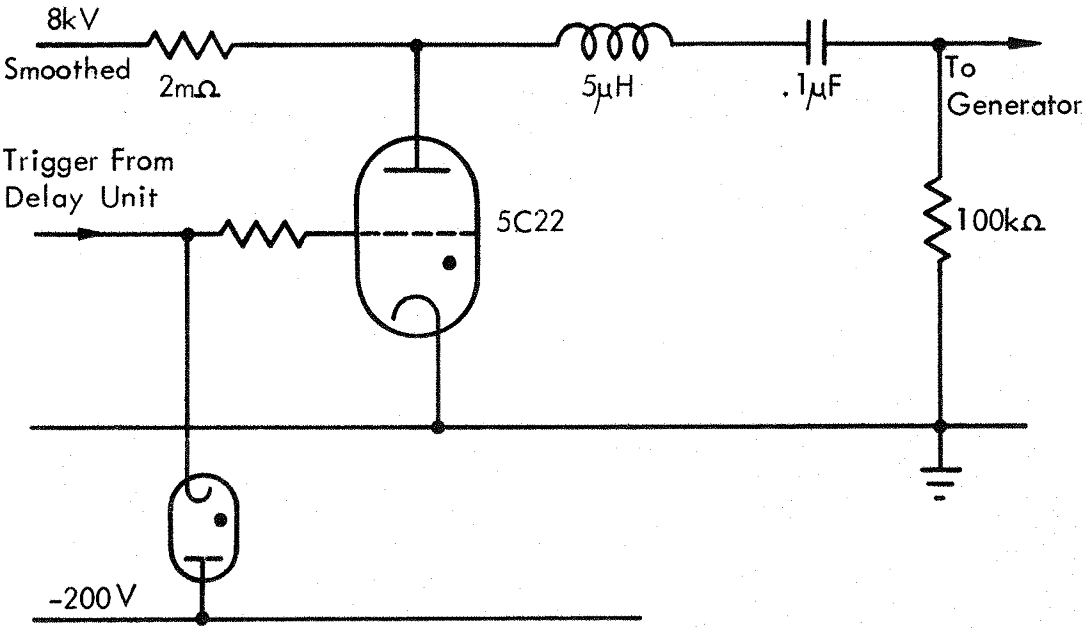
switching time of the monostable V5. Switch S3 selects either the short delays obtainable with the resistance capacitance network or the longer delays from the monostable. The output of V7 or V8, the two being in parallel, causes the chop gap to fire via the trigger unit, coupling being achieved with a ferrox-cube cored transformer. V8 is fired if the sample breaks down before the delay unit fires V7, thus chopping the gap immediately.

The thyratrons in the delay unit are self-extinguishing so as to avoid damage to the anode. On firing, the anode capacitor is discharged and the recharging current in the anode resistor depresses the anode voltage until the thyratron extinguishes.

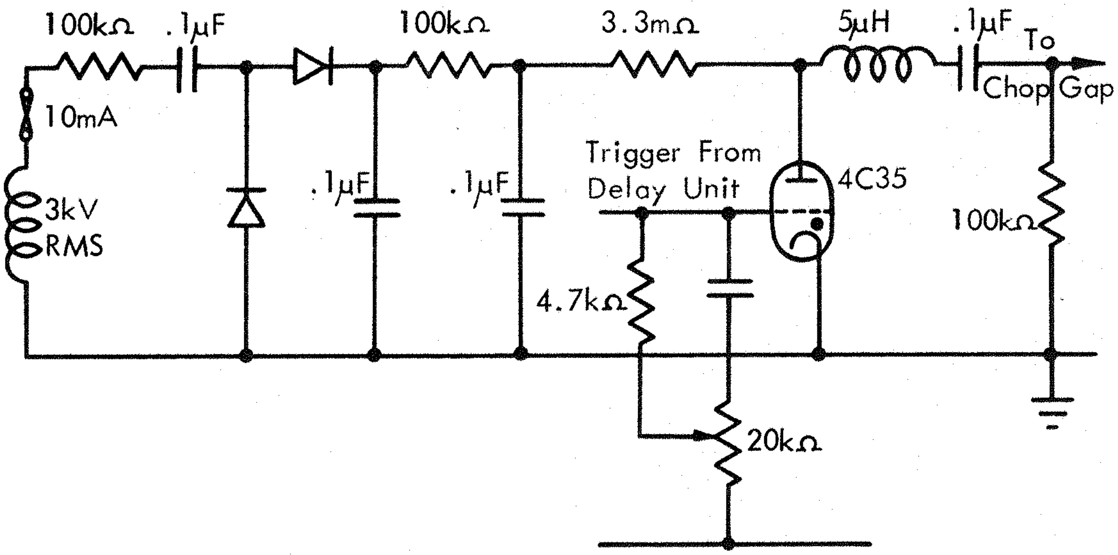
8.3 The Trigger Units

Figure 8.3 shows the two trigger units which are similar. A pulse from the delay unit fires the thyratron discharging the main capacitor across the 100 kΩ resistor. This voltage then triggers either the impulse generator or the chop gap depending upon which trigger unit is fired. The thyratrons are self-extinguishing due to the high series charging resistor. Gas clean up in these thyratrons will lead to current chopping and therefore must be avoided. Small air cored inductors are sufficient to limit the rate of rise of current to 1500 ampres per micro-second, a safe figure.

The impulse generator trigger unit caused maloperation of the control circuit due to the large negative pulse which appears at the grid of the thyratron during de-ionisation. A cathode



(a) Circuit Diagram of Generator Trigger Unit



(b) Circuit Diagram of Chop Gap Trigger Unit

FIGURE 8.3 CIRCUIT DIAGRAMS OF TRIGGER UNITS follower input and a reverse current diode were incorporated to eliminate this problem.

8.4 The Discriminator Unit

The logic of the discriminator is shown in figure 8.4. A signal A arriving and operating section A causes a signal $\overline{A}$ to paralyse section B until the reset is operated.

As shown in figure 8.5 the unit consists of two bistables with 'AND' gate inputs; their outputs switching a power transistor which lights a lamp. The off state is achieved by resetting; a pulse arriving at the input will cause the bistable to switch if the other bistable is off. Now a signal is sent to the AND gate of the second bistable thus paralysing it. The unit operated on a 6 volt pulse of 1 μs and discriminated between two such pulses 0.7 μs apart.

A general view of the control equipment is shown in figure 8.6.

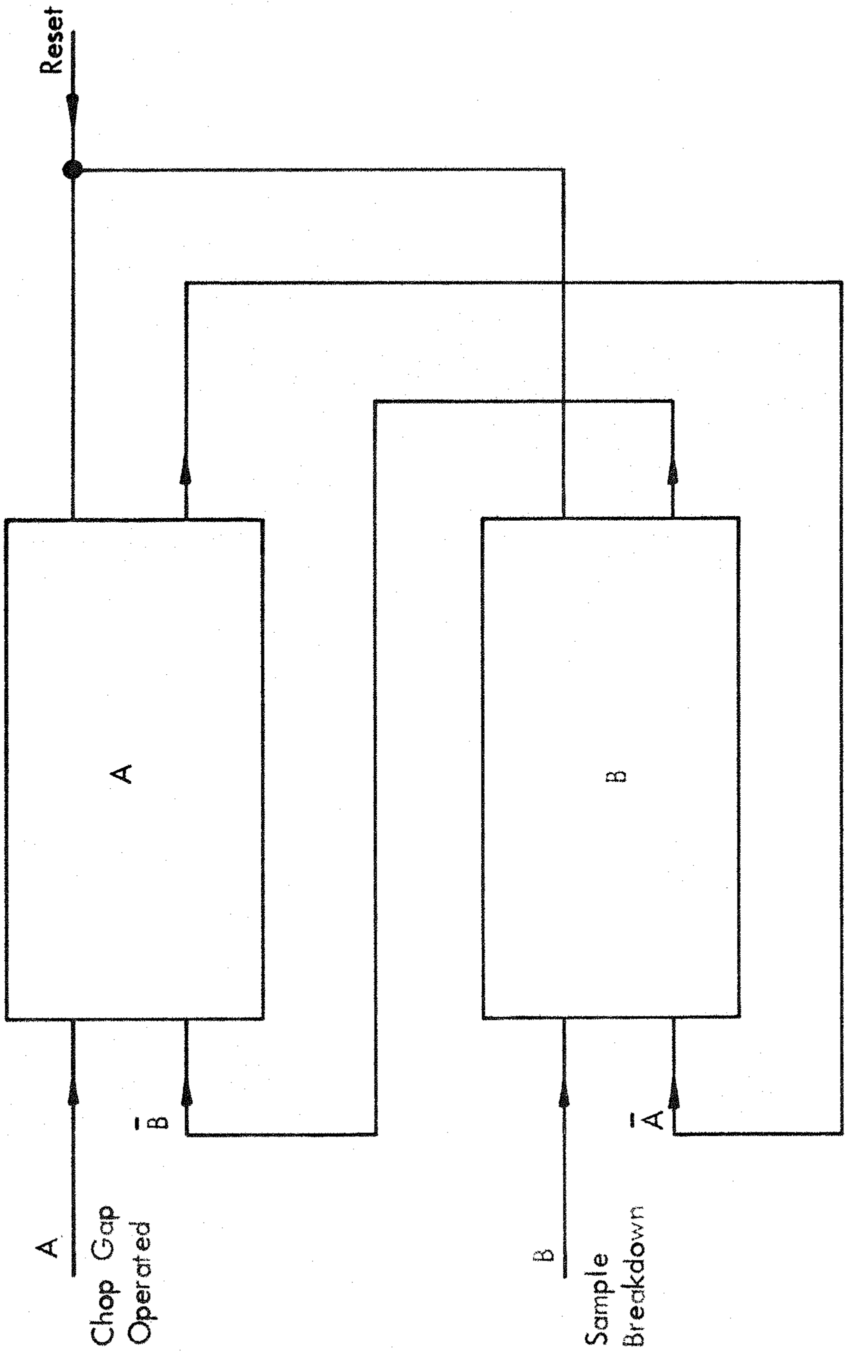


FIGURE 8.4 LOGIC DIAGRAM OF DISCRIMINATOR UNIT

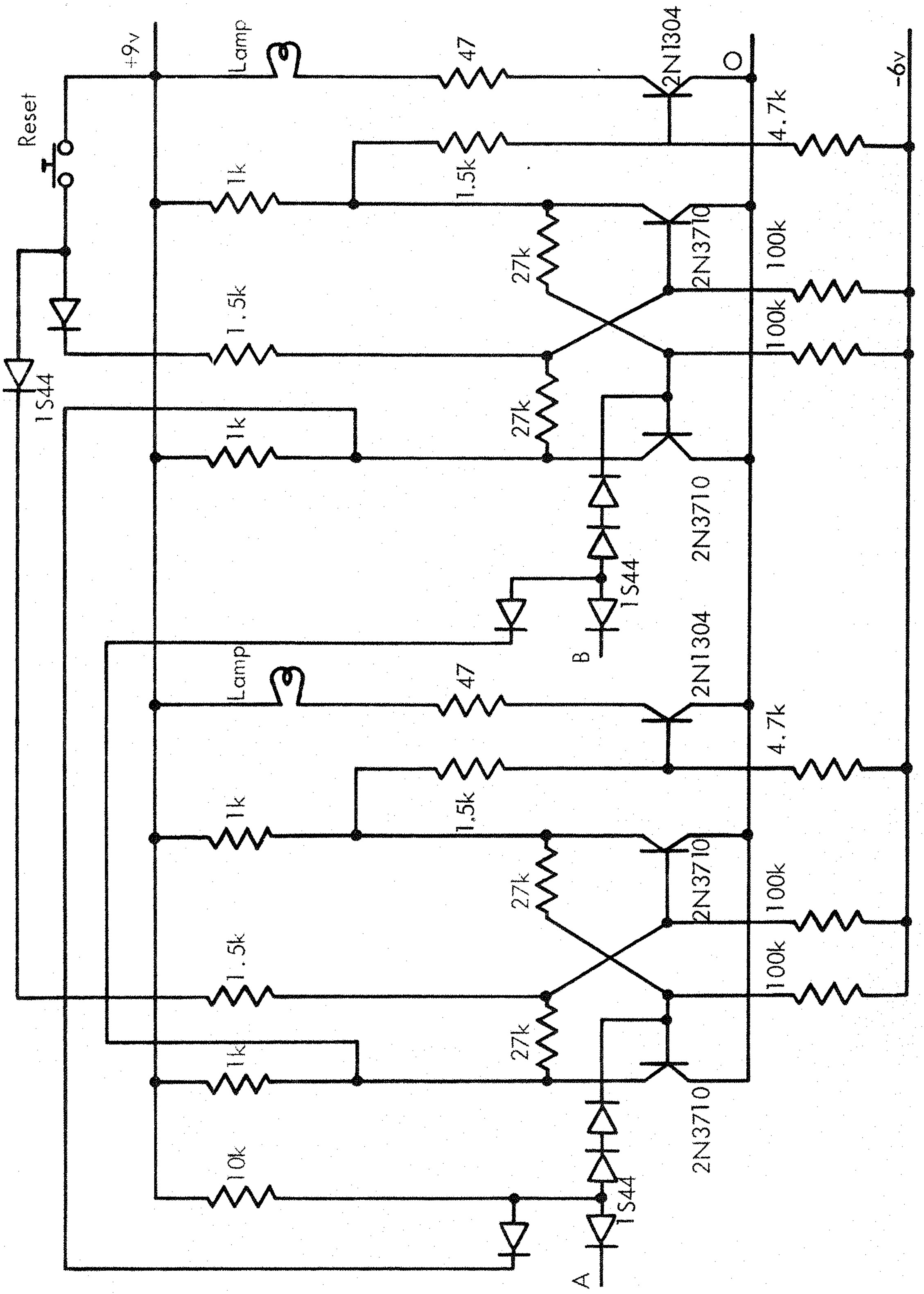


FIGURE 8.5 CIRCUIT DIAGRAM OF DISCRIMINATOR UNIT

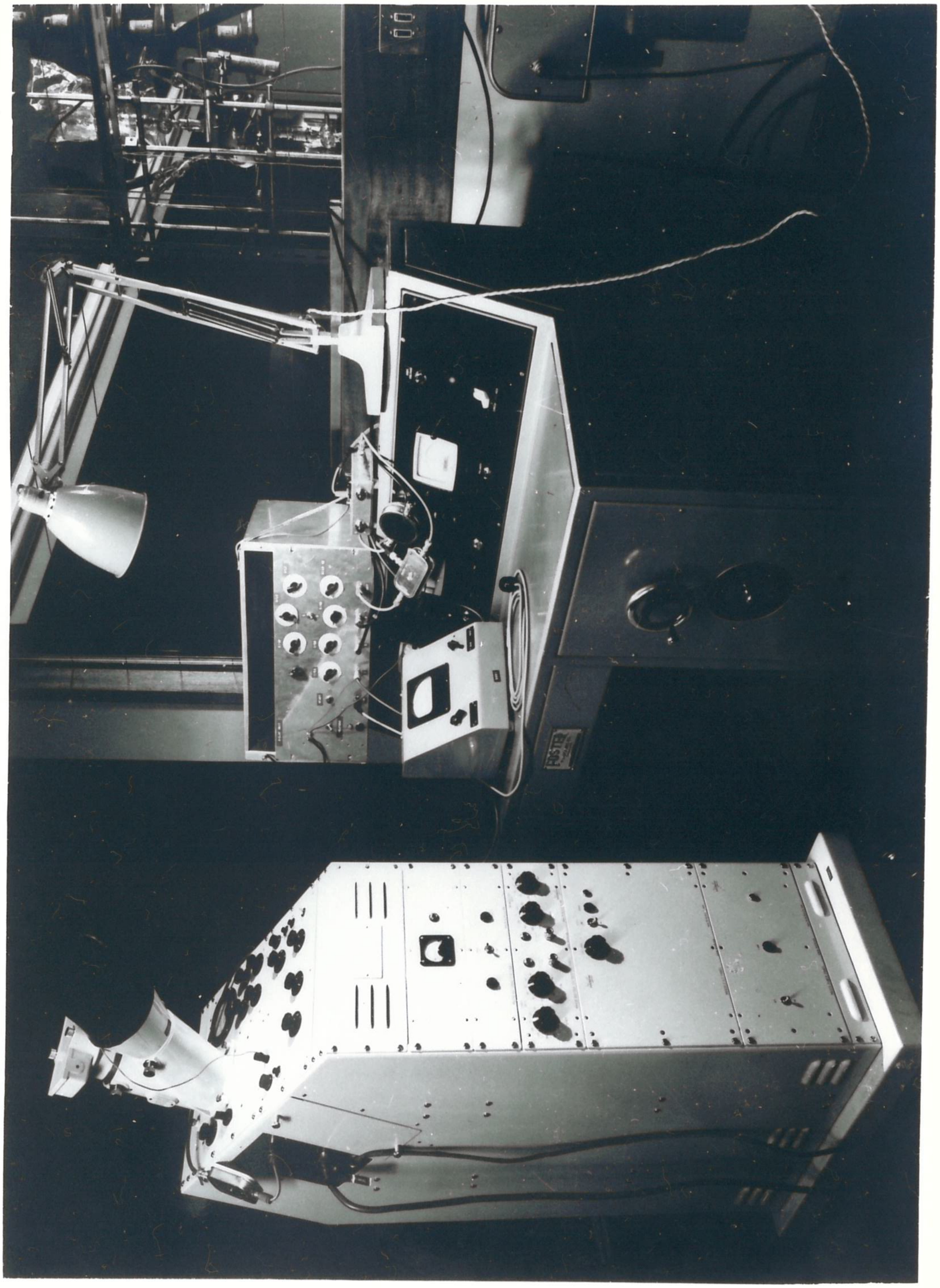


FIGURE 8.6 GENERAL VIEW OF CONTROL AND RECORDING EQUIPMENT

CHAPTER 9

RECORDING THE IMPULSE VOLTAGE TRANSIENT

9.1 The Transient Recorder

The instrument used was a type TR 12B, manufactured by Southern Instruments Ltd., the design of which is based on that described by White (9.1). An internal oscillator allows calibration of the variable (0.2µs to 1 ms) sweep to within 2% and an internal resistor chain allows calibration of the vertical axis to within 1%. The maximum level of input signal is 600v, thus allowing the use of a low resistance potential divider (chapter 6.2).

A 35 mm camera was built into the viewing hood of the transient recorder, and it was found by experimentation that a combination of fast film and forced development produced consistently good recordings.

9.2 The recording material and developing technique

Using Ilford HPS film and Johnsons Capitol developer with an extended development period, it was possible to use a rating of 3200 ASA for the blue phospher of the TR 12B. The fog level was raised by this technique but the traces were very dense and easily readable.

9.3 Analysis of the Oscillogram

The oscillograms were measured by means of a film motion analyser working in the single framing mode. Such a method allowed measurements to be made to within 0.1 mm.

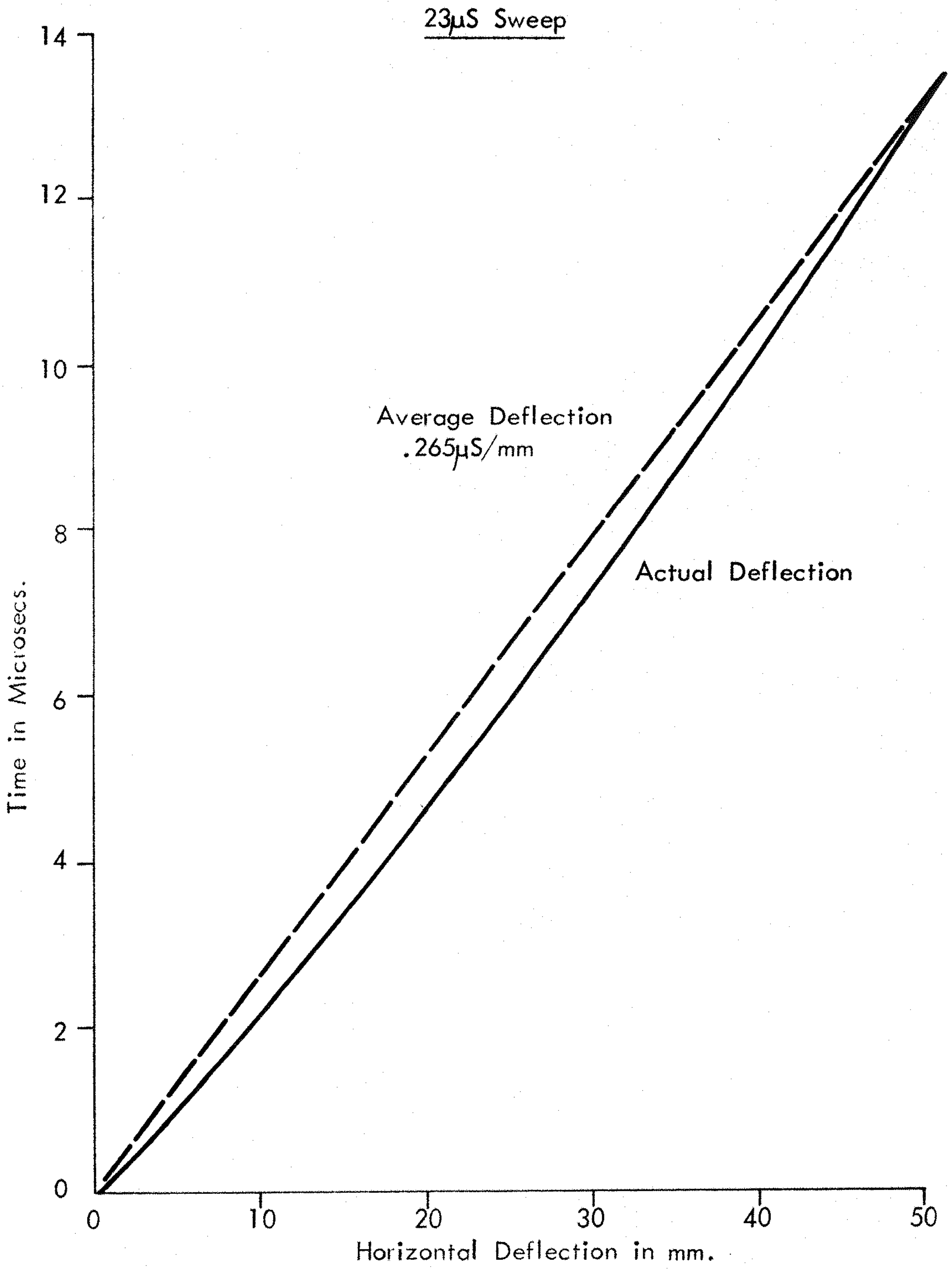


FIGURE 9.1 NON - LINEAR HORIZONTAL DEFLECTION

The horizontal and vertical deflection sensitivities were obtained by measurement of the oscillograms of the timing oscillator and vertical shift respectively. No variation in vertical deflection sensitivity was detectable over the working area of the tube face and hence was considered linear to within ± 2%, the estimated overall measuring accuracy.

The graph of sweep time against deflection (figure 9.1) shows a non-linearity of about 10% at the screen edges and also a curve which was noted with all other speeds. The average slope of this curve was used in subsequent calculations and all oscillgrams were positioned in the centre of the tube where it is estimated the linearity is within ± 5%. Figure 9.2 shows the error between each sweep speed which is not more than 7%, thus all sweep speeds were used without any correction. All the oscillograms were thus converted to voltages and times for further consideration.

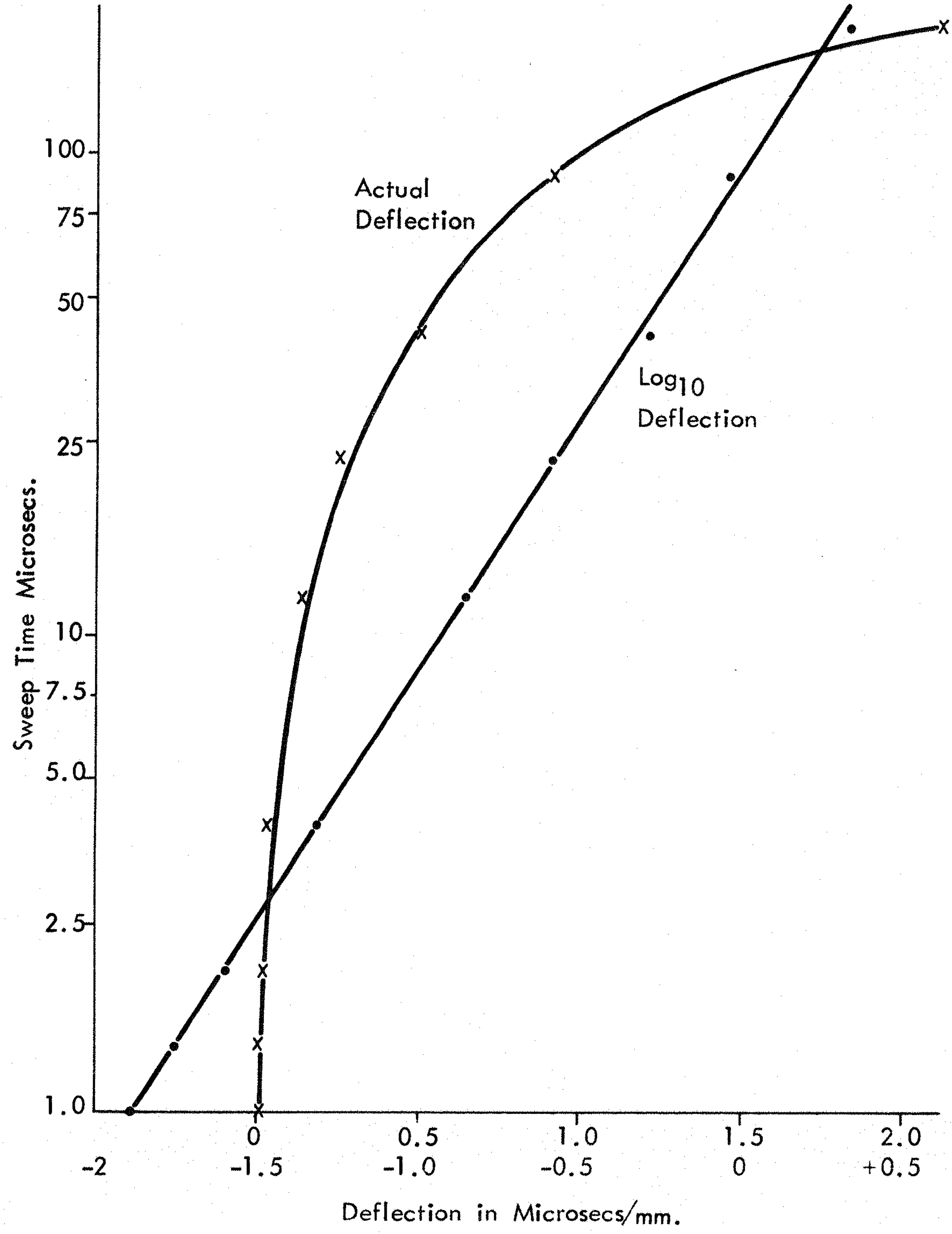


FIGURE 9.2 COMPARISON OF THE AVAILABLE SWEEP SPEEDS

CHAPTER 10

PROCEDURE

10.1 Preliminary Breakdown Measurements

Using a porosity No. 3 filter some breakdown measurements were made in order to ascertain that all the equipment worked correctly. The performance of the chop gap was also evaluated during this period. The electrodes were then removed, examined, repolished and the system re-assembled with a porosity No. 4 filter.

10.2 Breakdown Measurements

The following procedure was adopted for the breakdown measurement and adhered to for each sample and test condition.

The impulse level was gradually raised with successive shots until the sample breakdown point was reached. The protection and recording equipment was reset and the impulse level reduced, and the level once more raised until a breakdown occurred.

This was repeated ten times before any lowering of the breakdown level was observed; at this point the oil was re-circulated and filtered. The tests were then repeated to ensure no alteration of the breakdown level had taken place; the mean of these values was taken as the 'breakdown voltage' for that particular sample under the particular test conditions.

Three separate oil samples were tested with both negative and positive impulse voltages and at two different values of rate of voltage rise.

10.3 Results Analysis

The results of the breakdown measurements were analysed, and the breakdown values obtained converted into breakdown stress levels for comparison with other results. The values with which the results were compared include those expected from normal untreated oil; dried and de-gassed oil and oil prepared by very sophisticated cleaning plant.

The results for the three different oils are also compared.

CHAPTER 11

RESULTS

11.1 Preliminary Breakdown Measurements

Using a sample of the Gulf oil and a wavefront control resistor of 13000Ω the breakdown voltages were 61.8 KV with a positive impulse and 68.2 KV with a negative impulse.

The times to breakdown were measured as 7.5 μS and 9.0 μS respectively. These results were used to plan and set up the major part of the experiments.

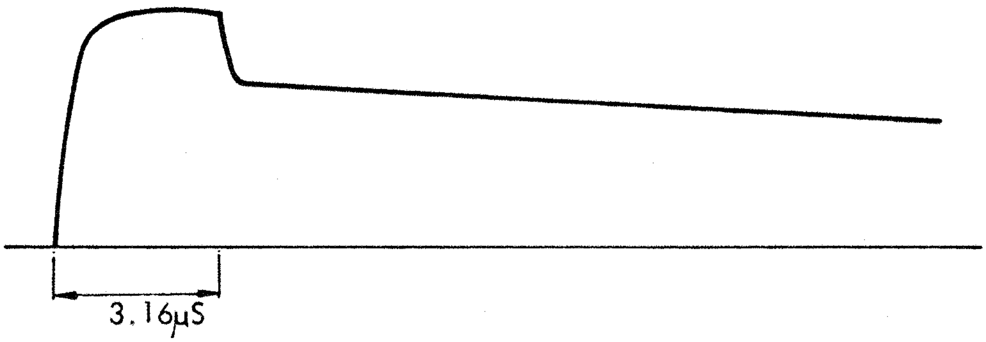
Figure 11.1(a) is an oscillogram of the impulse voltage showing a non-sustained breakdown of the sample. The energy stored in the capacitance of the test circuit and the cell was discharged into the sample; the voltage fell and the sample recovered. Measurements of the voltage fall were made for sixteen tests and the average was found to be 5.12 KV.

Now the energy discharged in the sample is :-

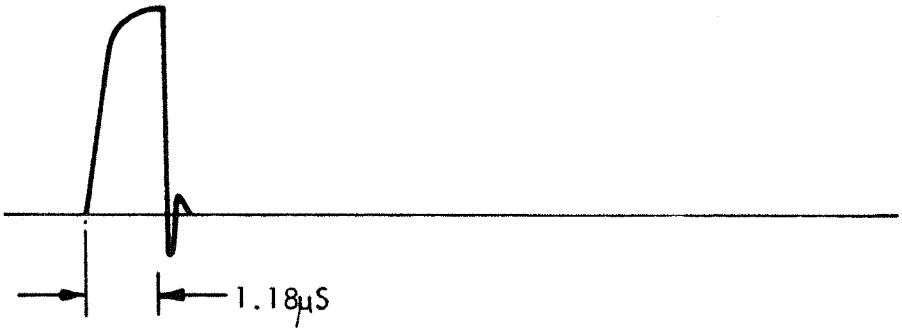
$$\frac{1}{2}\ CV^2 = \frac{1}{2} \times \frac{0.03}{10^6} \times (5.12 \times 10^3)^2 = 0.4 \text{ joules}$$

Figure 11.2(a) shows the damage sustained by the electrodes under these conditions. The oil rapidly became contaminated and required frequent re-circulating.

Figure 11.1(b) shows the effect of the chop gap operating, the voltage being forced to zero in a very short time. The energy now discharged in the sample is limited to that stored in the cell capacitance. Assuming a maximum operating voltage of 100 KV this will

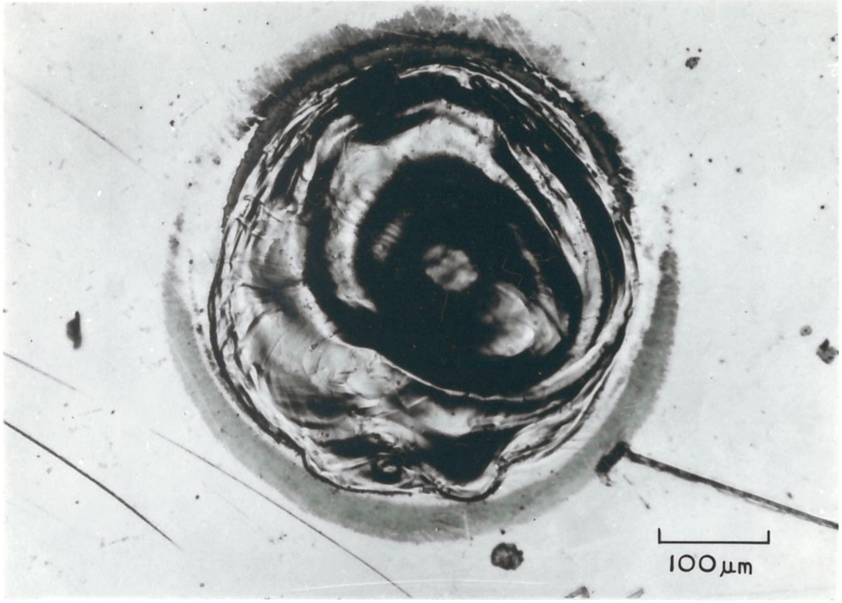


(a) Without Chop Gap Operating

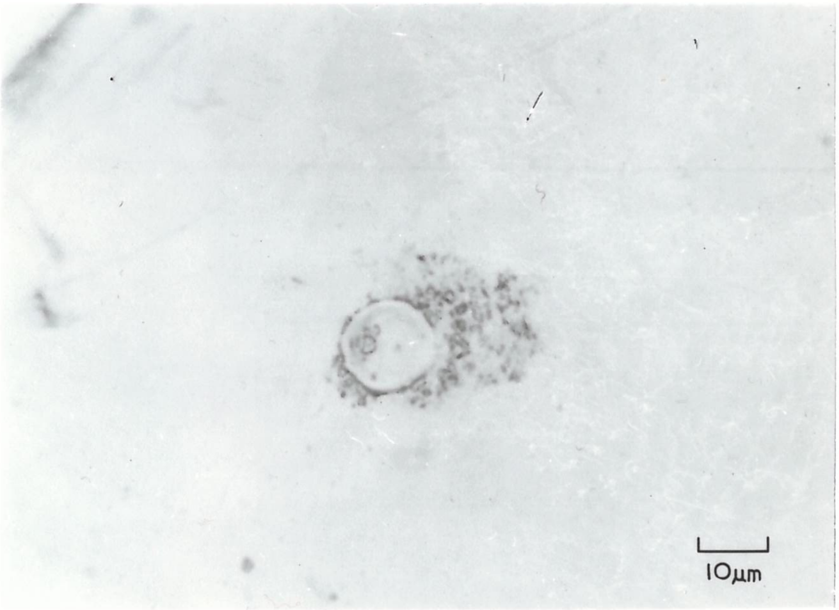


(b) With Chop Gap Operating

FIGURE 11.1 OSCILLOGRAMS OF BREAKDOWN EVENTS



(a) Preliminary Tests Without Chop Gap



(b) Breakdown Measurements Using Chop Gap

FIGURE 11.2 CRATER DAMAGE ON ELECTRODE SURFACE

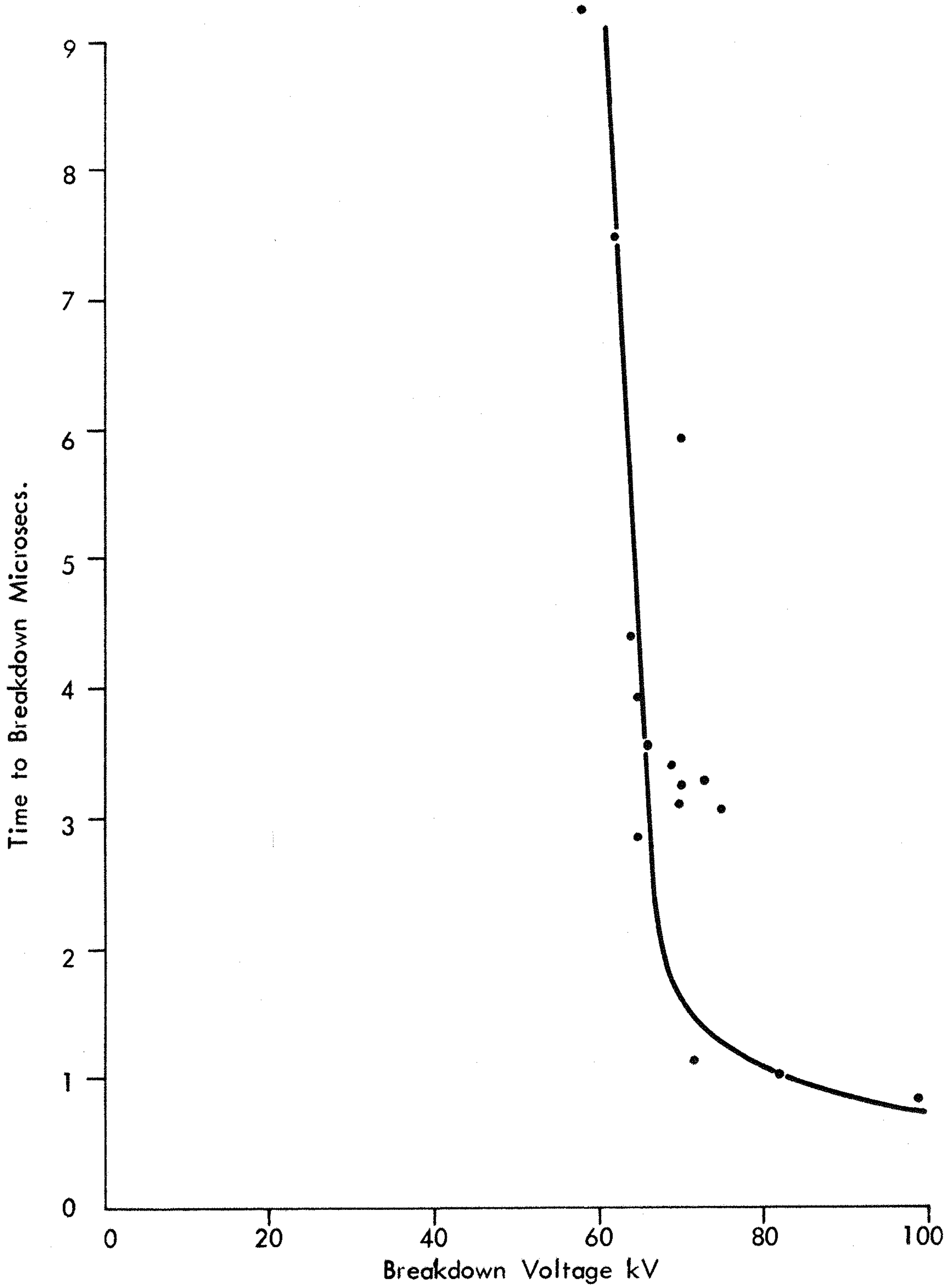


FIGURE 11.3 TIME TO BREAKDOWN

now be :-

$$\frac{1}{2} \times \frac{35}{10^{12}} \times (100 \times 10^{3})^{2} = 0.175 \text{ joules}$$

The damage to the electrodes is now much less as can be seen in figure 11.2(b). With the chop gap operating it was possible to carry out ten breakdown measurements before re-circulation became necessary.

11.2 Breakdown Measurements

The oil was filtered using a porosity No. 4 sintered glass filter.

POLARITY	POSITIVE		NEGATIVE	
FRONT CONTROL RESISTOR	13000 Ω	3000 Ω	13000 Ω	3000 Ω
GULF OIL	75	70	71.8	65
CASTROL OIL	75	70	82	72
TEXAN OIL	80	65	99	67

The results are expressed in KV/mm and the overall estimated accuracy is ± 2KV/mm.

The time to breakdown of all the samples for all conditions plotted against breakdown stress is shown in figure 11.3

CHAPTER 12

DISCUSSION

12.1 Results

The preliminary measurements were made in order to explore the levels at which breakdown was expected and to ensure that all the apparatus was working correctly. The results were also used to plan the series of breakdown tests.

The value of the high speed chop gap was demonstrated as applied to measurements on liquid dielectrics. The large craters formed when the chop gap was not operated would have led to erratic and inconsistent results. The sides of the craters are raised and so locally enhance the field, encouraging emission. Vapourised metal would form small particles drifting in the gap as would carbon from the decomposed oil.

With liquids which do not decompose on breakdown, for instance liquid Argon, the first two of these objections are valid. Using very fast chop gaps it may be possible to study partial breakdowns in liquids since electrode and sample damage would be much reduced.

No conditioning phenomena was observed, since within the limits of measurement there was no change in breakdown voltage until the oil became contaminated, when the strength dropped rapidly.

Previous work (for instance, 1.1, 2.4) has shown a conditioning process and such a phenomena is widely accepted and expected. The usually accepted explanation is one of successive clean up of both the liquid and electrodes. Dust particles within the liquid will be broken down into smaller particles by the breakdowns thus

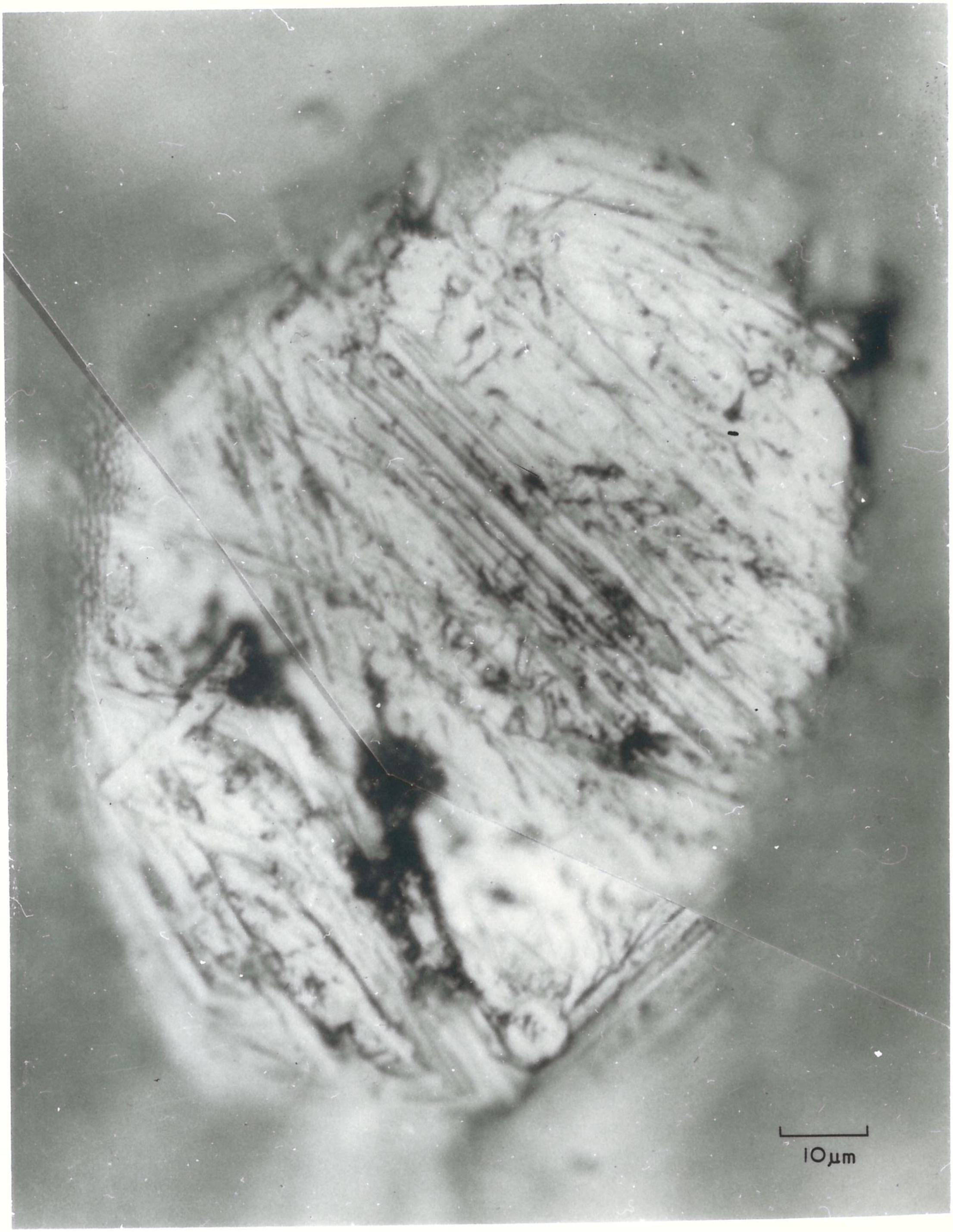


FIGURE 12.1 CENTRE OF LARGE CRATER ON ELECTRODE SURFACE

raising the strength of the liquid. Dust particles or protrusions on the electrode surface will be destroyed thus reducing the number of preferential emitting sites.

Maksiejewski and Tropper (12.1) showed that when great care was taken with filtering the oil and cleaning the test cell and electrodes no conditioning was observed. Krasucki (12.2) has also reported that no conditioning is seen with a clean system and pure liquid. In the present work, care was taken to ensure that any dust particles present were small and that the test cell and electrodes were clean. Conditioning therefore would probably be reduced in magnitude.

Crowe (2.15) has shown that the electric strength of a liquid will increase with decreasing voltage pulse duration, but that with pulse durations longer than some critical time t_o the electric strength is constant. It was demonstrated that this time increased with electrode separation; and interpolation of the results would give a time t_o of 1.6 μs for a 1×10^{-3} metre gap. Figure 11.3, although not very complete gives a t_o of 1 to 2 μs which is of the correct order.

The results for the Castrol oil and the Gulf oil are very close, and since they are of a completely different origin, demonstrate the effect of blending to achieve consistent oils. The Texan oil which does not conform to BSS 148, is a highly aromatic oil and in this case has the highest electric strength.

Figure 12.1 shows the centre portion of the crater in figure 12.2(a) greatly magnified. The centre consists of a flat

PREVIOUS WORK	REF.	STRESS KV/mm	GAP mm	SOLID IMPURITIES	WATER CONTENT	DISSOLVED GAS
MINERAL OIL BSS 148		15	4	None Visible	Crackle Test	No reduction+
KOK	2.20	20	4	-	-	Reduced
SKOWRONSKI	2.8	30-40	2.5	No filter	0.01%	No reduction
SCHOBER	12.3	30-35	0.75-2.5	Cellulose Fibre	1-2ppm	Reduced
WATSON, HIGHAM	2.4	60	1	20 µm	Reduced	0.1mmhg
GOSLING	12.4	70	0.5	Filtered	No reduction	No reduction
PRESENT		80-100	1	1 µm	Dried	10^{-2}torr
ZAKY ET AL	2.10	100	0.25	1 µm	Dried	10^{-2}torr
GOSLING	12.4	110	0.5	Filtered	Dried	Degassed
DARVENIZA	1.1	113-130	0.075-0.125	1 µm	10^{-2}ppm	10^{-2}ppm
N-HEXANE MAKSIEJEWSKI ET AL	12.1	40-70	0.25	1 µm	Refluxed	Varied*
CROWE	2.15	143	0.01	1 µm	Dry	No reduction *
WARD, LEWIS	2.16	180	0.1	1 µm	Dry	Reduced*
LIQUID ARGON SWAN, LEWIS	2.17	120	0.05	VERY PURE SAMPLE		

+ OIL OF TECHNICAL PURITY   * PURE GRADE OF N-HEXANE

FIGURE 12.2 COMPARISON OF PREPARATION TECHNIQUE WITH PREVIOUS WORK

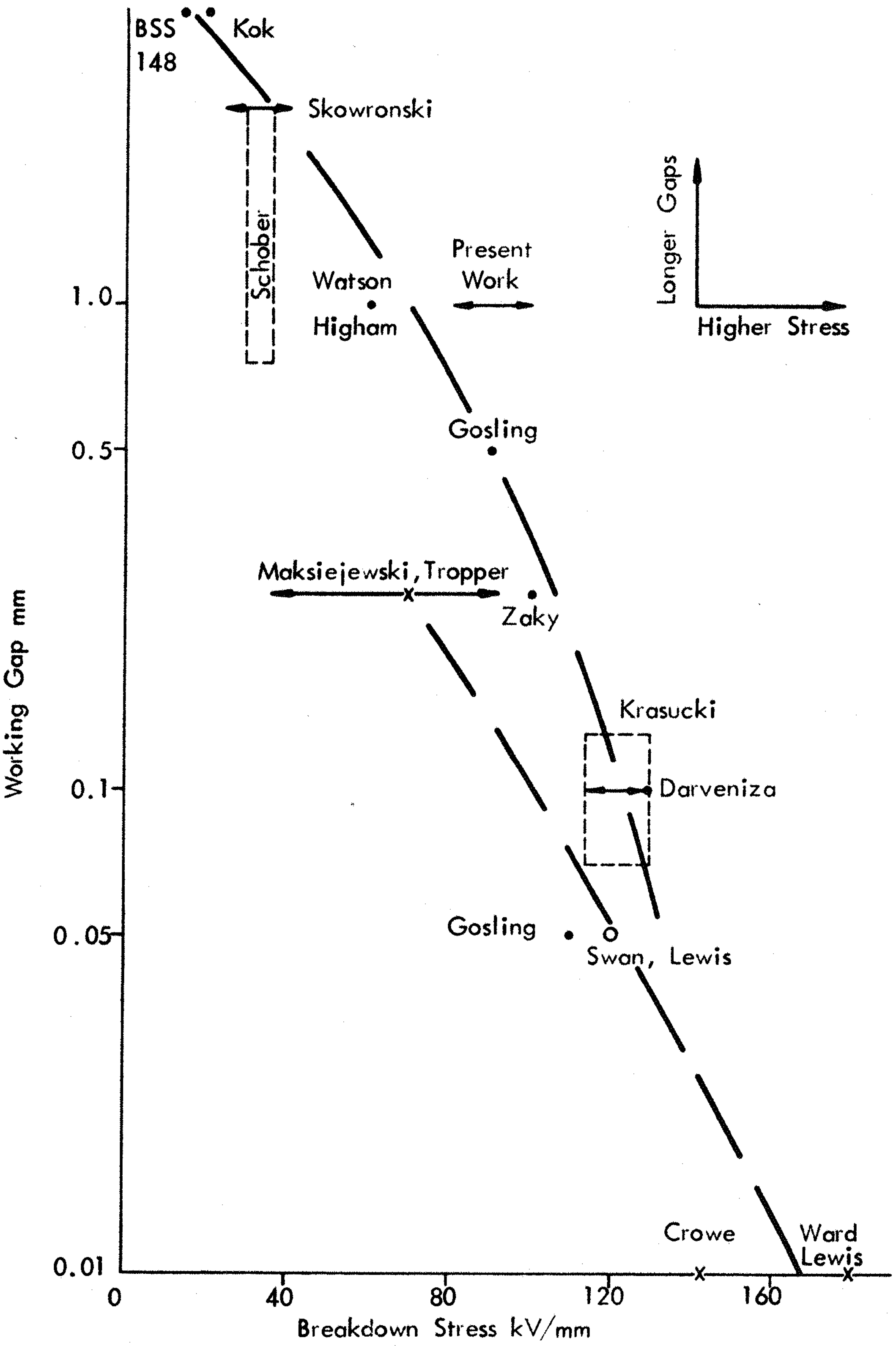


FIGURE 12.3 COMPARISON OF RESULTS WITH PREVIOUS WORK

area very nearly parallel to the surface, approximately 50 x 40 µm. A possible explanation is that during polishing, a small particle became embedded in the surface and upon application of the impulse, was torn free thus leaving a flat bottomed crater. The smaller craters formed when the chopping gap was in operation are too small for microscopic examination and very much shallower; such formations may exist in these as well.

12.2 Comparison with Previous Results

Much of the previous work on liquid breakdown has been carried out either using large gaps and relatively impure samples, or very small gaps and very pure samples. This tendency is shown in figure 12.2, where the various preparation techniques are compared. Figure 12.3 illustrates how the present work presents results that have not been obtained before. The area bounded by the curve represents well explored regions, hence any results outside this area will represent an improvement in breakdown stress at the gap length considered. The importance of using large gaps is discussed later.

It will be seen that Watson and Higham (2.4) and Schober (12.3) have previously investigated the breakdown stress using gaps of about 1 mm and have obtained lower results. Watson and Higham used a closed circuit filter, but their equipment differed in some details from the present equipment. The sintered glass filter was 20 µm pore size, and thus one could expect free particles of this size to be present in the sample; in fact fibres were reported to be seen after filtration. The oil is degassed more efficiently if the foam is heated; Watson and Higham did not heat the oil foam, neither did they subject it to a vacuum of the same order as that used in the present work. It is very probable therefore that their oil was not degassed or dried to the same degree.

During testing, a diverter was used, the time of operation claimed being 10 μs after breakdown, which is an order of magnitude slower than the present device, which would lead to greater degradation of the oil at each breakdown. Conditioning was reported and shown to be much less pronounced when additional purification was undertaken. During the present work no conditioning was observed and this tends to indicate that the sample and system is cleaner.

Schober's work was mostly conducted with oil of 'technical purity' but dried, and hence his results are seen to be somewhat lower. Glass wool filters were used to eliminate solid impurities but no figures are quoted as to probable pore size. Vacuum was only applied in order to dry the oil and hence limited degassing would have taken place. The work represents the improvement which is to be made by simply drying the oil (1 ppm of water) and doing very little else.

Klinkenberg (12.5) has extended the analysis of the Helmholtz double layer at electrodes to liquid dielectrics. Since there are always some impurities present in a liquid then it is possible for free ions to exist and such a double layer is a reasonable suggestion. Such a layer present at the electrode surface would lead to the effective gap being smaller than the measured gap, since the charge layer would become an extension of the electrode.

Calculation of the thickness of this diffuse double layer for hydrocarbon oil similar to that used in the present work gives a value of approximately 0.2 mm.

Much of the previous breakdown measurements carried out with gaps of 0.01 mm to 0.1 mm would have been influenced by this layer. In fact it is not unreasonable to assume that the charges of the diffuse layer extend throughout the gap and greatly influence the electric field. It is for this reason that more work is required at large gaps, since the small gap work is not representative of practical problems.

The present work has demonstrated that it is possible to prepare large samples of very pure oil for investigational work, and has shown that hitherto uninvestigated areas (viz large gap and high stress) may be satisfactorily investigated.

12.3 Future Work

The generally accepted conditioning phenomenon was not observed during the present work, and clearly this needs more investigation. A continuation of the present work in fact would involve changes in the electrode surface and the degree of sample purity in an effort to establish whether a conditioning process appears with a less 'clean' system. As has been previously discussed, it appears that a very clean system may not exhibit such a phenomenon; this however has not yet been demonstrated. If on contamination of the present system, conditioning appears then it could be shown that such a process is a function of purity. Such work could lead to a better understanding of conditioning and the mechanism of breakdown during the process.

If instead of oil a simple hydrocarbon, for instance hexane, is used a better sample purity may be achieved; since hexane is prepared in a laboratory and has never come into contact with most of the impurities found in oil. No previous work has been done with hexane using a 1 mm gap; presumably because of the high voltages necessary to produce breakdown stress. It would therefore be of value to use the present system to investigate the breakdown of hexane, particularly as so much of the previous work has been done with gaps of less than 0.1 mm. As has been previously suggested some doubt as to the validity of measurements at small gaps does exist.

It became apparent during the present work that very few previous workers had measured the conductivity of the sample as well as its breakdown voltage. This is unfortunate, because the conductivity has been shown to be very sensitive to the degree of purity of the sample. Changes in conductivity of 10^5 have been produced with only a 10^2 change in breakdown stress (12.6). Control of, and a knowledge of the purity is very important, particularly if investigation into conditioning is to be carried out; therefore some method of measuring the conductivity should be developed and incorporated into the present system.

LIST OF REFERENCES

(1.1) Darveniza, M., Jnl. Inst. Pet. Vol. 46, No. 435, March 1960, p 84.

(2.1) Whitehead, S., Dielectric Phenomena, Vol. II, Electrical Dischargesin Liquids, Chapter 1, (London, Benn Bros.Ltd, 1928).

(2.2) Hoover, W. G., and Hixon, W. A., Transactions A.I.E.E., Vol. 68, p 1047, 1949.

(2.3) Martin, R. G., and Thompson, C. N., Brit. Jnl. Appl. Phys., Vol. 2, p 222, August 1951.

(2.4) Watson, P. K., and Higham, J. B., Symp. on Insulating Materials, 17-3-53 (IEE).

(2.5) Priaroggia, P. G., and Palandri, G., Jnl. Electrochem.Soc., Vol. 107, No. 11, pp 884 - 886, November 1960.

(2.6) Hancox and Tropper. Proc. IEE, Vol. 105A, p 250, 1958.

(2.7) Darveniza, M., Jnl. Inst. Pet. Vol. 46, No. 435, March 1960, p 84.

(2.8) Skowronski, J. I., C.I.G.R.E., Vol. 2, No. 131, 1962.

(2.9) Sletten, A. M., and Dakin, T. W., IEEE No. 64-22, February 1964

(2.10) Zaky, A. A., Zein Eldine, M. E., and Hawley, R., Brit. Jnl. Appl. Phys., Vol. 16, p 437, 1965.

(2.11) Hirobe, T., Ogawa, W., and Kubo, S., Electrician 78, p 656, 1917.

(2.12) Güntherschule, A., Radio Akt, 19 p 92, (1922).

(2.13) Lewis, T. J., Proc. IEE, Vol. 100, pt IIA, p 141, March 1953.

(2.14) Bragg, J. K., Sharbaugh, A. H., and Crowe, R. W., Jnl. Appl. Phys. Vol. 25, No. 3, p 382, March 1954.

(2.15) Crowe, R. W., Jnl. Appl. Phys. Vol. 27, No. 2, p 156, February 1956.

(2.16) Ward, B. W., and Lewis, T. J., Jnl. Electrochem. Soc., Vol. 107, No. 3, p 191, March 1960.

(2.17) Swan, D. W., and Lewis, T. J., Jnl. Electrochem. Soc., Vol. 107, No. 3, p 180

(2.18) Chadband, W. G., Wright, G. T., Brit. Jnl. Appl. Phys., Vol. 16, p 305, 1965.

(2.19) Brière, G. B., Brit. Jnl. Appl. Phys., Vol. 15, p 413, 1964.

(2.20) Kok, J. A., Electrical Breakdown of Insulating Liquids, Philips Technical Library, 1961.

(2.21) Krasucki, Z., E.R.A. Report No. 5157.

(2.22) Krasucki, Z., E.R.A. Report No. 5212

(2.23) Garton, C. G., Krasucki, Z., Proc. Roy. Soc. A 280, p 211-226, 1964.

(2.24) Lewis, T. J., High Voltage Technology, Oxford University

(4.1) Hylten-Cavallius, H., Fryxell, J., Paper 104, C.I.G.R.E., 1962, Vol. 2.

(4.2) Krasucki, Z., Private Communication.

(4.3) I.C.I. Publication Sf B Dn 6, UDC 678-415.

(5.1) Bruce, F. M., Proc. IEE, Part II, 94, (1947), p 138.

(6.1) Edwards, F. S., Husbands, A. S., Perry, F. R., Proc. IEE, 98, p 155, 1951.

(6.2) Grover, F. W. G., Inductance Calculations, Dover, Chapter 8, 1946

(6.3) I.E.C., 60, High Voltage Test Techniques, 1962.

(6.4) Hawley, W. G., Impulse Voltage Testing, Chapman and Hall, 1959.

(6.5) Payne, M. R., Fiden 3, A Program for the Transient Response of Electrical Networks, C.E.G.B. Report RD/C/N190.

(6.6) Morton, A. H., Advanced Electrical Engineering, Pitman, 1966.

(7.1) Craggs, J. D., Haines, M. E., Meek, H. M., Jnl. IEE, Pt IIIA, 93, p 963, 1946.

(7.2) Broadbent, T. E., Cooper, R., Jnl. Sci. Inst., 38, p 504, 1961.

(7.3) Williamson, J. D., 1451-2 S.C.T.M. 186-59(14) May 1959. (Office of Technical Services, Department of Commerce, Washington 25 D.C.).

(8.1) Stark, K. H., Higham, J. B., E.R.A. Technical Report E/T 70, 1958.

(9.1) White, E. L., E.R.A. Technical Report S/70.

(12.1) Maksiejewski, J. L., Tropper, H., Proc. IEE, Vol. 101, pt 2, 1954, p 183.

(12.2) Krasucki, Z., Discussion Meeting, 13.12.67, Savoy Place, IEE, J2.

(12.3) Schober, J., Strittmatter, W., Bull. Assoc. Suisse Elect. Vol. 59, No.1, p 13.

(12.4) Gosling, C. H., JIEE, p 380, September 1963.

(12.5) Klinkenberg, A., Electrostatics in the Petroleum Industry, Elsevier Pub. Co., 1958.

(12.6) Bright, A. W., Private Communication.