

UNIVERSITY OF EDINBURGH
DEPARTMENT OF ELECTRICAL ENGINEERING

THE EFFECT OF PHASE CONTROL ON THE
ENERGY CONTENT OF A.C. ARCS

being a Thesis submitted by
NORMAN EDWARD McOUAT CUTHBERTSON, B.Sc. (Edin.)
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LIST OF SYMBOLS

in order of appearance

| | |
|-----------------|--|
| t_0 | instant of contact separation measured from current zero |
| I_a | arc current |
| v_a | arc voltage |
| 'L' | critical length of arc |
| v | velocity of contact separation |
| a | acceleration on contact separation |
| α | angle of rotation of machine rotor |
| N_s | number of turns on transformer secondary winding |
| N_p | number of turns on transformer primary winding |
| L | transformer inductance |
| m | mass |
| k | stiffness of spring |
| F_0 | spring load |
| x | displacement |
| v | velocity |
| P | acceleration |
| g | acceleration of gravity |
| t | time |
| s | total displacement |
| T | total time |
| M | bending moment |
| σ | ultimate tensile strength. |
| a | acceleration of trip lever |
| I | Moment of Inertia |
| P | Load |
| α' | angular acceleration |
| r | radius of flywheel |
| T | Torque |
| μ | coefficient of friction |
| R_a | arc resistance |
| K', K'', K''' | constants |
| n | number of ions in arc space |
| n_p | number of ions produced |
| n_r | number of ions recombined |
| T_a | arc temperature |

- δ angle of lag between arc temperature and current
 ϵ angle of lag between an ion recombining and being produced
 θ angle of contact separation before current zero
 Σ effectiveness ratio of phase control = $\frac{W_a (\theta = 180^\circ)}{W_a (\theta = 0^\circ)}$
 W_a arc energy
 P circuit power
 L extinction level
 l gap length
 F_n function of
 i instantaneous arc current
 v_c cathode voltage drop
 $\alpha, \alpha', \beta, \delta, \delta, \text{ etc}$ constants in arc voltage equations
 n exponent of Nottingham's equation
 T_B boiling point of arc anode
 \hat{V}_a peak arc voltage
 v_p photo-transistor output voltage
 W_a' theoretical arc energy from Howatson's equation
 W_a'' correction factor for W_a' to account for $v_a = 0$ at contact separation.

ABSTRACT

The energy content of a.c. arcs was investigated using a plain-break-in-air switch. It was found that by altering the phase of contact separation relative to current zero, the energy content of the arc space at subsequent current zeros was markedly affected and it seems that this may provide a useful method of increasing the rupturing capacity of modern air blast breakers.

The work follows that done by A. Howatson (1954) who showed theoretically that there would be an advantage in phase control and the results of these experiments are compared with those which he predicted. Close agreement is found and his theories are thus substantiated.

High speed photographs yielded much information about the development of an arc and also helped to explain some incongruities met in the oscillographic recordings which were used to obtain the bulk of the results.

Although the fault circuit was capable of delivering 80A at 3.3KV, the experimental switch could only interrupt 17A and so the range of results is rather narrow. However, by using capacitors to decrease the rate of rise of restriking voltage, indications of the effectiveness of phase control were obtained for higher currents. It is shown that, if contact separation occurs just before a current zero, the energy released by the arc after $1\frac{1}{2}$ cycles is approximately half that released after 2 cycles if the contacts separate just after a current zero. It is also shown that the optimum angle of contact separation is between 55° and 70° before current zero for a current of 17A at 2400^{V} and that the range of optimum angles increases if capacitance is connected in parallel with/

with the arc. No optimum angle was found for higher currents, except with added capacitance.

It is verified that Ayrton's Law holds for a.c. arcs at similar points on the voltage waveform and the peak arc voltage versus electrode separation graph is a straight line.

Minor investigations were carried out on copper tips which had been burned by the arc root. Photo-microscopy was used to enable quantitative analysis of the copper deposits to be made.

CHAPTER 1

INTRODUCTION

An electrical power system consists basically of generators, transformers, cables, loads and switchgear. The first four of these are vital parts of the system without which it could not function, while the last is a necessity - an expensive, but first class, insurance policy.

The purpose of switchgear is twofold; it is required for the connection and disconnection of, for example, a generator to a transformer, under normal working conditions of current and voltage, and it is required to interrupt any fault condition which may arise. As far as ordinary connection is concerned no great difficulties are encountered in the switching operation, the only qualities required of the circuit breaker being contacts of ample current-carrying capacity, and insulation strength sufficient to withstand the system voltage. However, if a low impedance connects a high voltage point to earth, a large current will flow in the circuit and the second requirement of the breaker is called into action, namely the quick and efficient interruption of the fault current. The circuit breaker must be designed to operate reliably under the most severe fault conditions and not be affected by the high temperatures and pressures associated with the interruption of currents which may be as high as 50 kA. Not only that, but the breaker must suffer no damage at the hands of the large electromagnetic and mechanical stresses generated within it. The importance of robust construction is evident and a fairly high/

high factor of safety is desirable, since the performance of certain types of circuit breaker is inherently erratic.

Innumerable workers during the past thirty years have strived to evolve comprehensive theories of arc interruption, in order that circuit breakers may be designed with a lower, yet sufficient, factor of safety. None have succeeded, although most have made useful contributions. Nearly all conceivable methods of improving breaker performance have been tried at one time or another, but it seems that very few workers have attempted to show that circuit breaker performance is increased if the instant of contact separation is controlled relative to current zero. The research work described in this volume shows that improved performance is available with this method of arc control.

Swig

Firstly, an outline of the properties of an electric arc will be given, after which a synopsis of the relevant arcing theories will be set out.

1.1 The Electric Arc

The basic action of any switch, when opening a circuit, is the separation of a pair of contacts which are normally engaged. If current is flowing in the circuit before the switch opens, an arc is created between the contacts at the instant of separation and the current is thus able to continue in the circuit until the discharge ceases. The processes involved in gaseous conduction are among the most complex in the realm of electro-physics, and the circuit breaker discharge, in its various forms and phases, represents a particularly intractable aspect of the subject.

Just before separation, the area and pressure of contact between the separating members decrease rapidly, giving an increase in resistance and, consequently, intense local heating which/

which may be sufficient for thermionic emission. Although this momentary resistance may be only a small fraction of an ohm, the current flowing may be sufficient to give a potential difference of a few volts. The small distance of separation, and the resulting voltage gradient, is believed to be sufficient to yield electrons from whichever electrode happens to be the cathode. Thus in the early stages of an arc's development there are two main sources of electrons - thermionic emission and field emission. The electrons which are liberated give rise to ions which in turn, by bombardment of the cathode give rise to more electrons and the discharge is termed self sustaining. It may be thought that thermionic emission from a low boiling point metal, such as copper, could not account for sufficient electrons to carry the high current, but it is believed that the ion bombardment of the cathode suppresses vapourisation, while allowing electron emission.

As a consequence of one or both of the above processes, the space between the electrodes becomes highly ionised and has a low resistance. The current flows in the circuit almost unhindered, and will continue to do so until such time as the ions are removed from the arc space or else the arc voltage rises to such an extent, usually because of increased length, that there is insufficient electron density to carry the current which then decays.

1.2 Theories of Arc Extinction

Because of the many unknown factors involved in circuit breaking, designers are obliged to build breakers using empirical formulae and large safety factors. There are, however, several basic theories of arcing, none comprehensive, which have been introduced/

L 9

L 12

L 13

introduced during the years.

1.2.1. Slepian Theory

It was as late as 1927, well after the invention of several extremely efficient circuit breakers, that Slepian presented his paper on the "Extinction of A.C. Arcs." It was in this, and later papers (1928, 1930) embracing a more practical form of arc, that he introduced his now famous "dielectric race" concept. Although Hilliard (disc.1927) appreciated that the performance of a breaker depended on the form of the voltage appearing across the gap after a zero pause, it was Slepian who realised that the restriking transient depended on the external circuit. He visualised the residual column, after current zero, as a mixture of electrons and positive ions, which gradually separated under the effect of the restriking voltage transient leaving a space charge layer of increasing thickness. This layer represented the dielectric strength at any instant. Slepian suggested that, if interruption was to be successful, then, during restriking, the dielectric strength curve of the gap must, at all times, lie above the restriking voltage transient. Attempts to calculate the dielectric strength curve were not very successful, but the concept is a useful one. It was he who introduced incidentally the idea of resistance switching in order to reduce the rate of rise of restriking voltage (r.r.r.v.).

1.2.2. Energy Balance Theorem

In a classic paper, Cassie (1939) put forward a new theory of operation of an a.c. circuit breaker, based on the conception of an energy equilibrium at current zero instead of that of a race between a curve of dielectric strength and the restriking voltage transient. For this purpose an equation representing/

representing the behaviour of the arc column at current zero was developed from the principles governing steady arcs carrying appreciable current.

Cassie was able to show that there was a maximum energy release corresponding to one value of gap resistance. Theoretical results corresponded well with experimental values and he deduced that a necessary criterion for successful interruption was a balance between the energy released in the gap and the energy dissipated by the arc resistance at current zero.

1.2.3 Displacement Theory

Prince (1931) introduced a theory which proposed that arc extinction was brought about by the introduction into the arc space at current zero of a wedge of unionised gas. This wedge provided an insulating gap on whose dielectric strength the success of extinction depended. Although Prince was able to show analytically that his theory was correct it never gained the general acceptance accorded to the theories of Slepian or Cassie.

Kesselring and Biermanns in Germany made an exhaustive research into the operation of circuit breakers but although an important series of papers was published (see references) there were still some first class mysteries. In general the problem was how to account for the extremely fast rate at which the arc column became deionised at current zero. The calculations of the loss of electrical conduction resulting from thermal conduction and diffusion led to results less than those observed.

Edels and Crawford (1957) broke down the recovery of an arc gap into three stages. During the first stage the properties of cathode emission are lost, this taking about $1\mu\text{s}$. This is followed by a period when the reignition voltage remains essentially constant (this has been verified by Dow and Timoshenko, 1930) and
after/

after this the gap recovers slowly to the full breakdown strength.

1.3 Possible Methods of Improving Circuit Breaker Performance

Whatever may be the real explanation of successful interruption, one thing is certain - that the condition of the arc gap at current zero is all important. If it is assumed that the rate-of-rise and energy balance theories both contribute to successful interruption then the following variables affect the operation of a breaker:

- (1) The inherent r.r.r.v. of the system
 - (2) Actual Power Factor
 - (3) Shunt Damping
 - (4) Conditions of the gap at current zero
 - (5) Deionisation means
- and (6) Variation of gap length after current zero.

Considering these individually, criteria (1) and (2) are inherent in the power system and cannot be controlled by the breaker. Factor (3) is controllable and has been exploited to the full in resistance switching. The conditions of the gap at current zero are affected by the extent of ionisation, the voltage across the contacts, the current which has been flowing, and the length of the gap - in short by the total energy released in the gap. Most of circuit breaking research has been devoted to improving the deionising means in switches and any contribution which could be made on the small scale available would be inadequate. The limitation on the last means of controlling circuit breaking performance is imposed by design factors and stresses. It is, however, linked to factor (4) in that the length of the gap at current zero affects the energy content of the arc. It appears, therefore, that the most promising approach to a radical improvement in breaker performance is through factor (4) and/

and this criterion is the one investigated in the following thesis.

The principle on which the research is based, is that, if the instant at which the contacts separated relative to current zero is varied, there will be found a point at which interrupting capacity is above average. The amount of energy in the gap at the first current zero (if not thereafter) must be primarily determined by the previous life of the arc. In order to establish whether or not there could be an advantage in controlling the instant of separation, it is necessary to consider its effect on current zero conditions in general terms.

If the contacts separate very shortly before a current zero then, by the time the current has reached zero, very little energy will have been liberated and the degree of ionisation will in consequence be low. But the gap will be so short that it will have little dielectric strength even so. A restrike will most likely occur followed by another half cycle of arcing. If, on the other hand, contact separation precedes a current zero by an appreciable part of a half cycle then when the current reaches zero a considerable amount of energy will have been liberated. The arc space will be highly ionised and its breakdown gradient low. To compensate for this, the gap will be much longer due to the greater period of contact movement, and the situation may be no better or worse than in the first case.

Since the trends of arc energy and arc length are in opposition, it follows that the dielectric strength at a particular time may have a maximum for one particular instant of separation. The probability of interruption may also, therefore, have a maximum.

The form of contact movement after separation will affect the balance both before and after current zero. It has long/

long been recognised that interruption without arcing would be achieved if the contacts could be separated exactly at current zero and thereafter accelerated rapidly enough for the breakdown strength of the non-ionised gap to exceed the restriking voltage at all times. For power systems this would require extremely large forces apart from the great accuracy of timing needed and must be regarded as impracticable. Even under the small scale conditions of the experimental switch described later, arcing ensued when the contacts were separated at current zero despite the fairly high acceleration.

The value of dielectric strength at any point for a particular length of gap may be regarded as a function of one of several variables namely, degree of ionisation, arc temperature, arc conductivity or arc energy; all of which are interdependent. In the present investigation the emphasis has been placed on arc energy which is more readily calculable than the other qualities.

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CHAPTER 2

2.1 Introduction

At the end of the introductory chapter it was stated that there appeared to be one method of arc control which had not been fully investigated. This was the control of gap conditions at current zero and it is in this direction that the following research was conducted. The gap length and arc energy at current zero were the two parameters varied, both being dependant on the phase of contact separation relative to current zero.

2.2 Optimum Speed of Contact Separation

Analytically it can be shown that there is an optimum speed of contact separation for which there will be a minimum energy release. This implies that, for a given circuit breaker operating under constant conditions, there will be an opening speed for which interrupting performance will be better than average.

Consider first a switch whose contacts open very slowly. At the first current zero the energy liberation ($\int_{\pi-t_0}^{\pi} I_a u_a dt$ where t_0 is the instant of contact separation measured from current zero) will be quite low since the arc length is short and the arc voltage consequently low. If, however, the contact separation is extremely fast the energy liberation will be great since v_a will be great. The breakdown voltage of the gap will also be great for these conditions whereas it would be low in the first case. Thus between the two cases there will be an opening velocity which strikes the optimum balance between energy liberation and dielectric strength of the gap. This will occur when the speed of contact separation is just sufficient to attain the critical length, L' ,
of/

of the gap after a half-cycle of arcing. If the contacts open at constant velocity, v , this condition will obtain when

$$v = 100 L \quad \dots 2.2.1$$

if L is in ft. and v is in ft./sec. For the constant acceleration case the corresponding equation will be

$$a = 20000 L \quad \dots 2.2.2$$

if a is in ft./sec.², the supply frequency being 50 c/s in both cases.

Eskin (1939) showed experimentally that there was such an optimum opening speed. He investigated short arcs with currents between 15 and 35 amps. The system voltage was 155V. and the frequency 60 c/s. He showed that the optimum speed of opening was 0.5"/sec. for the 15A arc and 1.5"/sec. for the 35A arc. From equation 2.2.1 the critical lengths are 0.006" and 0.018" respectively. With contact speeds slower than those quoted the arc energy increased rapidly with decrease in speed; the rate of increase is less with higher speeds. The conditions under which Eskin experimented were similar to those used in the author's tests except for the system voltage. The effect of this is to increase the critical length of the gap which (it is presumed) is proportional to voltage.

It is but a short step to realise the importance of the optimum phase of contact separation. It is naturally inconvenient to alter the speed of contact separation for each different condition under which a circuit breaker has to operate. But it is very easy to alter the phase of separation (if control is available). This effectively alters the speed of contact separation/

separation since the time taken to reach current zero is altered.

2.3 Methods of Controlling the Phase of Contact Separation

The research work involved conducting experiments on arcs whose phase of contact separation is variable along with several other parameters. The timing of the contact separation in a circuit breaker, relative to current zero, would best be achieved in practice by electronic timing of an impulse to the trip coil. This method has been used by Wildi (1951) who obtained the current pulses from saturable reactors, and these had already been used for synchronising recording apparatus in early circuit breaker tests by Poitras, Keuhni, and Skeats (1935). The main difficulty in applying this device, which consists of a peaking transformer and a phase-shifter plus power amplifier or relay, to a circuit breaker lies in the time lag, due partly to the trip coil time constant and partly to mechanical inertia.

In designing a single-phase experimental switch with which to investigate the theoretical results derived by Howatson on an adequate scale it was considered desirable to adopt a method of timing which would dispense with trip coil lag and have negligible inertia delay.

When a synchronous induction motor is running with no slip there will be a stationary field linking the rotor and stator and so if the stator rotates through an angle α the field follows, pulling the rotor through the same angle α . Thus by rotating the stator of a synchronous machine a point on the periphery of a disc attached to the rotor will alter its phase with respect to a fixed point in space. Consequently for a given system, supplied from the same source as the motor, this provides a datum of time referred to the current phase, when the motor is in the steady state.

Assuming/

L m

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Assuming that the time actually required to move the switch tripping lever and release the contacts can be neglected the instant of separation depends only on the synchronous motor.

The stator used in the experiments was fitted with a scale marked off at intervals of 5° electrical and could be set with reasonable accuracy to within $\frac{1}{2}^{\circ}$. Care had to be taken, however, to ensure that the load angle of the machine remained constant during the period of operation. To ensure this the motor was started long enough before each test to allow the rotor to reach constant speed and similarly the fault current was switched on long enough before the tests to allow all switching transients reaching the motor to die away; the inevitable drop in voltage on switching in the fault produced a slight oscillation in the rotor speed, which was then allowed to regain its steady state.

The motor used to drive the synchronising disc was a six pole synchronous machine with flats machined along the rotor laminations. These provided sufficient saliency to pull the rotor into synchronism while coupled to the disc which housed the tripping devices. The squirrel cage formed an effective damping winding. The disc was 2 ft. diameter and 1" thick, being directly coupled and overhung. The tripping plunger and spring (see figure 3.6.1. and section 3.6.1.) were contained in a steel casing which passed completely through the disc near its periphery. The inertia of the rotor and disc had to be large compared with the switch trip lever so that the force of impact did not appreciably affect the speed of rotation. This also resulted in consistency of the time taken to trip the switch.

Howatson suggested that the values of voltage and current required to test his theories satisfactorily were an open circuit voltage of not less than 3 kV and a short circuit current of about/

about 100A. He realised that while this was not comparable in scale to power system practice the conditions would at least be representative of large circuit breakers. In fact the minimum powers which he suggested were never reached since the maximum current which the transformer could deliver was only 80A. However, since it was found that some low power arcs were extinguished at the first current zero some results which might have been missed were obtained by virtue of the low power.

CHAPTER 3

EQUIPMENT

The research work was carried out in a laboratory, constructed of wood, 20ft long and 12ft broad, adjacent to the S.S.E.B. Sub-Station at Kings Buildings, Edinburgh. In a laboratory of this size, space considerations are paramount, and all the equipment was designed with this in mind. A darkroom, 8ft x 6ft, is included, so that oscillograms may be developed as they are recorded. A plan view of the laboratory is shown in Figure 3.1.1.

The main pieces of apparatus are two circuit breakers, a transformer, a make switch, and the experimental switch. These items will be described in detail below.

The electronic apparatus is housed in a 19" rack, integral with the oil circuit breaker.

All units are totally enclosed, either in steel cubicles, soundly earthed, or in hardboard boxes so that danger to operators is eliminated. The high voltage cables inside the laboratory were kept, as far as possible, beneath the floor.

3.1 Sub-Station Supply

The main supply to the laboratory is brought from the S.S.E.B. Sub-Station which is adjacent to the building. 4 x 0.3 sq.in. cable is used to bring the supply to the English Electric switch at 440v. At this point the 230v supply for the low voltage apparatus and auxiliary equipment is tapped off. The same type of cable is used to connect the low voltage switch to the transformer, but 11.V. armoured cable is employed between the secondary of the transformer and the O.C.B. All the cable is laid underground, being

fed through ducts built into the foundations of the laboratory.

3.2 English Electric O.C.B. 2 Low Voltage Switch

This is a standard 3-phase arc-chute switch, equipped with adjustable time-delay overload coils. It serves several purposes; to isolate the transformer so as not to leave it on no-load and to facilitate tap changing, to isolate the circuit when D.C. measurements are being taken, and to interrupt the circuit should the O.C.B. fail to open. Although this switch is only rated at 100^A/ phase, it operates satisfactorily at 600^A/phase with the overload relays held out.

3.3 110volt/3.3KV Transformer

This is a single phase, high reactance transformer. It is equipped with taps giving a variation in output voltage between 2400 volts and 3200 volts in three steps. The transformer has a short circuit current of 46.6 amps. at the low voltage and 79.2 amps at the high voltage.

By measuring the voltage drop across the resistive load for different values of resistance, the inductance and resistance of the transformer referred to the secondary can be calculated. They are as follows:-

$$\text{Turns Ratio } \frac{N_s}{N_p} = 7.5$$

$$\text{Inductance } L = 0.07H$$

$$\text{Resistance referred to secondary} = 48.9 \Omega$$

$$\text{Secondary D.C. resistance} = 5 \Omega$$

$$\text{Primary D.C. resistance} = 0.78 \Omega$$

3.4 H.V. Oil Circuit Breaker

The switch on the high voltage side of the transformer is a three pole plain-break-in oil breaker of 15 MVA rating.

Solenoid/

Solenoid or manual tripping is available.

3.5.1. Johnson and Philips Make Switch

To avoid any uncertainty in the manual operation of the Metro-Vick Oil Circuit Breaker a spring actuated switch was installed to close the fault. A spring mechanism was kindly supplied by Messrs. Johnson & Philips and the blades and contacts, and other auxilliary parts, such as connecting links, mounting plates, and beds, were constructed by the University Engineering Workshops to drawings kindly supplied by the Balmos Company Limited.

3.6.1. Experimental Switch

The original experimental switch was designed by Howatson and manufactured by Messrs. Bruce Peebles Limited. It was devised to minimise any time lag due to inertia of moving parts or solenoids such as are used in circuit breakers of industrial design.

The switch had a bakelite frame held rigid with angle irons. The contacts, of which only one moved, were made of brass and had replaceable copper butt contacts. The contacts were opened by a compression spring and provision was made for springs of different lengths. The switch contacts opened linearly, and it was intended to have constant acceleration over the total separation of 3".

When tests were first begun it was not long before the bakelite frame cracked in several places. It had also been found that the speed of opening of the switch and the length of gap were insufficient for the circuit and so it was decided to build a stronger switch incorporating a much stiffer spring and a longer arc gap.

The new switch, shown in figure 3.6.1. has an angle iron frame with $\frac{1}{2}$ " x $\frac{3}{8}$ " Whale Brand Tufnol sheet sides. The moving/

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moving contact is of 1" diameter $\frac{1}{8}$ " wall steel tube, treated with the "Progreg" anti-friction process, as were the brass bushes through which it travels. The tube is 33" long and at one end has a steel cone. This is used as a buffer so that the movement of the contact will not be complicated by "overshoot" i.e. continued movement after the spring has reached its free length. The buffer strikes a 13lb steel weight riding freely on two bars which form part of the loading mechanism. This weight absorbs most of the Kinetic Energy of the moving contact and as can be seen from the displacement curve (Figure 4.5.1.) the rebound is quite small. The compression spring has a free length of 12" and compressed length of 5" its stiffness being 40lbs/in. It is held at one end by a 7" long steel collar which retains the switch in the loaded position. It is $\frac{1}{8}$ " thick, fluted at both ends, and held in position with $\frac{3}{8}$ " U.H.T. bolts. At the other end of the collar a 3" diameter $\frac{1}{8}$ " thick washer keeps the spring from extending beyond its free length. The washer moves with the contact and is stopped by a $\frac{1}{2}$ " thick steel plate carrying the trip lever. The trip lever is made of steel and will be the subject of a later paragraph. The switch is loaded by a screw. The fixed contact is also made of steel tube and, like the moving contact, rides in two bushes. A compression spring ensures initially good contact between the copper contacts. The dimensions of the switch are:-

| | | |
|-----------------|---|--------|
| Overall length | = | 5'-0" |
| Overall breadth | = | 9" |
| depth | = | 1'-10" |

To prevent rotation of the moving contact, the centre bolt holding the collar to the contact was made with a 3" extension above its head. This extension passes through a slot in a $\frac{1}{4}$ " bakelite sheet which/

which is securely bolted to the frame of the switch, and was found useful in the measurement of contact displacement as will be mentioned. The whole switch, including the synchronous motor, is housed in a hardboard box.

3.6.1 Tripping of Experimental Switch

The tripping of the experimental switch can be initiated (a) by a push button switch or (b) as an intermediate operation in an electronically controlled sequence.

In the flywheel of the synchronous motor there is a spring loaded plunger (Figure 3.6.1.) held flush with its mounting by a steel catch lever. This lever is pivoted on a screw so that when it is rotated approximately 10° the plunger flies out to protrude by $\frac{3}{8}$ ". The lever is displaced by the tripping solenoid which is actuated by either of the methods (a) or (b) above. The plunger spring is of such a strength that the plunger reaches its fully extended position 10msecs after release, which is equivalent to about 30° rotation of the flywheel. As the solenoid is mounted diametrically opposite the main trip lever there is no chance that the plunger will be incompletely open and jamming against the trip lever is impossible.

The sequence of tripping is, therefore, that the solenoid plunger rotates the plunger catching lever, thereby releasing the plunger. This strikes the main trip lever, which in turn releases the moving contact. The trip lever is held in place by friction against the action of a spring which is included to prevent the trip lever rebounding and fouling the moving contact.

3.6.2. Experimental Switch Operating Spring

In deciding the best type of spring to use to achieve the/

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the minimum opening time for the switch, an investigation was made into the properties of a spring-mass system. This led to the choice of a 40lb/in. spring which gave a good acceleration and yet was not so bulky as the optimum spring which, as will be seen, was extremely long and weak.

Time Taken for a Spring-Mass System to move a given Distance

The mass to be moved = m lbs

Let the spring have a stiffness k lbs/in. and a load, when fully compressed of F_0 lbs.

The load of the spring at displacement x ins = $(F_0 - kx)$ lbs

and therefore the velocity of the system after x ins of travel is given by

$$\begin{aligned}
 v_x^2 &= 2 \int_0^x p_x dx \quad \text{Where } p_x = \text{accel. at } x = \frac{g}{m} [F_0 - kx] \text{ ins/sec}^2 \\
 &= 2 \int_0^x \frac{g}{m} (F_0 - kx) dx \\
 &= 2 \frac{g}{m} \left[F_0 x - \frac{kx^2}{2} \right] \\
 \text{or } v_x &= \sqrt{\frac{2g}{m} \left[F_0 x - \frac{kx^2}{2} \right]}
 \end{aligned}$$

and the time taken to reach this distance, x , is given by

$$\begin{aligned}
 t_x &= \int_0^x \frac{dx}{v_x} \\
 &= \int_0^x \frac{dx}{\sqrt{\frac{2g}{m} \left[F_0 x - \frac{kx^2}{2} \right]}}
 \end{aligned}$$

so that the total time taken to reach the open gap length, s , of a switch is:

$$T = \int_0^s \sqrt{\frac{m}{2g}} \frac{dx}{\sqrt{F_0 x - \frac{kx^2}{2}}}$$

$$\begin{aligned}
&= \sqrt{\frac{m}{2g}} \int_0^s \frac{dx}{\sqrt{\left[\frac{F_0^2}{2k} - \left(x \sqrt{\frac{k}{2}} - \frac{F_0}{\sqrt{2k}} \right)^2 \right]}} \\
&= \sqrt{\frac{m}{2g}} \sqrt{\frac{2}{k}} \left| \frac{\sin^{-1} \left\{ x \sqrt{\frac{k}{2}} - \frac{F_0}{\sqrt{2k}} \right\}}{\frac{F_0}{\sqrt{2k}}} \right|_0^s \\
&= \sqrt{\frac{m}{2k}} \left[\sin^{-1} \left(\frac{ks - F_0}{F_0} \right) - \frac{3}{2}\pi \right]
\end{aligned}$$

Clearly for a given s , F_0 , and m , the time T depends on the stiffness k and varies between the extremes where $k = 0$ and $k = \frac{F_0}{s}$. The effect of varying k is best shown graphically and a few examples are shown in Figure 3.6.3. These graphs are, of course, theoretical and do not account for friction in the bushes or spring losses during extension.

It can readily be seen that the time taken to travel a given distance is only slightly different between the two extremes of stiffness, the ratio between T ($k = 0$) and T ($k = \frac{F_0}{s}$) being 0.9. This can be verified theoretically, the proof being given in Appendix (a).

Since the time taken for all springs to move the mass a given distance was so close there seemed to be little advantage in choosing a spring which would have proved inconveniently long, especially during the frequent assembly and dismantling of the switch which later was found necessary. The stiffest spring which met with the load requirements of the switch was therefore chosen. It was a 45wg single coil spring of 26 turns, with a free length of/

of $12\frac{1}{2}$ " , a compressed length of 5" , and a stiffness of 40 lbs/in. Its inner diameter was 1" . This spring gave a compressed load of 300 lbs.

The performance of the spring under working conditions is discussed later in section 4.5 .

3.6.3. Experimental Switch Triplet Design (Figure 3.6.4.)

The experimental switch is tripped, as already mentioned, by the pin in the flywheel of the synchronous motor striking against the lever which retains the main spring in the loaded position. This lever is subject to large stresses resulting from two main forces, that due to the spring pressing the lever against its mounting plate and that due to the impact of the rotating pin.

The first force introduces three subsidiary forces all of which tend to fracture the lever. The greatest of these is the frictional force to be overcome when impact of the pin against the tip of the lever occurs. This force would cause fracture across the pivot hole. The other two subsidiary stresses are set up around the hole in the lever mounting plate, through which the moving contact passes. The spring attempts to push the lever through the hole, that is, a shear force is set up around the edge of the hole and a bending stress is introduced in that part of the lever lying across the hole.

The really troublesome force, however, is the impact force. Because of its indeterminate nature, the original "design" of the lever was by trial and error. This large force involves one stress only, besides bringing into play the friction force mentioned above, and this is a bending moment between the fulcrum and the tip. There is also a substantial reaction at the fulcrum at impact since the end of the trip lever retaining the spring may be considered fixed at that instant of time.

The/

The trip lever in the original switch was a plain bar of Tufnol, 11" x 1½" x ⅜", with a brass plate on the impact face to prevent shattering of the Tufnol. The spring pressure, however, was only 60lbs and this lever was satisfactory. It was obvious that, with the spring pressure increased to 300lbs, a more substantial trip lever would have to be developed. The original trip lever is shown in Figure 3.6.4.a

To offset the frictional force a spring of 10lb/in was attached to the end of the trip lever, as shown in the first design for the new switch (Figure 3.6.4.b). This was fixed to the frame by an adjustable screw so that the initial tension on the spring could be adjusted to a maximum, i.e. so that the minimum force was required to displace the lever. This meant that the impact force had only to be great enough to overcome the inertia of the lever. To strengthen the lever across the hole in the mounting plate, a ⅛" case hardened plate was screwed onto the lever and to absorb the impact force a brass faced rubber pad was attached to the face of the lever. Mass and inertia were held to a minimum. Fracture occurred behind the steel plate as shown and the rubber pad was dislodged. It was thought at first that the fracture was caused by the spring trying to push the lever through the hole and so the latter was reduced in diameter from 3" to the bare minimum of 2". In the light of more recent occurrences it is now believed that this rupture was caused by the lever rebounding from its stop and fouling the collar fixing bolts.

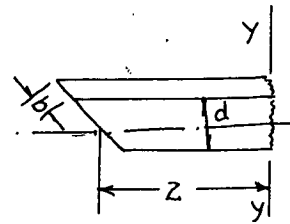
The rubber pad was replaced by a steel tip but this lever, too, was inadequate and fracture occurred in two places as shown in Figure 3.6.4.c. It was apparent that Tufnol was not strong enough for this component and the next lever was made of steel. An attempt was made to keep its mass to a minimum but the lever sustained bending as shown in Figure 3.6.4.d.

It/

It was thought that there was now sufficient data to design a steel trip lever which would withstand the forces illustrated above. The calculations are given below for this lever, which has proved most satisfactory.

From Tubal Trip Lever (a)

$$\begin{aligned}
 (1) \quad \text{Bending Moment } M &= b \int_{\frac{d}{2}}^z \sigma x^2 dx \\
 &= b \int_{\frac{d}{2}}^z \frac{\sigma_F}{d/2} x^2 dx \\
 &= \frac{\sigma_F}{d/2} I_{yy}
 \end{aligned}$$



$\sigma_F = \text{U.T.S. of Tubal}$

Taking $\sigma_F = 16000 \text{ lb/in}^2$ then,

$$\begin{aligned}
 M &= \frac{16000}{\frac{1}{2}} \cdot \frac{0.375 \cdot 1^3}{12} \quad \begin{matrix} b = \frac{3}{8}'' \\ d = 1'' \end{matrix} \\
 &= 1000 \text{ lb.ins} \quad \& \quad M = 1.75P
 \end{aligned}$$

Therefore $P = 572 \text{ lbs}$, which is a minimum value

(ii) Maximum load which could be taken at the root without fracture

$$\begin{aligned}
 4P_1 &= \frac{16000}{\frac{1}{2}} \times \frac{.5}{12} \\
 &= 1330 \text{ lb.ins}
 \end{aligned}$$

therefore 333 lbs applied at the tip should cause fracture near the root.

(iii) The pin should be in contact with the tip of the lever for approximately 1". So, assuming that the trip lever is accelerated from the rest to the peripheral velocity in 1", the acceleration is given by

$$\begin{aligned}
 a &= \frac{v^2}{2s} = \frac{1000 \text{ r.p.m.} \times 2 \times 11''}{60} \times \frac{1}{2.1} \quad \text{radius of flywheel} = 11'' \\
 &= 67.0 \times 10^4 \text{ ins/sec}^2
 \end{aligned}$$

so the angular acceleration, assuming that the lever remains rigid/

rigid is

$$\alpha' = \frac{a}{r}$$

$$= 13.4 \times 10^4 \text{ rdns/sec}^2$$

Mass of steel tip = $\frac{1}{8}$ lb at a radius of 5" from the fulcrum therefore

$$\text{the moment in Inertia } I = \frac{1}{4} \times \frac{25}{386}$$

$$= 0.0162 \text{ lb.in.}^2$$

therefore, the Torque = $T = I\alpha'$

$$= 0.0162 \times 13.5 \times 10^4$$

$$= 21.7 \times 10^2 \text{ lbs.ins.}$$

therefore, the force required at pin = $\frac{21.7}{5} \times 10^2$

$$= 435 \text{ lbs.}$$

(iv) However an additional torque is required to overcome the spring friction. Taking $\mu = 0.3$ and the spring force as 400 lbs., the frictional force = 120 lbs. This acts at approximately 2.75" from the fulcrum so that the torque is approximately 330 lbs.ins. From this the force required at the trip to overcome friction is about 66 lbs. This gives a total force at the pin of say 500 lbs.

(v) Steel Lever

$$\text{Moment of Inertia} = \frac{bd^3}{12}$$

$$= \frac{\frac{1}{2} \times \frac{1}{2}^3}{12}$$

$$= 0.00521 \text{ ins.}^4$$

$$\text{Moment Arm} = 3.75''$$

$$\text{Yield stress of steel} = 45000 \text{ lbs/in}^2$$

$$\text{and } \frac{P}{y} = \frac{M}{I}$$

$$\text{i.e. } \frac{3.75 P}{0.0052} = \frac{500}{.25} \text{ lbs/in}$$

$$\text{so that } P = \frac{50000 \times .0052}{3.75 \times 0.25}$$
$$= 277 \text{ lbs.}$$

since/

since the bending yield point may be higher, P might be as large as 350 - 400 lbs.

(vi) New Steel Trip Lever

In the design of this lever

$$= 10000 \text{ lb/ins.}^2$$

$$\frac{P}{y} = \frac{M}{I}$$

$$\text{so } P = \frac{400 \cdot x \cdot V}{I}$$

where x = distance from tip along lever

$$\frac{I}{y} = \frac{bd^3}{12} \times \frac{2}{d}$$

$$= \frac{d^2}{12} \text{ for a thickness of } \frac{1}{2}''$$

$$\text{so that } d = \frac{400 \cdot x \cdot 12}{10000}$$

$$= .693 x$$

| | | | | | | |
|-------|-----|-----|-----|-----|------|------|
| x ins | 1 | 1½ | 2 | 3 | 4 | 5 |
| d ins | .69 | .85 | .98 | 1.2 | 1.39 | 1.56 |

(vii) Cross Sectional Area at Fulcrum

From table of cross sections, at x = 5", d = 1.56"

Diameter of hole for pin = $\frac{3}{8}''$

$$I = \frac{\frac{1}{2} \times (.4)^3}{12}$$

$$\text{therefore } I_{GG} = \frac{\frac{1}{2} (.4)^3}{12} + \frac{1}{2} \times .4 \times (.575)^2 \times 2$$

$$= .1412 \text{ ins.}^4$$

$$\text{Moment at x} = 5$$

$$W = 400 \times 5$$

$$= 2000 \text{ lbs.ins.}$$

therefore/

$$\begin{aligned} \text{therefore } P &= \frac{Mv}{I} \\ &= \frac{2000 \times 7}{.1412} \\ &= 1050 \text{ lbs/sq.ins.} \end{aligned}$$

This is satisfactory.

3.7 Power Factor, Current, and Rate of Rise of Restriking Voltage Control

In high voltage electrical systems, such as those used in transmission and large consumer supplies, there are innumerable combinations of short circuit power factor, current, and rate of rise of restriking voltage. Any research, with practical application to such circuits, must attempt, therefore, to cover as many variations as possible of these three parameters.

In order to vary the short circuit current of a circuit it is necessary to alter the circuit impedance, the most convenient method being to introduce resistance. To vary the power factor, either reactance or resistance may be added. Capacitive reactance would give the best variation of power factor but large capacity condensers for high voltage operation are costly and the inclusion of inductive reactance to a circuit which already has a large inductance would give only a narrow range of power factor variation, possibly between 0.01 and 0.1. The power factor, can be raised by the use of resistors to a relatively high value, say 0.9, current control being effected using the same resistors. Although this is not ideal, insomuch as the current and power factor are not independent variables, it is an extremely neat and inexpensive method of control.

Variation of the rate of rise of restriking voltage can be effected by the conventional method using condensers connected in parallel with the arc.

3.7.1 Resistive Load /

3.7.1 Resistive Load

Resistance nets, capable of carrying 100^A for short periods were installed on an asbestos frame against one wall of the laboratory. Each net, of which there are seventeen, has a resistance of 5.5Ω , giving a load variable between 5.5Ω and 93.5Ω , and power factor variation between 0.24 and 0.97.

3.7.2. Capacitor Board

Banks of capacitors were used to control the rate of rise of restriking voltage. The capacitors are 1500^V D.C. working, and each bank, of which there are six, consists of five capacitors in series each shunted with a $4.7 M\Omega$ leakage resistor.

The values of capacitance which can be introduced across the arc gap are $0.5 \mu F$, $0.1 \mu F$, $0.04 \mu F$, $0.02 \mu F$, $0.01 \mu F$ and $0.005 \mu F$ or any combination of these. A $500 mA$ fuse is connected in series to protect the capacitors against excess over-voltages.

The variation of rate of rise of restriking voltage with capacitance is shown in figure 3.7.3. and a fuller discussion of the effect of shunt capacitance on the arc is given in Section 5.7.

3.8 The Fault Circuit

The fault circuit contains all the units 3.1 to 3.7 above.

After the English Electric OB2 switch (3.2) the yellow phase is dispensed with, the red phase becoming the live line and the blue phase the neutral. A fault consists of the short circuiting of the red and blue phases through the O.C.B., the make switch and the experimental switch. The complete layout is shown in figure 3.8.1.

3.9 Timing Sequence

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3.9 Timing Sequence

The sequence of operations is such as to give the shortest duration of fault current. All subsidiary operations are electronically controlled by the apparatus described below (Sections 3.9.1 - 3.9.4.).

All switches are loaded, and the camera loaded immediately prior to a test. The Johnson & Phillips switch is then tripped by press-button control. An auxiliary switch then starts Timing Unit No. 1. (Section 3.9.1.). After a pre-determined time, Timing Unit No. 2. (Section 3.9.2.) is fired by a pulse from Timing Unit No. 1. It is this Unit which, in sequence, operates the subsidiary apparatus. The experimental switch tripping solenoid pulse is applied, thereby releasing the flywheel plunger which in turn trips the experimental switch. 20 milliseconds after the solenoid has been operated a pulse is applied to the oscilloscope brightening unit which brightens the traces for a pre-determined length of time (Section 3.9.3.). After this the O.C.B. is tripped by solenoid and the O.B.2 tripped open by hand.

3.9.1 Timing Unit No. 1.

This Unit provides the delay to allow the initial application-of-fault-current transients to die away, and to permit the synchronous motor to re-adjust itself after the application of such transients to its terminals. The Unit is deuterium operated and is capable of a delay of up to 2 seconds in 1/5th second steps.

Its output consists of a series of 50^v negative pulses, of approximately 10 m sec. duration, from a cathode follower. The circuit is shown in Figure 3.9.1.

3.9.2. Timing Unit No. 2.

Timing Unit No. 2. is used to operate the auxiliary apparatus and to control the sequence of events after the Johnson

& Phillips switch is closed. The first output pulse from Timing Unit No. 1. fires the ignitron V_3 (Figure 3.9.2.). This operates Relay 1 which discharges the external $32 \mu\text{f}$ condenser through the experimental switch tripping solenoid and starts the oscilloscope brightening unit. A further set of contacts starts the dekatron V_5 which after a preset delay pulses the ignitron V_4 . This then closes Relay 2 which operates the O.C.B. trip coils.

The unit can be operated by the closing of the O.C.B. and can control the oscilloscope brightness independent of the brightening unit.

3.9.3. Oscilloscope Brightening Unit

This unit controls the length of time for which the oscilloscopes are brightened during a test. The circuit is shown in Figure 3.9.3. It is operated by a pulse from No. 2 Timing Unit, which actuates a CR circuit controlling the output pulse duration. Composite with this part of the circuit is a unit for differentially brightening the current and voltage waveforms so that fast transients are clearly seen on the record. (It had been previously found that the high frequency transients were too fast to leave a trace on the photographic paper). The unit is supplied from a stabilised power supply. It also permits individual brightness control of each oscilloscope. Both traces on either oscilloscope are differentially modulated together, but this has not been found inconvenient.

It was also necessary to modify the intensity modulation units of the oscilloscopes. The original and modified circuits are given in Figure 3.9.4.

3.10 Beam Camera

There is undoubtedly only one way to record the voltage, current/

current and other parameters of an arc, and that is to photograph these waveforms displayed on a Cathode Ray tube. The permanent records thus obtained are indispensable for future reference. 1 87

In the author's study of the arc it was of paramount importance to be able to examine the traces in great detail with respect to time especially around current zero, and so a recording camera of fairly high time resolution was desirable. It was desirable to have a film speed of up to 100 ft/sec and to meet these requirements a drum camera was most suited since the recordings needed only to be of short total duration. The drum camera also had the advantage that speed control was simple.

The camera consists of a wooden box $18\frac{1}{2}$ " high x 25" x $25\frac{1}{2}$ ". In this box is housed the drum, a steel cylinder 80mm high and 60" circumference, mounted on a vertical shaft. The drum is driven by a 240V $\frac{1}{2}$ h.p. motor through a belt and pulley giving a speed reduction of about 3/1. The face of the drum was turned in a lathe and there are two grooves to take 35 mm and 70 mm recording material.

The lens is a Wray f1 C.R.O. lens. It is mounted in one wall of the box, the mount being equipped with a 40 t.p.i. thread so that the very sharp focus of which this lens is capable can be achieved.

The traces to be photographed are displayed on two Cossor 1049 MKIII oscilloscopes with blue tubes of short persistence. The oscilloscopes are mounted facing each other and at right angles to the lens, mixing of the traces being accomplished by surface silvered mirrors.

As has been mentioned the lens is capable of very sharp focus, 50 kc/s being resolved quite easily. It is however, difficult to achieve sharp focus for both pairs of traces simultaneously/

simultaneously as the tube-face/lens distance is not quite the same for both 'scopes and the distance between the lens and drum face is extremely critical being about 7 mm. As little as 0.001" change in this dimension has an appreciable effect on the focus.

The size of trace obtained was governed by the distance between the oscilloscope faces and the lens. The minimum to which this could be reduced was $9\frac{1}{2}$ ", the corresponding magnification being 0.2. This meant that the maximum amplitude of trace would be 0.6". Both traces from one oscilloscope were superimposed so that the maximum amplitude could be obtained for both traces. It was seldom found to be inconvenient or confusing.

3.10.2 Recording Paper and Processing

The first essential in the recording of the arc parameters using the drum camera was to have clarity of trace for examination. It was also convenient to use a photographic medium which lent itself to ease of handling and developing.

Various types of film were experimented with. 35 mm film and paper were used initially, and both green and blue C.R.T's were tried. Finally it was decided that, for ease of handling, cheapness and clarity of trace, Ilford B.P.1 blue sensitive recording paper was the most suitable.

The paper was developed in a $2\frac{1}{2}$ gallon Polythene bucket using ID 33 high contrast developer. A stainless steel trough 6 feet long was used for fixing. Those records suitable for examination were thoroughly washed and glazed.

3.11 Forced Extinction of the arc using Nitrogen

When the r.r.r.v. tests were being conducted, it was necessary that the arc be blown out so that a record with a fast time base could be obtained.

A cylinder of nitrogen was used to blow a high velocity jet of gas onto the arc. The jet was formed by a piece of $\frac{1}{8}$ " I.D. rubber tubing through which the gas was forced under a pressure of 1500 p.s.i. The jet was played onto a point about $\frac{1}{2}$ " from the fixed contact because the actual arc root is extremely difficult to move. The method was surprisingly successful, even the most severe arcs were always extinguished at the first current zero.

C H A P T E R 4

M E A S U R E M E N T S

The medium used for the recording of a test was photography of the arc parameter waveforms. To avoid unnecessary complexity, two double beam oscilloscopes were used to photograph only four waveforms on one record. The choice of these four parameters and the method of translating them into voltages suitable for recording is the subject of this chapter (see fig 4.11)

4.1 Current Measurement

There are two distinct regions of current flow in an arc. During the major part of a half-cycle the arc current is sinusoidal and very nearly equal to the short circuit current of the system. For a brief period, around what, in a linear system, would normally be current zero, there is an interesting region of nearly zero current flow, known as the zero pause. In a high power circuit breaker this zero pause is actually an interval of, at the most, a few tens of microseconds where there is no appreciable current flow. In a free arc it would be expected that the different conditions experienced would have a different influence on this particular region, and an oscillogram of the zero pause might well have proved interesting. However, since only one trace could be allotted to arc current the latter was dispensed with, in the hope (which was fulfilled) that, given a good oscillogram, one could examine this region fairly accurately with an optical magnifier.

4.1.1 Measurement of Arc Current by Transformer

As it was necessary to take frequent direct readings of the short circuit current, a current transformer was used to drive an ammeter. It was found that the resistance of the ammeter was sufficient to develop a small voltage across its terminals;

about/

about 0.1 volt for a primary current of 25A. This, at first sight, appeared to be a suitable way of measuring the arc current but, due to certain peculiarities in the waveform it was discovered that there was inductive pick-up sufficient to make a small error in the current measurement.

4.1.2. Measurement of Arc Current by Resistor

Mason (1952) studied the problem of current measurement in arcs, primarily around current zero, and found that the most accurate method was to use a low value of resistance and to record the voltage drop across it. This device eliminates any phase shift or inductive lag such as is encountered with current transformers.

The value of resistance had to be sufficient not to require a pre-amplifier and low enough not to affect materially the fault circuit, and yet not introduce high frequency oscillations in the cable connecting the resistor to the oscilloscope. The resistor chosen was a 0.02Ω standard with a continuous rating of 50A, the voltage developed varying between 0.4 volt and 1.6 volts r.m.s. according to the circuit current.

4.2. Voltage Measurement:

There are two commonly accepted ways of reducing a high voltage to one of suitable value for application to, say, an oscilloscope. They are the resistor and the capacitor divider, both of which are simple and accurate.

With the resistor divider, the balance of two criteria must be found. A relatively large voltage must be applied to the oscilloscope to make any interference from mains "hum" negligible and the current flowing in the resistive loop must not be sufficient for the arc to be shunted to give a form of resistive switching. To satisfy these requirements the resistors would have to/

to dissipate about 300 watts and have a resistance of about 30 - 35 K Ω

Because capacitors can be kept low in value and still withstand the high voltage, they do not alter the circuit to the same extent so far as arc extinction is concerned. A capacitor divider was used to measure the arc voltage and it consisted of five 0.005 μF condensers in series as the input limb and five 0.005 μF condensers in parallel as the output limb giving a voltage division of approximately 25:1.

4.3 Arc Power and Energy

The principle investigations of the research involved the quantitative measurement of arc energy. There are three possible ways of measuring the arc power. The first is by incremental measurement of voltage and current with respect to time read directly from the oscillograms using a magnifier. This method is tedious and an electronic multiplying device would have been advantageous. Two were experimented with, one a valve circuit and the other making use of the Hall effect.

4.3.1 The $\frac{1}{4}$ -square Method of Multiplying

The operation of multiplying two voltages electronically is one which, until recently, has proved very difficult to perform accurately. Although a valve can be constructed to square a voltage accurately, there are difficulties in producing a valve with a sufficiently linear characteristic, to carry out multiplication. However one can, by the $\frac{1}{4}$ -square method use adding, subtracting and squaring circuits to multiply. A block diagram of such a circuit is shown in figure 4.3.1.a and a suitable squaring circuit is given in figure 4.3.1.b. Such a circuit was constructed and tested. The addition and subtraction circuits were of the conventional type and were accurate over a wide working range. The individual squaring circuits, too, were satisfactory, but, when the complete unit was assembled, /

assembled, the distortion, especially around the current and voltage zeros, was far in excess of that which could be tolerated if accurate results were to be obtained. The constantly changing valve parameters introduced varying distortion, which would have necessitated elaborate zeroing controls if it was to be eliminated. The error in each unit of the circuit was of the order of 2% which led to an error in the output of at least 10% according to the amplitude of the respective input signals.

4.3.2 Analogue Multiplier

This device was kindly provided by Messrs. Metropolitan-Vickers Ltd. It is a recent development using the Hall effect in an indium arsenide crystal.

The principle of operation is that if a field is applied perpendicular to the largest face of a thin slice of semiconductor and a current is passed across the crystal perpendicular to the field, then a current is induced perpendicular both to field and applied current. This current can be used to develop, across a suitable load, a voltage which is proportional to the product of the field and applied current.

The plate current was supplied from a 0.02Ω standard resistor inserted in the main current-carrying circuit. The field was supplied from a coil incorporated in the device; the current for the coil was bled from the high voltage end of the switch through a $50 \text{ k}\Omega$ resistor. The output voltage was thus proportional to the arc current times the arc voltage.

The multiplier worked well and accurately under d.c. conditions. It was, however, unsatisfactory under a.e. conditions in the region of current or field zeros. This was due to difficulty in balancing the device at zero output. The effect was to produce a large/

large spike on the output voltage.

4.4 Arc Severity

The majority of arc research workers have found the inconsistencies in their experimental results inexplicable. Even if electrical, mechanical, and physical conditions remain identical during successive experiments, the arcing time is not necessarily constant, giving rise to the idea that some arcs are more "severe" than others. It is the author's contention that these discrepancies are due to the lack of control over the point of contact separation relative to the current cycle.

The problem arising from this is how to estimate the severity of an arc by observing the arc itself and not by analysis of its current and voltage.

The value of the experiments conducted with a view to solving this problem is lessened by the lack of control over the physical conditions in the arc space.

The first attempt at measurement was to detect the 50 c/s noise content of different arcs. A microphone was attached to the switch frame and its output fed to an amplifier connected to a C.R.O. The waveform recorded was distorted due to spurious noise from the switch itself, so much so that the arc noise was swamped. The method, consequently, was unsuccessful.

In the next experiment an R.F. amplifier replaced the A.F. amplifier but no cyclic variation in output was obtained. It is thought, however, that observation of radiation in the 'S' or 'X' bands might have yielded useful information.

The most promising method seemed to be the measurement of the light from the arc using a photo-transistor. If one arc is more difficult to interrupt than another, given the same interrupting conditions, /

conditions, then its degree of ionisation must be more intense. This will lead to an increase in temperature and consequently an increase in light. The light output from the arc can be transferred to a voltage, using a photo transistor, and this voltage can be compared qualitatively with the arc power.

Temperature measurements were not attempted as the equipment necessary for this is complicated, and it was felt that the limited results which would be available from the low-power arc used would not contribute anything to the findings of other workers.

The behaviour of the arc and any relation which this bears to severity was investigated using high speed photography and is discussed in section 4.6. The results of measuring the light output from the arc are given in section 5.4.

4.5 Moving Contact Displacement

Howatson (1954) has shown that the energy content of an arc gap at any given instant of time depends on the mathematical nature of the contact displacement. By evaluation of the formulae which he obtained for the cases of constant velocity and constant acceleration of contact separation, it can be shown that the nearer this is to the constant velocity case the greater will be the chances of interruption.

To simulate the case of constant velocity displacement the contacts would have to be separated by a very stiff spring so that the equilibrium position is reached in a small part of the total travel. The contact would then be free to continue at constant velocity the only deceleration being due to friction, which could be kept small. This condition is very difficult to obtain and naturally there will always be some period of acceleration.

For/

- 38 -

For the constant acceleration case a very long weak spring would be required, highly compressed. It can be shown, however, (appendix A) that the time taken for any spring-mass system to obtain its totally uncompressed position can only be 11% greater than the time taken for the ideal system (i.e. a long weak spring) to move the same distance.

The constant acceleration case is much easier to obtain than the constant velocity case (by the use of springs) and, since for the purpose of verifying the theoretical formulae it does not matter which case is selected, the constant acceleration case was chosen (section 3.6.2.).

It was necessary to measure accurately the opening time and speed of separation of the contacts so that the effects of the movement of the contacts on the arc could be studied.

The acceleration of the moving contact was much too great for the use of any purely mechanical measuring device such as a Fletchers' Trolley mechanism. Electro-mechanical devices held a certain amount of promise but it seemed that with a switch of the type used the only really successful measuring devices would have to be purely electrical.

A Tufnol rod, 1" in diameter and 10" long was wound with 16 s.w.g. resistance wire. The potentiometer so formed was supplied with 24V D.C. A spring loaded wiper was attached to the steel collar on the moving contact but no matter how tightly the wire was wound, the wiper inevitably distorted and stretched it.

A linear carbon tracked potentiometer was next used. It had a resistance of 100 Ω . The wiper, which ran on rails, was an integral part of the potentiometer. A brass, and later a steel, rod/

rod was used to drive the wiper. The wiper supplied was rather flimsy and a more substantial one was fitted. However, although the wiper was smooth running under no-load conditions, it jammed in the guide rails when running at speed. It was therefore apparent that the most successful measuring device would be the one which had no mechanical attachment with the switch.

Fourteen holes, $1/32''$ diameter, were drilled vertically through the moving contact, $\frac{1}{2}''$ apart. A beam of light was shone through the holes onto a photo-transistor beneath so that, as each hole passed across the beam of light, the photo-transistor was energised, transmitting a pulse to the C.R.O. The displacement-time graph can be readily obtained by measuring the distance between the pulses on the oscillograms.

The holes in the rod, however, became clogged with oil from the bushes under operating conditions and while it would have been possible to enlarge the holes and so eliminate the clogging, it was deemed unwise because of the already high stresses obtaining in the rod.

It was possible to discontinue further investigation in this direction when it was arranged to take high speed films of the arc. By this method the displacement of the moving contact was easily and accurately determined.

A graph of displacement versus time for the switch is shown in figure 4.5.1. The graph shows the average of eighteen opening operations. The maximum deviation from the average was 2 milliseconds in the total opening time. The movement consists of 22 milliseconds of constant acceleration, the parabolic constant of which is 0.0068 for the units used. The maximum deviation in this constant between openings is ± 0.0003 . These figures illustrate/

illustrate the consistency of operation. The final 11 milliseconds of travel consists of a decrease in acceleration; in fact the movement becomes approximately constant velocity in the last 5 milliseconds.

The great improvement in opening time with respect to the travel of the new switch compared with that of the old switch is also illustrated in the figure.

4.6 High Speed Photography

It was realised that if a comprehensive study of arcs was to be made then it was desirable, if not essential, to correlate the physical properties of the arc with its electrical properties. Examination of the initial stages in the growth of the arc and of the period around zero pause were the main objects of the high speed photography.

The ideal camera for the purpose would have been one which had a framing rate of the order of 100,000 per second and would cover about 30 milliseconds of arcing. Examination of the relevant literature (Reports in Progress in Physics, 1954, The Journal of Motion Picture Engineers and other similar articles) showed that cameras could be, and have been, designed to meet the above specifications being mainly of the rotating prism, multiple lens, or image dissection, types. As far as is known, however, such cameras have been built only by the user and they are not in production, so that no camera which would meet the above specification was available.

There were two cameras available which could photograph the arc for a reasonable duration and at a fairly high speed. These were the "Fastax Camera" manufactured by Wollensac Ltd. and the Langham/

Langham Thomson "Courtney Pratt Series 600" Camera. The Langham Thomson camera uses the image dissection technique perfected by Professor Courtney-Pratt (Courtney-Pratt 1956, and Courtney-Pratt & Thackeray 1957). It is a variable speed machine with a framing rate between 1,000 and 150,000 frames per second. It takes 300 pictures on a 5" x 4" photographic plate. At 100,000 frames/second each frame is 12 μ secs in duration. Each exposure therefore covers 3.6 milliseconds. This means that the camera could only be used for specialised study of the arc such as zero pause or extinction. The camera embodies a projection device for playback but the resolution of the picture is only 5 lines/mm (a normal photograph has a resolution of well over 100 lines/mm) and the picture is subject inherently to "ghosting." A camera of this type was available and several exposures were made using it. A picture was obtained in all cases but the definition was low and the frame by frame change in intensity did not permit any measurements to be taken.

The Wollensac "Fastax" camera is a rotating prism, moving film camera with a normal framing rate of 10,000 pictures/second. By reducing the frame size with a smaller "gate" and by increasing the speed of the prism the framing rate can be increased to 20,000 pictures/second. This camera is extremely suitable for photographing long duration arcs because it can take 100 ft of film covering over 1/3rd sec. of arcing. When run at 15,000 frames/sec. over 5,000 pictures are taken.

Twenty arcs were photographed using this camera and a great deal of useful information was obtained.

4.7 Development of the arc/

4.7 DEVELOPMENT OF THE ARC

The first study of the high speed film was to find how the arc develops from the tiny spot at the instant of contact separation to the characteristic arch shape which one sees with the naked eye. The movement is very much more complex than was at first thought. A sequence of photographs for the development of a typical arc is shown in figure 4.6.1. It can be seen that the arc remains relatively straight until the third half-cycle or, to be more general, until the moving (left-hand) contact reaches the end of its travel. During this early stage of arcing, a small cloud of arc gas builds up around the fixed contact. The importance of this cloud is discussed in section 5.3. On picture 4 the moving contact has just rebounded from the energy absorber. This results in a "kink" in the arc which accelerates its upward rise which is now increasing in velocity. The arc column becomes thicker in section and gives the impression of being more stable by virtue of the build up of ionised gas around the arc channel. During the period of contact separation each zero pause results in almost complete diffusion of the arc column whereas at later zeros a considerable cloud of high-temperature gas persists. It would appear, therefore, that it would be easiest to extinguish the arc at current zeros falling between the time when the moving contact leaves the cloud of gas surrounding the fixed contact and the time when the moving contact reaches the end of its travel.

From picture 5 onwards, it can be seen that the arc leaves the fixed contact upwards, and the moving contact downwards./

downwards. This is a general effect, for which no explanation can be found. The reason is probably that magnetic fields set up around the contacts are such that no matter the polarity of the contact the effect is to deflect the arc upwards at the fixed contact and downwards at the moving contact. These electro-magnetic effects are probably responsible for the helical shape which the arc adopts during the early and middle stages of its development. The exact shape of the arc cannot be determined from two dimensional photographs but a good estimation of the shape can be determined from pictures such as 7 et seq. It seems that the arc starts as a straight filament and develops to a small diameter helix, having a pitch usually equal to the gap length. Sometimes the helix, which is distinctly irregular, has a pitch of $\frac{1}{2}$ the gap length as shown in figure 4.6.1. As the arc duration increased the diameter of the helix increases until it is destroyed by a short circuit in the arc channel. This is shown in picture 15. The arc then assumes the characteristic arch shape as shown in picture 16. The whole sequence covers 8 cycles of arcing. In this time the arc has attained a length of more than 12" (its exact length cannot be determined since the arc does not lie in one plane). Since the arc reaches a length of 7" in 30 msec the natural rate of increase of arc length can be estimated to be about 40 inches per second. The arc rises at a rate of about 25 inches per second due to convection.

The short circuit in the arc channel provided the explanation/

explanation to an unusual feature in the arc voltage waveform. This is shown in more detail in figure 4.6.2. Picture (a) corresponds to (a) on the oscillogram. The loop in the arc is closing down on the upshoot at the fixed contact. At (b) a streamer has broken across the narrow gap which contains a large number of ions and consequently has a low dielectric strength. Although it may appear that the gap is approximately 1" wide and therefore fairly cool and strong, the camera aperture was f 22 and in fact the background to the arc was pure white. It seems likely that the extent of hot gases is much broader than indicated by the photographs. At (b) the majority of arc current is flowing along the original path and so the arc voltage remains high. At (c) however the arc current is flowing through the short circuit, the loop being in the process of decay. This results in the sudden drop in arc voltage of about 100 volts from an original level of over 200 volts, the arc length being reduced by approximately half. This adds weight to the argument that Ayrton's law holds for this type of arc (section 5.5). At (d) the arc has assumed its new shape and the loop of gas is rapidly diffusing and cooling.

Copper and its alloys have been used widely as contacts in circuit breakers. That copper should be chosen is unquestioned because of its high conductivity but it also possesses another property which makes it preferable to other metals for use as contacts. This property is illustrated well in figure 4.6.3. The sequence of three photographs/

photographs shows the arc burning on copper at the left hand contact and on the steel rod at the right hand contact. The arc is burning much more intensely on the steel rod and the arc channel does not decay to the same extent, during a current zero, at the right hand side as it does at the left hand side. It appears that the number of ions in the arc space is greater when the arc has its roots on steel than when these roots are on copper. The work function of copper lies between 3.85eV and 4.55eV while that of iron is between 4.04eV and 4.76eV. It may well be that in the case in hand the work function of the copper is higher than that of the steel, thus explaining the enhanced emission on the steel contact. It is probable, however, that the high emission is due to the presence of a fairly high percentage of carbon in the steel. This, of course, would make the arc incandescent and thus appear more highly ionised.

Figure 4.6.4, apart from illustrating the very complicated shape which an arc can assume, also depicts an unusual phenomenon which the author has termed a secondary arc. Unfortunately this secondary arc only occurred once and so no detailed information can be given. The secondary arc is the offshoot from the left hand contact. The first photograph in the sequence was taken 2 msec. after current zero. The secondary arc reaches a length of $1\frac{1}{2}$ " in 4 msec. resulting from a velocity of over 30 ft/sec. The arc reaches its maximum length in picture (c) and then decays as rapidly as it appeared. The term "arc" is something of a misnomer in that it appears to have only one root. It is interesting to note that the direction of the secondary arc is/

is the same as that followed by the main arc when in its initial stages. It is also worthy of note that the arc root from which the secondary arc emanates is burning on the steel rod. It seems unlikely that the offshoot is actually an arc. It appears to have only one root and its appearance is not that of an arc since there is no well-defined channel. It cannot be a droplet of boiling metal since this would drop vertically and not at the angle of 45° shown. It may be a jet of hot gas from a hole in the steel rod but there is no definite explanation.

Another striking feature of the arc which was revealed by the high speed photography was the considerable time taken for the arc channel to decay after extinction. Figure 4.6.5. shows three photographs of the post extinction period. It can be seen that, even after 60 msec., remnants of arc gas can still be distinguished. Bearing in mind that the background to the arc is white, the arc probably takes well over 100 msec. to diffuse completely.

The rate of rise of the arc due to convection was measured and found to be 25 inches per second. This can be compared with the speed of travel of 300 ft/sec. reached by arcs in circuit breakers, such as the arc chute types, designed to extinguish the arc by increasing its length and consequently its voltage. The inefficiency of a switch with no forced extinction media is consequently illustrated.

An attempt was made to observe the zero pause phenomena but because of the short duration of this period not much detailed information could be obtained. The zero pause period usually covers about $1/20$ th msec., which means that the whole period occurs within one frame of the film.

The/

The only information which was found was that there was a time lag of approximately $40 \mu\text{secs.}$ between the arc restriking at one contact and the other. The rate of travel of the arc "front" is thus of the order of $0.175\text{ins}/\mu\text{sec.}$ ($2\frac{3}{8}$ miles/second).

In several arcs there appeared just after a current zero a small bright spot about $\frac{1}{8}$ " in diameter within the arc channel. These spots are apparently tiny droplets of metal which have become detached from the contacts at the arc root. They then evaporate due to the high temperature and become dense balls of metal vapour. The film indicated that they must be extremely light since they were carried back and forth at half-cycle intervals as the ions moved from one contact to the other. The spots gradually dispersed after about 6 half-cycles.

The preceding pages will have shown just how useful high speed photography can be in the investigations of arcs and provided a study by itself.

CHAPTER 5

EXPERIMENTAL RESULTS

This chapter contains the major results of the research, namely the effect of altering the instant of contact separation relative to current zero, on the total arc energy up to four half-cycles. In all, four main tests were carried out, two at 2400 volts and two at 3200 volts. In both cases the maximum and minimum currents, and, consequently, power factor were used.

Several other minor investigations were carried out and the results of these are also fully discussed.

5.1 Arc Current Waveform

The arc current waveform was sinusoidal except at the zero pause region. Sometimes at the higher currents there was slight distortion in the waveform due, in all probability, to overloading the transformer. These small deviations from sinusoidal were neglected when calculating the arc energy.

5.2 Arc Voltage Waveform

The principal of arc extinction in circuit breakers is to increase the resistance of the arc space, by the application of a strong deionising medium, to such an extent that its dielectric strength is sufficient to withstand the restriking voltage. The shape of the arc voltage waveform shows, to a large extent, whether or not a circuit breaker is performing as it should. It is worth examining the reasons for the shape of arc voltage waveform usually encountered so that the unusual waveform found in these experiments may be/

be treated in its true perspective.

When the contacts of a circuit breaker open, the current continues to flow in the space between them through a channel of ions, formed initially by thermionic emission at the contacts and sustained by ionisation due to the high temperature generated by the arc. As the current decreases towards a current zero, the number of ions being produced per unit time decreases while the number of ions recombining under the effect of the gas blast or other deionising medium remains at a high level. The resistance of the arc space, and, as a consequence, the voltage, rises until at current zero it reaches a maximum. If this resistance is sufficient to withstand the restriking voltage, the arc will be extinguished, but, if not, the voltage will reverse its polarity as the current proceeds on another half-cycle. As the current increases so the number of ions produced will increase, the resistance will decrease, as will the voltage and the process will be repeated. There is, therefore, in the course of a half-cycle, an initial peak of voltage (the reignition peak), the major portion of the half-cycle where the arc voltage is relatively low and virtually constant, and a final, or extinction peak, towards the end of the half-cycle.

In a free burning arc in air there is no such forced deionising process and the reignition and extinction peaks are degenerate as shown by the typical arc voltage waveform in figure 5.2.1. By making general assumptions it can be shown that these waveforms are exactly as would be expected in this kind of arc.

The arc voltage is determined by the current and resistance/

resistance thus:-

$$V_a = I r_a \dots\dots\dots (1)$$

Neglecting the zero pause region for the moment, the rest of the waveform can be built up as follows.

The arc resistance at any instant of time depends on the inverse of the number of ions, n , present in the arc space, i.e.

$$r_a = k' \left[\frac{1}{n} \right]$$

At any instant of time the numbers of ions present is equal to the difference between the number of ions produced, n_p , and the number of ions recombined, n_r . The number of ions produced depends on the temperature of the arc, T_a , and is governed by Saha's equation, so that

$$n_p = k'' [T_a]^2$$

Slepian (1930) indicated that the number of ions recombining per unit length of arc is proportional to the number of ions present (diffusion loss) plus the square of the number present (recombination loss) but it is unlikely that the latter term will apply to an arc in which there is no forced deionisation. So that

$$n_r = k''' [n_p] = k''' [T_a]^2$$

If the arc is to be sustained n_p must be greater than n_r but the difference between n_p and n_r will be greater when the arc current is increasing than when it is decreasing.

The arc temperature lags the arc current by an angle δ (section 5.9) and it can be assumed that there will be a further time lag, ϵ , between an ion being produced and the same ion being lost by diffusion. The temperature variation/

variation over a half-cycle will be as shown in figure 5.2.2.a. The number of ions produced will increase greatly with increase in temperature as given by the Saha equation.

As the arc temperature does not fall to zero at $I_a = 0$ there will always be a certain number of ions in the arc space. This puts a limitation on the arc voltage at current zero because, if $n = 0$ at $I_a = 0$, r_a would be infinite and so at $I_0 + r_a$ would be large. The waveforms of n_p and n_r will thus be as shown in figure 5.2.2.b. n_p has its peak value at $(\frac{\pi}{2} + \delta)$ while n_r has its peak value at $(\frac{\pi}{2} + \delta + \epsilon)$. The value of n_p will be less at $0+$ than at $\frac{\pi}{2}-$ because the temperature will fall appreciably during the zero pause. The values of n_r at $0+$ and $\pi-$ will be similar because the number of ions recombining will also depend on the size of the arc channel, which determines the distance they have to travel to reach a suitable temperature for recombination and which depends on the current flowing.

The number of ions present in the arc space is then the difference between $n_p - n_r$, this being shown in figure 5.2.2.(c).

The arc resistance r_a is derived by taking the reciprocal of n and by multiplying r_a and I (figure 5.2.2.d.) the theoretical arc voltage waveform is arrived at in figure 5.2.2.e.

Most of the conditions of the arc parameters have been satisfied in this analysis. It would be expected that the arc resistance would be considerably greater at the beginning of the half-cycle than at the end. As the arc duration increases one would expect δ to increase, and this would/



would consequently shift the voltage peak away from zero.

This is confirmed by the oscillograms.

It has been assumed that the arc length has remained constant throughout the duration of a half-cycle. Since n_r is also a function of arc length, in the practical case n_r will be greater towards the end of a half-cycle. This will make only a small difference to the value of n_r and does not effect the principal of the analysis.

The assumption that the arc resistance is likely to be greater just after current zero than before it is supported by Mason (1952) who gives a graph of arc resistance versus time just before and after current zero. He found that for a circuit breaker working at 10 lbs/sq.in. the maximum resistance was reached 2μ secs. after current zero. For higher pressures the maximum resistance was reached nearer the current zero.

The arc resistance is of the order of 44Ω at the peak arc voltage during the third half cycle and has a minimum value of 2Ω .

When a deionising medium (nitrogen) is applied at high pressure to the arc, it can be seen (figure 5.2.3.) that the extinction and reignition peaks are more distinct.

5.3 Arc Power and Energy

The methods previously described were used to evaluate the power and energy dissipated in about 250 different arcs. The results of these measurements are discussed in this section, and the effect of altering the phase of contact separation on arc energy is shown to be considerable.

In/

In all cases the powers and energies quoted are for that part of a half-cycle during which separation took place and the subsequent three half-cycles. Any conclusions drawn refer only to a free arc in air between copper electrodes, the results to be expected from other interruptors being estimated later.

The arc power was plotted to a base of time using measurements taken directly from the oscillographs and four typical curves are reproduced in figure 5.3.1. θ is the angle at which separation took place prior to the first current zero. No distinction was drawn between separations on the negative or positive half-cycles.

The arc power dissipated in each successive half-cycle increases in nearly all cases and the power is approximately sinusoidal in shape. It can be seen that, at the first current zero, the difference in the power dissipated by the arcs is very marked. From a purely energy point of view it would be very much easier to extinguish the $\theta = 20^\circ$ arc than the $\theta = 122^\circ$ arc. It can therefore be concluded that the nearer to current zero the contacts separate the less likely it is that the arc will reignite at the start of the following half-cycle.

In the second half-cycle the respective maximum powers increase greatly; by a factor of about 3.5 for $\theta = 122^\circ$, about 7 for $\theta = 40^\circ$, and about 20 for $\theta = 20^\circ$. The arc energy is correspondingly increased, so that at the second current zero the arcs are very much more difficult to extinguish than at the first zero.

In the third half-cycle the marked difference in the power and energy of the respective arcs, observed in the first/

first and second half-cycles, has decreased considerably, although the $\theta = 20^\circ$ arc power continues to increase. This is possibly due to the arcs becoming more stable or to some peculiarity in the individual arcs such as enhanced emission at the contacts (which would reduce the arc voltage). It may also be due to ^{the} inherent disadvantage in the method of measurement, namely the difficulty of positioning the zero voltage and current line accurately. This error gives a large value for the arc power in one half-cycle and a smaller value the next; the total error will be negligible over four half-cycles however.

In the fourth half-cycle the maximum power reached in the $\theta = 122^\circ$ arc is much greater than might be anticipated from consideration of the previous half-cycles. In this arc, the moving contact has reached the end of its travel and so the change from a straight filament of arc gas to a twisted channel will have taken place. This results in an increase in arc voltage, which is proportional to arc length and does not depend on time. The $\theta = 40^\circ$ arc dissipated less power in this half-cycle than the 20° arc. This shows the effect of a short circuit in the arc which was shown by the oscillogram to have occurred just prior to the maximum current.

The graphs also show that the greater the maximum power the later in the half-cycle is this power reached. Since the current has its maximum at $\frac{\pi}{2}$, $\frac{3\pi}{2}$, $\frac{5\pi}{2}$, the first arc voltage peak must be reached later in the case of arcs of longer duration. This supports the theory that the phase difference between temperature and current changes with increase in arc duration.

The/

The phase of contact separation has, therefore, an appreciable effect on the power dissipated especially during the first and second half-cycles of arcing.

The arc power was integrated using a planimeter and the total energy was plotted against θ . Not all values of energy measured are plotted in figure 5.3.2 for the sake of clarity, a random selection being chosen to give an impression of the scatter of the results.

The graphs all slope upwards showing that there is more energy released if the contacts are separated further from current zero. The graph indicates that at the fourth zero the arc is more likely to be extinguished if θ is nearer to 0° than if it is near to 180° . The ratio of arc energy W_a when $\theta = 180^\circ$ to that when $\theta = 0^\circ$ is approximately 2:1 for all powers used.

For the case when the short circuit current was 17.8 amps and the open circuit voltage was 2400 volts, $W_a(\theta = 0^\circ)$ was 54 joules and $W_a(\theta = 180^\circ)$ was 108 joules giving

$$\Sigma = 2.00$$

$$\text{where } \Sigma = \frac{W_a(\theta = 180^\circ)}{W_a(\theta = 0^\circ)}$$

The corresponding values for the other tests are given in the following table. P is the short circuit current, I, times the open circuit voltage, V, in kilowatts.

| P kw | W_a $\theta = 0^\circ$ joules | W_a $\theta = 180^\circ$ joules | Σ |
|------|---------------------------------------|---|----------|
| 42.7 | 54 | 108 | 2.07 |
| 86.5 | 83 | 163 | 1.96 |
| 111 | 111 | 232 | 2.09 |
| 255 | 157 | 328 | 2.09 |

It can be seen that Σ , which is a measure of the effectiveness of phase control is nearly constant, having an average value of 2.06. The close agreement in the values of Σ is somewhat suspicious due to the deviation in several readings of W_a of 10% from mean, but the general indication is that it is nearly constant. It is reasonable to assume that Σ will remain about 2.0 for free arcs in air no matter what their value of P . It appears, too, that the arc energy dissipated by the arc is not the only criterion of the chances of extinction of an arc since it is recognised that a 20 kA arc is much more difficult to interrupt than a 10 kA arc, irrespective of their relative voltages. However, the remarkably high value of Σ obtaining after four half-cycles cannot be overlooked, and it seems that, even if the picture is not complete, the experiments are worthy of further investigation on a more realistic, that is, higher power, scale.

It was found that, at some values of phase setting the 17A, 2400V arc was extinguished at the first current zero. This is shown by the drop in values of W_a in the graph for those arcs in figure 5.3.2. Between the solid lines no arcs survived the first zero and between the dotted lines, some arcs continued to burn for many more half-cycles, while others were extinguished. In no case was an arc, which survived the first zero, extinguished at the second, third or fourth zero; extinction was achieved only when its arc voltage became comparable with the system voltage.

After it has been shown that an arc which commences to burn just before zero is easier to interrupt than one which has started at a greater value of θ , and yet these/

these successful interruptions take place only for separations between 55° and 70° there are evidently other factors affecting interruption. In a free-arc switch the only other variable is the displacement of the moving contact.

If in an ideal circuit breaker the contacts could separate with sufficient velocity to hold off the reignition voltage at any point in its travel, then clearly it would be best to separate its contacts at current zero. In practice, however, where some acceleration period is inevitable, separation at current zero would lead to immediate breakdown of the gas, because the gap length would be infinitesimal. As θ is increased there will come a point when the energy content of the gap is low and the gap length is sufficient to hold off the restriking voltage. In the case of the experimental switch this region lies between 55° and 70° . Beyond this the energy content of the gap is too great to allow sufficient deionisation in the zero pause to withstand the reignition voltage, although the gap length would be ample to withstand it if called upon to do so. This also explains why no extinctions occur at the second zero or until such time as the arc voltage becomes comparable with the system voltage.

That there is an optimum phase of contact separation can be explained analytically by consideration of arc energy and contact displacement as follows. Suppose there is an extinction level, \mathcal{L} , dependant on gap length and arc energy such that when it is exceeded the arc will extinguish at the first zero. \mathcal{L} must be a function of the gap length, l , and an inverse function of the arc energy, W_a . The arc energy for/

for the first half-cycle increases rapidly with increase in θ , and so $\frac{1}{W_a}$ will be infinite for $\theta = 0^\circ$, dropping rapidly as θ increases and reaching a minimum as θ approached 180° . The gap length increases parabolically (constant acceleration) and so $F_n \left(\frac{1}{W_a} \right) (1)$ will have a maximum value which, in this case lies between 55° and 70° and the extinction level (ξ) will be exceeded between these values of θ .

The values of 55° and 70° only apply to the circuit used. If any parameter is altered the phase angles between which extinction occurs will also alter. In the experiment described in section 5.7 the rate of rise of restriking voltage was altered and the results shown in figure 5.7.1 were obtained.

Howatson (1954) suggested that the optimum arc duration would occur when θ was between 2 and 3 radians. In his calculations he used figures obtained from an actual circuit breaker. He also neglected dissipation. The effect of neglecting this is to decrease θ . In an actual circuit breaker it is unlikely that the value of U_a would be so large as in the case of the switch used and this, too, would decrease θ . His calculations involved the use of the rate of dielectric recovery in the arc space and, of course, the rate of recovery would be many times greater in an actual switch than in the experimental switch. If the rate of dielectric recovery is low the optimum value of θ will be lower.

The values of W_a were compared with those obtained using Howatson's equation. In figure 5.3.3 the solid lines represent W as obtained from Howatson's equation while the points were plotted from the experimental results. Several typical/

typical values are quoted in table 5.3.1 and the close agreement is satisfactory. Nearly all the experimental values lie below the theoretical values which is to be expected since dissipation was neglected in the calculations.

The manufacturers of modern air-blast circuit breakers hope to achieve extinction at the second current zero. The figure 5.3.3 shows that if the contacts are separated just before the first current zero i.e. at $\theta = \pi (+)$, the energy liberated by the time of the second current zero is only about a fifth of that which would be liberated had the contacts been separated at $\theta = 2\pi (-)$. The use of phase control is therefore more effective with a more efficient circuit breaker.

In figure 5.3.4, W_a is plotted against current with θ as a parameter. The graphs are straight lines which shows that for a given θ , W_a is directly proportional to the circuit current. This indicates that the system voltage does not affect the energy content of the gap during the arcing period. In a free arc in air the system voltage only determines the duration of the arc. The large difference between the energy content of an arc when separation occurs at $\theta = 2\pi$ compared with that at $\theta = \pi$ is shown clearly.

5.4 The Zero Pause Region

During the transition period when the arc current is reversing its polarity there is a complicated period of voltage and current oscillations. There was no consistent pattern of transition in this region and so no general rules of the restriking phenomena can be laid down.

The zero pause region usually lasts for about

T A B L E 5.3.1.

Comparison of Theoretical and Experimental Values of Arc Energy
between $\theta = 120^\circ$ and $\theta = 360^\circ$

| θ° | 17 A. 2400 V. | | 46 A. 2400 V. | | 26 A. 3200 V. | | 80 A. 3200 V. | |
|----------------|------------------|------|------------------|------|------------------|------|------------------|--------|
| | Wa | We | Wa | We | Wa | We | Wa | We |
| 120 | 2 | 1.3. | 4.0 | 5.0 | 2.2 | 2.6 | 5.4 | 3.8/11 |
| 180 | 4.6 | 5.2 | 9.8 | 8.6 | 5.6 | 5.0 | 17.6 | 18.2 |
| 240 | 12.1 | 11.7 | 24.1 | 21.8 | 13.5 | 12.5 | 35.1 | 34.1 |
| 300 | 20.2 | 19.6 | 41.0 | 37.4 | 23.0 | 22.2 | 59.0 | 43/54 |
| 360 | 34 | 30.3 | 68 | 61.8 | 37.6 | 34 | 106 | 97 |

N.B. In this table Wa = Theoretical arc energy (joules).

We = Experimental values of arc energy (joules).

1 millisecond. During it the current is virtually zero
20 but undergoes a high frequency oscillation of around 100 kc/s. of amplitude less than 300 mA. A typical zero pause is shown in figure 5.4.1.

The voltage generally takes the form of a recovery transient, that is, a negative peak followed by a fast rise in voltage and then a high frequency transient of about $\frac{1}{25}$ millisecond duration. This high frequency transient has a variable duration between 0 and $\frac{1}{10}$ msec. The gap then breaks down resulting in a sudden drop in the arc voltage after which the arc voltage settles down to continue the half-cycle in the normal manner. The negative spike is usually about 200 volts and the positive transient occurs at a level of 250 volts. The general values of total swing are usually between 450 volts and 680 volts. These values are independent of θ and of the duration of the arc.

The difference between the arc voltage just prior to zero pause and just after it is usually 140 volts and this value, too, is independent of θ and arc duration.

The effect of blowing nitrogen across the arc space was to reduce the duration of the zero pause to about 200 secs. This is approaching the low values which occur in actual circuit breakers.

If external capacitance is added to the circuit across the arc gap the zero pause assumes a definite pattern as illustrated in figure 5.4.2. There is no negative voltage spike and the rate of rise of the positive transient is, as would be expected, much slower. The transient reaches a value of 650 volts after 150μ secs. before breakdown occurs.

This may lead to a simple method of determining
the/

the dielectric recovery curve of the gap. Using different values of capacitor, the voltage level reached and the time taken to attain it could be measured, so that a curve of dielectric strength against time could be constructed. It appears, from the limited results available that the dielectric strength increases rapidly with time at first and then levels off.

5.5 Measurement of Light from the Arc

As mentioned in section 4.4 several methods of estimating arc severity were investigated. The only method which showed possibilities of qualitative analysis was the measurement of the light output of an arc using a photo-transistor. The reason for investigating this in the first place was that some arcs appeared to the naked eyes to be brighter than others. It was thought that this might be due to the difference in duration of one arc from another, but this was discounted when it was later found that an arc usually burned for between 35 and 40 half-cycles.

The circuit shown in figure 5.5.1.a was all the apparatus necessary. The photo-transistor was placed inside the hardboard box surrounding the experimental switch. The box was painted matt white and the direct rays from the arc were screened from the photo-transistor so that the box formed an integrating cube. The photo-transistor used was a Mullard OCP 71. From figure 5.5.1.b. it can be seen that the current output is proportional to the light input for constant wavelength light.

It will be seen from figure 5.5.1.c., however, that if the wavelength of the light is not constant the photo-transistor output will not be linear. This is one of the drawbacks/

drawbacks of the method since it is very likely that the arc will be predominantly green (the characteristic colour of copper) at the beginning of its life and will gradually change to white as the arc duration increases. It is also likely that there will be a cyclic change in colour, probably from yellow to white and back to yellow, in the course of a half-cycle. There will always, of course, be a green component in the colour.

However, using the oscillographic records qualified by the above conditions it was noted that the light output was very low during the first half-cycle but after the third half-cycle the output increased greatly. This is to be expected since while the contacts are separating the arc current has to heat up a large volume of air in order to maintain itself. It is also very narrow and so does not emit much light.

The arc light waveform is not sinusoidal in the course of a half-cycle, increasing slowly at first, until after 3 msecs. it assumes a sinusoidal shape for about 4 msecs. and then decays towards current zero. At the first and second, and often the third, current zeros there is no measurable light output from the arc, showing that the arc channel deionises almost completely. At subsequent zeros there is an increasing quantity of remanent light. The light waveform also becomes more sinusoidal and after the sixth half-cycle the cyclic amplitude decreases while the general level of light emanated increases steadily. After extinction the light decays exponentially, reaching its original zero level after about 40 msecs. The high speed films showed that the arc was still visible after 60 msecs. and/

and so the photo-transistor was unable to detect low values of light, possibly due to defects in the integrating cube.

5.6 The Relationship between Arc Voltage and Length

5.6.1 General Laws

The voltage drop which occurs between the anode and cathode of an arc is split into three distinct regions; the cathode drop, the anode drop, and the positive column drop. The first two have large voltage gradients (the cathode drop may be as high at 10^5 volts/cm) while the third, which occupies the major portion of the arc length, has a relatively low voltage gradient.

Mme Ayrton (1910) was the first worker to investigate any relationship there might be between arc voltage and length. For d.c. arcs of short length between carbon electrodes she showed that

$$v_a = \alpha + \beta l + \frac{\gamma + \delta l}{i}$$

where v_a = arc voltage l = arc length (mm) i = arc current: the current used was less than 30 amps. For an arc burning between copper contacts the values of the constants are

$$\alpha = 15.2$$

$$\beta = 10.7$$

$$\gamma = 21.4$$

$$\delta = 3.0$$

Not long after Mme Ayrton's work was first published in 1902, Professor Steinmetz (1906) gave

$$v_a = \alpha' + \beta' l + \left(\frac{\gamma' + \delta' l}{\sqrt{i}} \right)$$

In 1925 Norberg showed that

$$v_a = \alpha'' + \left(\frac{\beta''}{\sqrt{i}} \right) l$$

and E.R.A. workers found that the arc voltage fitted the equation/

equation

$$v_a = v_c + \left(\frac{\alpha'''}{\sqrt[1]{i}} \right) l + Al$$

In the above equations the constants α , β , γ , δ , etc., depend on the contact material and other physical parameters.

l is the arc length

A is the instantaneous voltage per unit length of arc proper

v_c is the cathode drop

Nottingham (1923, 1926) found that the atmospheric arc of constant length could be represented by a general equation of the form

$$v_a = K_1 + \frac{K_2}{i^n}$$

for a large number of contact materials. The exponent, n , of this equation was found to depend on the absolute boiling point, T_B , of the anode. n is a linear function of T_B , thus

$$n = 2.62 \times 10^{-4} T_B$$

Thus for carbon $n = 1$, and Nottingham's curves agree well with those of Eme Ayrton. For most non-refractory electrodes n lies around 0.5 (CuO = 0.64) which adds support to the formula where v_a is a function of $\sqrt[1]{i}$. For tungsten however $n = 1.4$ and consequently Nottingham found that, in some cases, it was necessary to use the boiling point of the metal oxides. n varies slightly with pressure and the nature of the electrode surface.

Grotrian (1915) found that for low current arcs between copper contacts the arc voltage could be expressed as

$$v_a = 60 + \left(12.8 + \frac{35.5}{i} \right) l$$

l is in cms.

He also found that the length dependant term was approximately the/

the same for all contacts, suggesting that it is a characteristic of a long arc in air. The first term represents the anode + cathode drops.

It is probable that each of the above equations, which profess to express the same thing, is nearly right within the limits of its own application, yet none is strictly correct. Mme Ayrton's refers to short d.c. arcs up to 30 amps while the E.R.A. equations are for long a.c. arcs up to 1600 amps.

The majority of workers on the theoretical study of arcs have found it necessary to assume a linear relationship between the arc voltage and length, in order to simplify their calculations. There is good experimental support for this assumption if the extinction and reignition peaks are neglected. But Seelinger found that, for currents such as those encountered under fault conditions,

$$v_a = \alpha i + \frac{\beta}{i} + \gamma i^2$$

there being no length dependant term. This could be explained by the arc becoming saturated with ions at high currents.

In order to supplement the above work it was decided to attempt to find a law governing the arc voltage for a long a.c. arc with currents up to 46 A R.M.S.

5.6.2 Method of Approach

Ter Horst and Brinckmann (1936) using a constant length arc measured the arc voltage by evaluating the R.M.S. value. It is a very different proposition to apply this method to an arc whose length is constantly changing.

It is, however, reasonable to assume that a law might/

might be found if a given point in the voltage cycle is chosen at which to take measurements. By varying the instant of contact separation, the time taken to reach this point will be different. So that, assuming the arc length is the same as the gap length during electrode separations, some form of relationship between arc voltage, length, and current should be found if Ayrton's law holds.

A suitable point to choose is that at which peak arc volts are reached since it is more clearly defined than the minimum arc voltage which occurs near the middle of the half-cycle. Also a greater degree of accuracy is obtained since the peak arc voltage is approximately three times the minimum value.

5.6.3 Results

The following results therefore apply to a long a.c. arc in air, the arc voltage always referring to the peak potential difference reached during a half-cycle. This peak usually occurs 1 msec. after a zero pause and so the current used in the calculations is $i = I_0 \sin 18^\circ$.

The results are plotted in figure 5.6.1 and it can be seen that there is a definite relationship between the arc voltage, length and current. The arc voltage is greater the greater the arc length inferring that there is a βl term. The graphs cut the voltage axis, and since the abscissae depend on the current two constant terms are implied one of which is inverse current dependant. These are the α and $\frac{\gamma}{i}$ terms of Mms Ayrton's equation. The slope of the graphs varies inversely as the current suggesting that there is also a $\frac{\delta l}{i}$ term. However, in the light of Nottingham's work, the current dependant terms are assumed to depend on the inverse square root of the current so that the equation of/

of the arc voltage is

$$\hat{v}_a = \alpha + \beta l + \frac{\gamma + \delta l}{i}$$

If l is in cms, the values of the constants are

$$\alpha = 35.6$$

$$\beta = 96.0$$

$$\gamma = 14.9$$

$$\delta = 77.0$$

These results agree up to a point with those of other workers. Relating the author's equation with Mrs Ayrton's (which it resembles most) it can be seen that of the constants only β agrees with the values quoted in section 5.6.1. β also agrees with the corresponding equation in the Grotrain equation. In this equation the non length dependant terms total 60 volts whereas in the author's equation these terms are $(35.6 + \frac{14.9}{i})$. This is less than Grotrain's value, his current being 3 amps. His δ term is very much less than the author's and this is probably due to taking measurements at the peak value of v_a .

However the results have shown that the arc voltage does depend on the arc length and that the assumption that Ayrton's Law holds for long a.c. arcs is valid. The correctness of using \sqrt{i} instead of i cannot be verified with the limited graphs available.

For large currents, such as those met with in circuit breaking the current dependant terms become insignificant and the equation reduces to

$$\hat{v}_a = \alpha + \beta l$$

At current zeros however these terms become large and indicate the presence of extinction and reignition peaks. The equation/

equation must therefore be qualified by the fact that there are no peaks and so the equation does not hold for low values of current.

5.7 The Effect of Altering the Rate of Rise of Restriking Voltage on the Range of Optimum Power Angles:

It was mentioned in section 5.6 that the successful interruption of an arc at the first current zero depends not only on the energy content of the gap at current zero, but also on the gap length if all other circuit parameters remained constant. Increase in arc current or circuit voltage, for example, would affect the success of interruption. Another important parameter, which Skoplon believed to be the extinction criterion, is the rate of rise of restriking voltage. This controls the time available for deionization before the reignition voltage is reached. If, for example, the r.r.r.v. is high then there will be little time for the gap to recover and consequently the breakdown voltage will be low and will be reached in a short time. If the r.r.r.v. is low then the dielectric strength of the gap will have appreciable time to rise to a value sufficient to hold off the restriking voltage.

The r.r.r.v. of the circuit can be conveniently varied by the connection of the capacitor bank, described in section 3.7.2., in parallel with the arc. By holding the other parameters constant and varying the value of capacitance across the arc, the effect of altering the r.r.r.v. on the range of phase angles at which extinction occurs can be studied.

The results are shown in figure 5.7.1. The extinction level is defined as that level of deionization which, if it is exceeded, will give the arc space sufficient dielectric/

dielectric strength to withstand the restriking voltage. It is constant for a given current and voltage, but will increase if the voltage increases (since the maximum restriking voltage increases) and if the current ^{increases} (since the arc space will be more highly ionised). The most prominent effect is that the range of phase resulting in extinction widens considerably as the capacitance increases. The range of phase is not symmetrical about the phase angle at which extinction occurs with minimum shunt capacitance. With a current of 17A and an O.C. voltage of 2400v. the range of phase is between 55° and 70° . For a parallel capacitance of $0.5 \mu F$ it is between 25° and 180° . This indicates that increasing the capacitance is more effective in extinguishing the arc if the arc length is long. It is to be expected that even if the r.r.r.v. is low the arc will restrike if the phase angle is low because of the arc's short length. The limiting case is when contact separation occurs just after current zero. Then the r.r.r.v. would have to be slow enough to allow the gap length to increase sufficiently during the current zero period to hold off the system voltage. If the gap length is large then the gap length r.r.r.v. has only to be slow enough to enable deionisation (which is enhanced because of the long arc length) to exceed the breakdown level.

The experiment was repeated for 25A and 46A arc current and the extinction levels are shown. It can be seen that, as the current increases, the optimum phase angle increases. This is because the deionisation has to be more intense to hold off the restriking voltage for the same gap length. Unfortunately the exact shape of the constant capacitance/

capacitance lines and so the relative extinction levels for different currents could not be determined.

The r.f.r.v. varies between $11V/\mu$ sec. when the parallel added capacitance is $0\mu F$ and $.98V/\mu$ sec. when the capacitance is $0.5\mu F$.

5.8 Burning of the Copper Contacts

It was noticed that, on a pair of contacts between which an arc had burned, there were a number of small deposits of copper. There has been a deal of controversy on the matter of contact erosion and it was thought that a study of the depositions might yield some useful information on metal transfer and electrode current density.

Highly polished copper contacts were used and the arc was allowed to burn for about 6 - 8 half-cycles. Study of the deposits was through the medium of high-magnification photographs.

The arc is initiated by the rupture of a bridge of molten copper, resulting from the intense local heating which occurs during contact separation. It was thought at first, (since the contact surfaces of the electrodes were flat), that the deposits were the direct result of the rupture of a number of bridges. This was ruled out because the position of the deposits on one contact did not correspond with those on the other.

Figure 5.1.a shows a plan view of one burn mark magnified 60 times. It consists of an area of contact erosion and within it a conical deposit similar to that shown in side elevation in figure 5.1.b., which is magnified 170 times. Each burn mark on the contacts is similar in general/

- 12 -

general form, although in some cases the area of erosion appears to move over the contact during a half-cycle.

The question arises as to the mode of formation of these marks, to which electrode each belongs and why the deposit lies within the eroded portion.

In his book "The Physics of Electrical Contacts" Professor Llewellyn Jones, describes the erosion pattern for copper as a hemispherical crater and a ring of deposited copper concentric with it. He also says that in one case where there was arcing, "... the direction of transfer was clearly directed from anode to cathode." In a later chapter on metal transfer he gives the view that the greater electrode loss should be from the anode in short arcs while in long arcs the predominant loss would be from the cathode. It would appear by the following analysis, however, that the deposit occurs at a cathode and the erosion at an anode.

The electron flow in an arc is from cathode to anode and any ions will attempt to reach the cathode. Because of the high temperature of the arc roots (2400°K) evaporation of the contact material will take place. However, it seems likely that the atoms released will be ionised by electron bombardment and will thus tend to make for the cathode. Furthermore evaporation at the cathode will be suppressed by the above process. The ions will thus tend to collect at the cathode and will cover an area more or less equal to the root area. Similarly the evaporation will cover an area equal to the anode root which is generally accepted to be the larger.

If a cycle of arcing is considered, a deposit of copper will appear on the cathode and a crater will be burned in the anode. During a zero pause there will be a period/

period of time between the last electron leaving the cathode and the first electron arriving back at the start of the next half-cycle. During this time the arc channel will have risen slightly and no preference will be given to a restrike onto the exact spot of the previous cathode. At the other electrode, however, the first electron will leave the new cathode almost immediately after the last electron has arrived there (the interval of time being that for the voltage to rise to the arc reignition voltage). There is thus very little time for the arc channel to move and the new cathode will form inside the previous anode.

This argument, although it is feasible and ties up well with the experimental observations, does not agree with the results of other workers. Seelinger observed that the presence of electrode vapour in the arc channel could only be detected around the cathode and anode, whereas in the above argument it must be distributed (though not necessarily evenly) throughout the arc space. However, there is some evidence that there is copper throughout the arc space. Cobine, for example, states that for an arc in nitrogen between copper electrodes "... spectroscopic examination shows a strong N_2 band spectrum, together with some copper lines." Deductions from analyses by Suits (1935) shows that about 97% of the charge concentration in an arc is contributed to by ionized copper vapour.

Cobine also says that the cathode spot on a low melting point metal "... is usually in continuous random motion over the surface." This did not happen in the arcs observed, the motion being random but cyclic.

It was possible to draw a few quantitative conclusions/

conclusions from the photographs illustrated. It is estimated that the copper deposit represents the passage of an average current of 11.8 amps. The arc in question had an average current of 15 amps, the difference being presumably carried by gas derived electrons. The anode current density was found to be 24 amps./sq.mm. while that of the cathode was about 165 amps./sq.mm.

The unsymmetrical shape of the deposit is probably due to bending under the force of gravity during cooling.

5.9 Time Constant of the Arc

The time constant of an arc has proved a necessary function in energy balance theories of arc extinction. Although Cassie (1939) introduced it indirectly, Mayr (1943 a, b) defined the arc time constant and used it extensively.

The time constant can be determined from the phase angle between the arc current and temperature (assuming the arc to be a linear CR network). This angle can be found directly from the oscillograms; the angle of lag between V_p and I gives δ directly.

The angle δ was measured at the third half cycle of arcing for various currents, the following results being obtained:-

| V Volts | I amps. | δ ^o |
|------------|------------|-----------------------|
| 2400 | 17 | 21 |
| 2400 | 46 | 7.8 |
| 3200 | 27 | 13.1 |
| 3200 | 80 | 5.4 |

A graph of I verses δ was drawn (figure 5.9.1.)

and the values are found to agree well with those of Ter Horst

Brinkman & Ornstein (1935, 1936) and von Engel & Steenbeck (1933),

5.10 The Relationship between Arc Radius and Current

The relationship between arc radius and current was found to obey the laws suggested by, for example, Cassie (1939). The results were obtained using the high speed films, and are shown in figure 5.10.1.

The radius increases linearly with increase in current being larger the longer the arc duration and greater the distance from the arc root. The arc radius has a lesser cyclic variation the longer the arc has burned indicating that the arc radius may be temperature rather than current, dependant. The arc radius increases greatly with distance from the arc root up to about $\frac{1}{2}$ " when the radius becomes approximately constant until the other contact is reached.

CONCLUSIONS.

The preceding work has been carried out with one object in view, namely to justify the adoption of synchronised switching. It is the object of this final chapter to tie together the foregoing work and use the results found to verify the relevant theoretical work done by Howatson. It is shown thereby that synchronised switching has real possibilities in the field of industrial switchgear.

6.1.1. Arc Energy Input for the 1st and 2nd Half-cycles

As far as investigations into the energy input of arcs, which have been initiated at different points in the current cycle, are concerned, only Goldenberg has published a paper on the subject. It is unfortunate to find, therefore, that in his treatment he does not concern himself with the form of the moving contact displacement which Howatson has shown to be so important. However the experimental values of energy input to the arc can be compared with values using Howatson's equations, provided a modification is made with respect to the arc voltage. Assuming that the arc voltage per unit length of arc, U , is constant except at reignition and extinction (where the relaxation of this assumption is warranted by the short duration of the phenomena) the following expressions were derived for the arc energy.

$$W_{a_1}' = \frac{I u a}{\omega^2} \left(\frac{\theta^2}{2} + \cos \theta - 1 \right) \quad \dots\dots 6.1.1.$$

where $W_{a_1}^1$ is the arc energy input for the case when and the arc length increases with constant acceleration a .

$$W_{a_2}' = \frac{\hat{I} U_{a_0}}{\omega^3} \left(\frac{3\theta^2}{2} - 2\theta\pi - \cos\theta + \pi^2 - 3 \right) \dots\dots 6.1.2.$$

Where $W_{a_2}^1$ is the arc energy input for the case when $2\pi > \theta > \pi$. θ is the total arc duration up to the first current zero in equation 6.1. and up to the second current zero in equation 6.2.

It can be seen from figure 5.6. that the peak arc voltage/gap length equation is of the form $\hat{U}_a = \alpha + \beta l$ that is the value of \hat{U}_{a_0} is not zero as would be required if the peak arc voltage/unit length was to be constant for a given current. Similarly the average arc voltage as $l \rightarrow 0$ is not zero but has a value of approximately 7 volts. It is reasonable to assume, also, that the average arc voltage/gap length graph will be a straight line parallel to the peak arc voltage graph for the same current but having a value $U_{a_0} = 7$ volts. By drawing these graphs the following values of average arc voltage/unit length are obtained:-

| I amps. | V Volts | Volts/inch |
|------------|------------|------------|
| 17 | 2400 | 111 |
| 46 | 2400 | 82 |
| 26 | 3200 | 135 |
| 80 | 3200 | 62.1 |

To obtain the total arc energy input for the first and second half cycles a correction term must be added to $W_{a_1}^1$, and $W_{a_2}^1$ to allow for $U_{a_0} \neq 0$. The correction terms are

given by $W_{a_1}'' = \frac{\hat{I} U_{a_0}}{\omega} \int_{\pi-\theta}^{\pi} \sin \theta d\theta$ for $\pi > \theta > 0$

and $W_{a_2}'' = W_{a_1}'' - \frac{\hat{I} U_{a_0}}{\omega} \int_{\pi}^{2\pi} \sin \theta d\theta$ for $2\pi > \theta > \pi$

so that the complete expressions for the arc energy input are

$$W_{a1} = \frac{\hat{I} v_a}{\omega^2} \left(\frac{\theta^2}{2} + \cos \theta - 1 \right) + \frac{\hat{I} v_a}{\omega} [1 - \cos \theta] \dots\dots 6.1.3$$

$$W_{a2} = \frac{\hat{I} v_a}{\omega^2} \left(\frac{3\theta^2}{2} - 2\theta\pi - \cos \theta + \pi^2 - 3 \right) + 2 \frac{\hat{I} v_a}{\omega} + \frac{\hat{I} v_a}{\omega} [1 - \cos \theta] \dots\dots 6.1.4$$

The expressions are worked out for various values of θ and are given along with the corresponding experimental values in figure 6.1. Because the arc length is greater than the gap length, the value of arc voltage per unit length will be lower than is the actual case but this will be offset by a corresponding increase in the acceleration due to the same error. The contact separation is not quite constant acceleration so that there is an inherent error in applying formulae 6.1.3. and 6.1.4. to this switch. The value of acceleration chosen was an average obtained from the high speed films. It is conceivable that since the oscillograms were taken several months afterwards the spring might have weakened and the switch friction increased. It is possible therefore, that the value of acceleration, 1,405 ins/msec.² is in error by about +0.05 ins/msec.² This error would decrease W_a by about 3½%. The agreement between experimental points and the theoretical values is remarkable. The experimental values in table 6.1. have been taken from the graph and approximated to the nearest whole number.

The values in table 6.1 can also be used to yield an interesting graph. If W_a is plotted against current for different values of θ , the resultant graph is a straight line. This graph can then be used to determine the arc energy/

TABLE 6.1. ARC ENERGIES FOR ARC DURATIONS UP TO TWO HALF CYCLES

| θ rads | $I_a = 17^A V = 2400^V$ | | | | $I_a = 46^A V = 2400^V$ | | | | $I_a = 26^A V = 3200^V$ | | | | $I_a = 50^A V = 3200^V$ | | | |
|------------------|-------------------------|----------------|------------|------------|-------------------------|----------------|------------|------------|-------------------------|----------------|------------|------------|-------------------------|----------------|------------|------------|
| | $W_{a'}$ J | $W_{a''}$ J | W_a J | W_e J | $W_{a'}$ J | $W_{a''}$ J | W_a J | W_e J | $W_{a'}$ J | $W_{a''}$ J | W_a J | W_e J | $W_{a'}$ J | $W_{a''}$ J | W_a J | W_e J |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $\frac{\pi}{4}$ | .0205 | .158 | .178 | - | .041 | .431 | .472 | - | .0252 | .243 | .265 | .72 | .065 | .75 | .815 | .1 |
| $\frac{\pi}{2}$ | .277 | .532 | .809 | - | .541 | 1.45 | 1.99 | - | .354 | .81 | 1.16 | 1.0 | .861 | 2.5 | 3.36 | 3.0 |
| $\frac{3\pi}{4}$ | 1.27 | .913 | 3.54 | - | 2.48 | 2.48 | 4.94 | - | 1.57 | 1.4 | 2.97 | 3.0 | 3.95 | 4.31 | 8.26 | 8 |
| π | 3.57 | 1.07 | 4.64 | 4.0 | 6.97 | 2.9 | 9.87 | 7 | 4.42 | 1.64 | 6.06 | 6.0 | 11.1 | 5.05 | 16.15 | 15 |
| $\frac{5\pi}{4}$ | 7.55 | 1.23 | 8.75 | 8.1 | 14.75 | 3.33 | 18.08 | 13 | 9.32 | 1.78 | 11.10 | 10.5 | 23.4 | 5.8 | 29.2 | 28 |
| $\frac{3\pi}{2}$ | 12.9 | 1.60 | 14.5 | 12 | 25.2 | 4.35 | 29.55 | 25 | 16 | 2.45 | 18.45 | 19.0 | 40.2 | 7.55 | 47.7 | 46 |
| $\frac{7\pi}{4}$ | 20.0 | 1.76 | 21.76 | 19 | 39.2 | 5.38 | 44.5 | 42 | 24.9 | 2.7 | 27.6 | 26 | 62.1 | 8.31 | 70.4 | 70 |
| 2π | 30.0 | 2.14 | 32.14 | 31 | 58.8 | 5.8 | 64.6 | 64 | 37.4 | 3.28 | 40.68 | 40 | 93 | 10.1 | 103.1 | 103 |

$W_{a'}$: arc energy released during period θ to π or 2π
 $W_{a''}$: correction factor for $U_a \neq 0$ at separation
 W_a : total arc energy released = $W_{a'} + W_{a''}$

W_e = experimental arc energy released

energy input in a given switch for various angles θ , without having to work out the arc voltage per unit length for each value of current.

It might be expected that for zero current there would be zero energy but, of course, there is a minimum current at which an arc will burn for a given contact acceleration and duration. In other words as $\theta \rightarrow 0$ so the current tends to 0 and a greater current will be necessary to sustain the arc as θ increases. The graphs indicate both of those criterias.

6.1.2. Arc Energy Input over the First Four Cycles of Arcing

Howatson indicated that, by continued integration of equations 6.1.1. and 6.1.2. expressions could be found for the energy input of an arc over as many half-cycles as desired. Such an equation would not, in all probability, serve any useful function in indicating the energy content of the arc since the assumptions and approximations become less valid as time advances. It is also unlikely that any circuit breaker would have constant acceleration or velocity over more than two half-cycles. In explaining why the graphs of arc energy versus phase over 4 half-cycles is a straight line whereas the corresponding graph over 2 half-cycles is parabolic, the change in contact movement from constant acceleration to constant velocity gives the answer. The equation for the arc energy input with constant velocity increase in arc length is much more linear than that for the constant acceleration case, and, since the energy input for the third half-cycle is considerably greater than for the first and second half-cycles (of the order of 2:1) considerable flattening of the $W_a - \theta$ graphs over/

over 3 half-cycles would be expected. Since there is a considerable reduction in increase of arc length/unit time in the fourth half-cycle (it drops from about 200 ins/sec. to only 25 ins/sec.) the $W_a - \theta$ graph would tend to flatten out still further.

6.2 General Comments

Because of space limitations the power rating of the apparatus was of necessity low. Although it is doubtful whether this has had any effect on the consequences of the results, it is possible that the assessment of the effectiveness of phase control has been optimistic. In the case of a circuit breaker dissipation of energy cannot be neglected, and this will reduce the "effectiveness ratio" of phase control. It is known that in the case of some air blast gear the only criterion affecting interruption is the gap length; interruption is generally successful at the first zero if $\theta > \frac{\pi}{2}$ and at the second zero if $\theta < \frac{\pi}{2}$.

6.3 Future Work

The design of the switch and phase control apparatus was not in keeping with modern circuit breaker practice and it is suggested that in future compressed air is used to open the switch rather than a spring. By providing a buffering loop in the operating cylinder much of the mechanical failure which the switch suffered could be avoided. A suggested design is shown in figure 6.3.1.

The practical possibilities of phase control could have been better investigated had a more practical control system been used. A peaking transformer and phase-shifting circuit, although perhaps not giving the consistency of operation obtained with the rocking stator system, would have/

have been a more realistic scheme. It is also suggested that a controlled arcing atmosphere be used, for example, by providing an air blast or similar deionising means.

This would also give results of a practical type as the arc voltage waveform would resemble that met with in high power breakers. The first zero extinction range would have been widened in the case of the low current arcs (see figure 5.3.2.) and it would have been found that there was an extinction range for higher current arcs.

ACKNOWLEDGEMENTS

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Time taken for a body-mass system to cover a given distance with
ranges of varying stiffness

As was shown in section 3.6.3 the stiffness of a spring for a given initial lead and moving a given mass may vary between $k = 0$ and $k = \frac{F_0}{\delta}$

The effect of this can be shown on a diagram of velocity of travel against time (figure A.1). As can be seen all graphs are sinusoidal, having the same initial slope $\Delta = \frac{F_0}{m}$ (which is constant) and all have peak values Δ/ω , their angular frequency. On this diagram equal areas represent equal distances so that the time taken to travel a given distance can be found for any k , since peak velocity $\hat{v} \propto \frac{1}{\omega} \propto \sqrt{k}$, by taking the abscissa which supports the area equivalent to the distance moved.

Considering figure A.1.

For a sine curve $\frac{BC}{AC} = \frac{2}{\pi}$ (1)

Area of $\frac{1}{2}$ sine curve = $\frac{2}{\pi} EC \cdot t_1$

Area of shaded triangle = $\frac{1}{2} v_0 t_0$

So we require $\frac{1}{2} v_0 t_0 = \frac{2}{\pi} EC t_1$ (2) for same distance S

But from (1) $EC = \frac{2}{\pi} AC = \frac{2}{\pi} v_2$

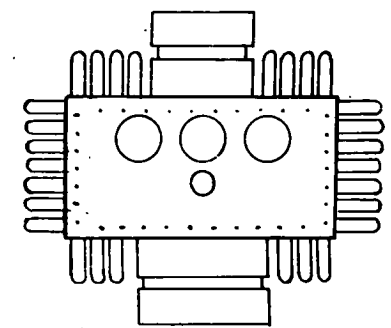
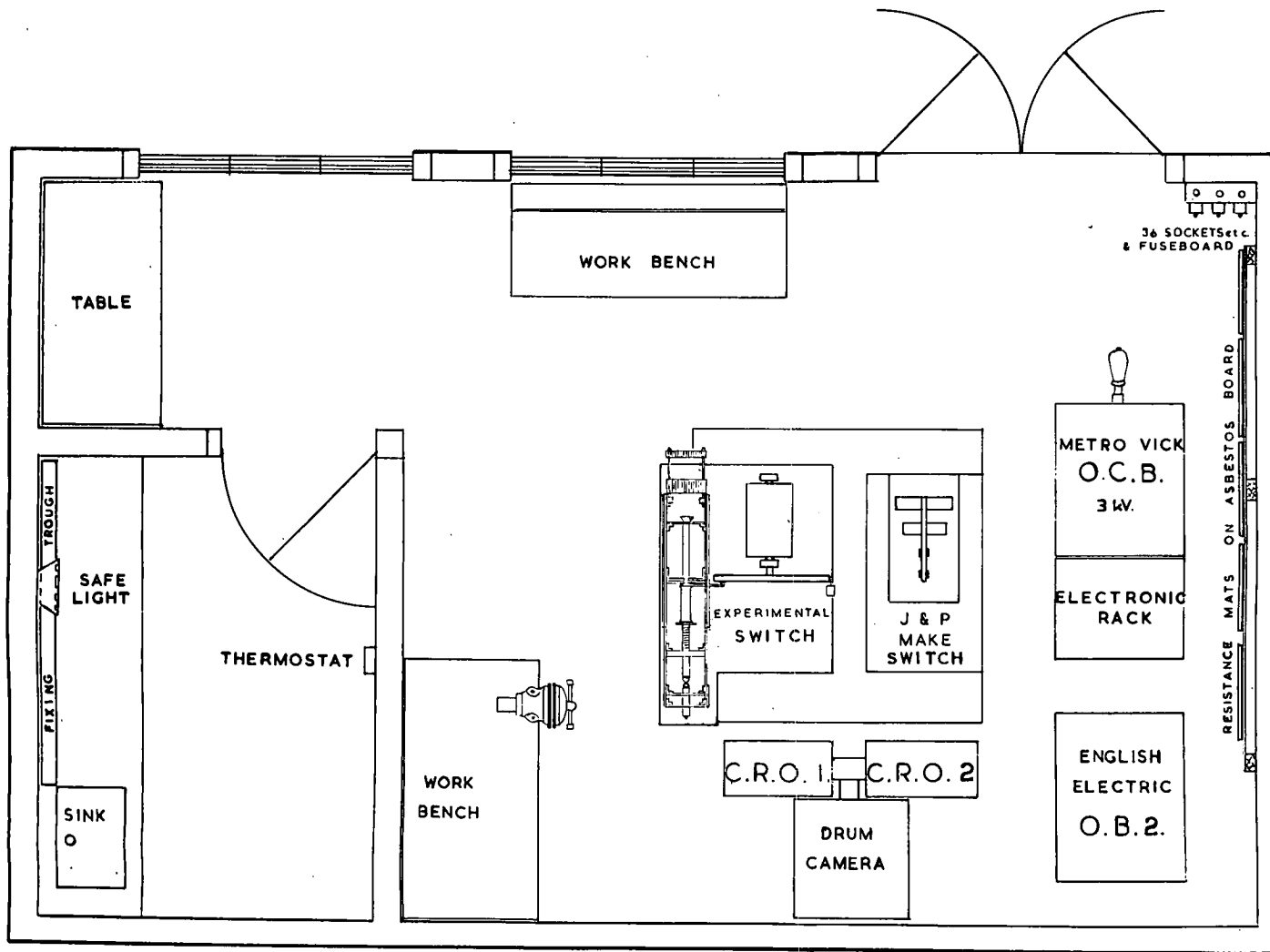
and from similar triangles $\frac{v_2}{v_0} = \frac{t_1}{t_0}$

So (2) becomes $\frac{2}{\pi} \frac{2}{\pi} v_2 t_1 = \frac{1}{2} v_0 t_0$

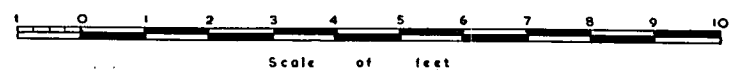
or $\frac{1}{\pi^2} \frac{2t_1}{t_0} = \frac{v_0}{v_2} = \frac{t_1}{t_0}$ or $\left(\frac{t_0}{t_1}\right)^2 = \frac{6}{\pi^2}$

$t_0 = 0.9t_1$

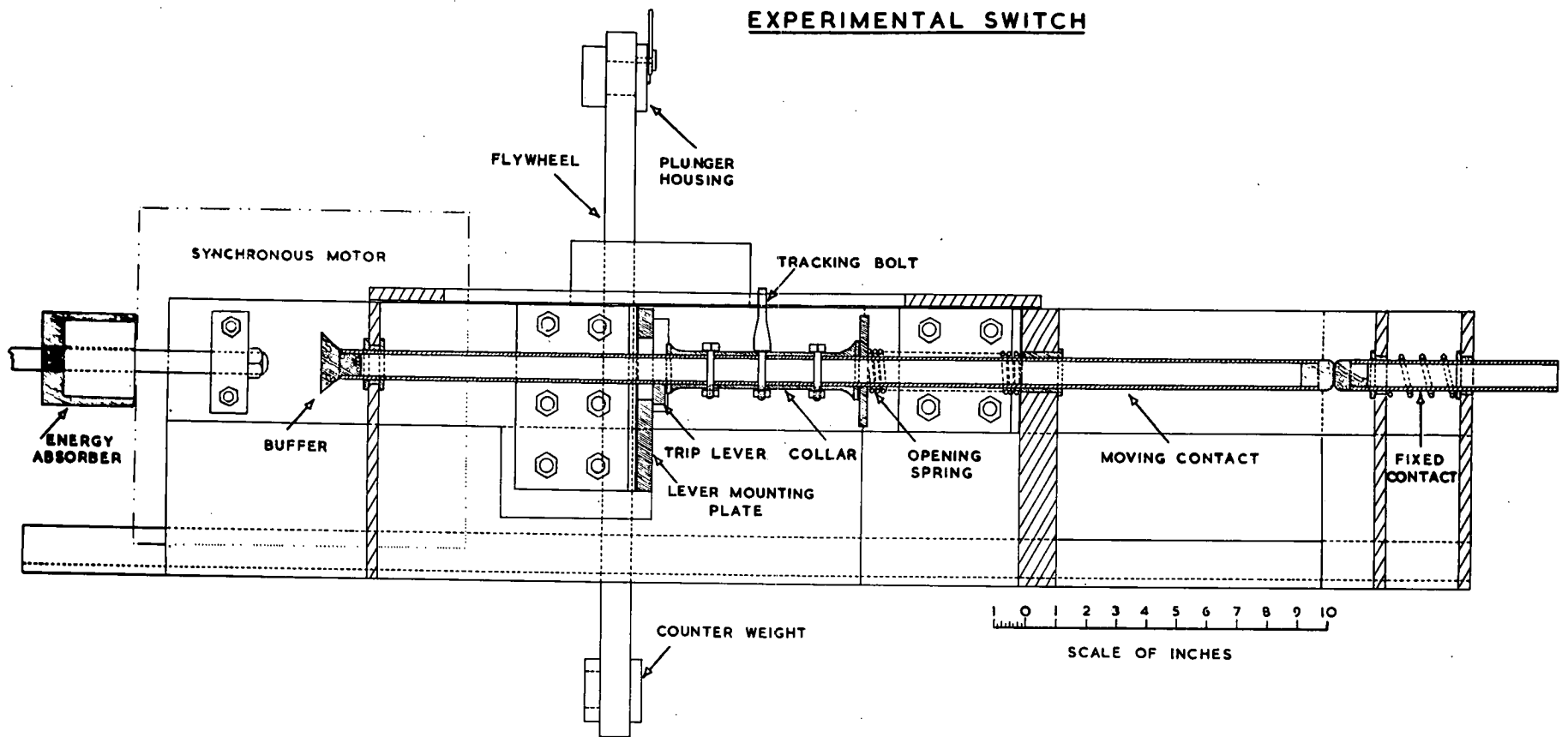
SWITCHGEAR LABORATORY



TRANSFORMER
440v/53w.



EXPERIMENTAL SWITCH



PLUNGER MECHANISM

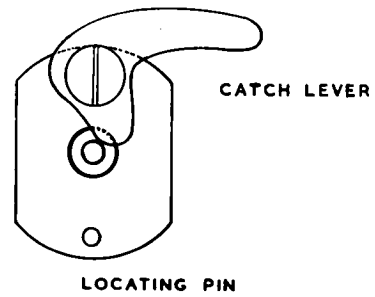
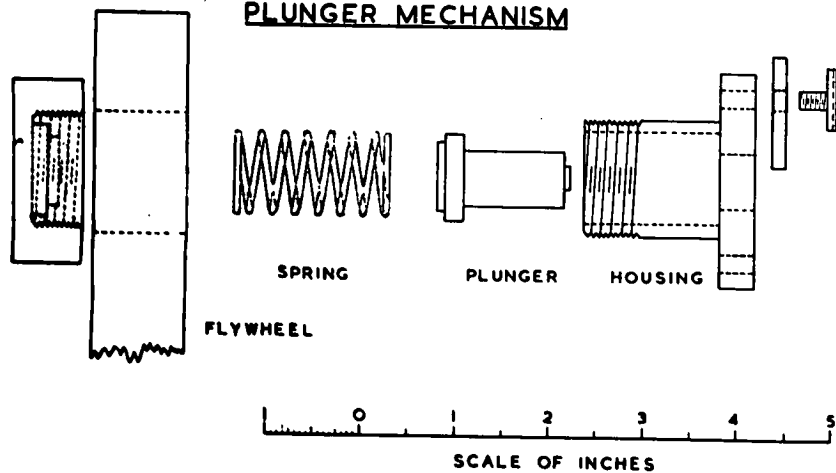


FIGURE 3.6.1.

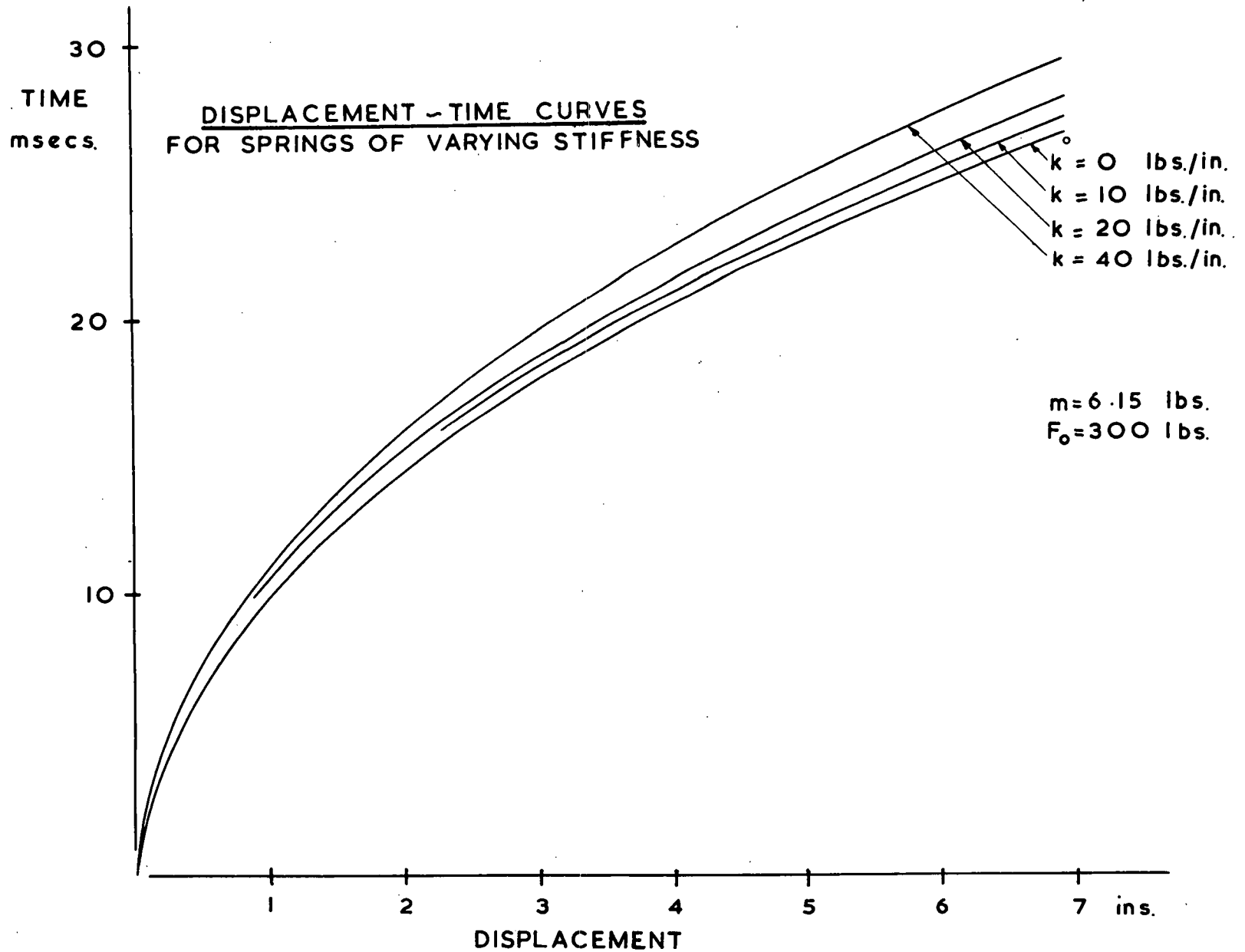


FIGURE 3.6.3.

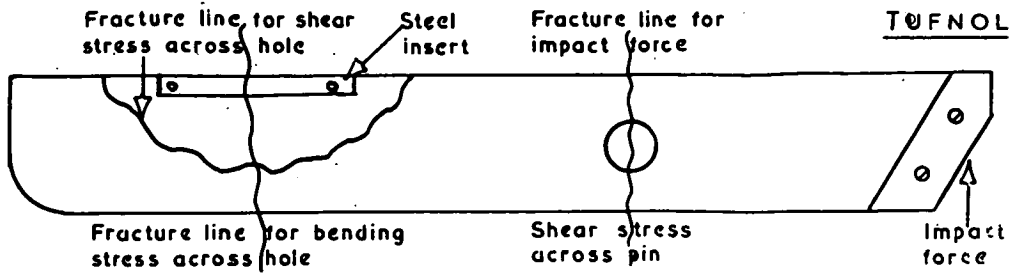


FIGURE. 3.6.4. a.

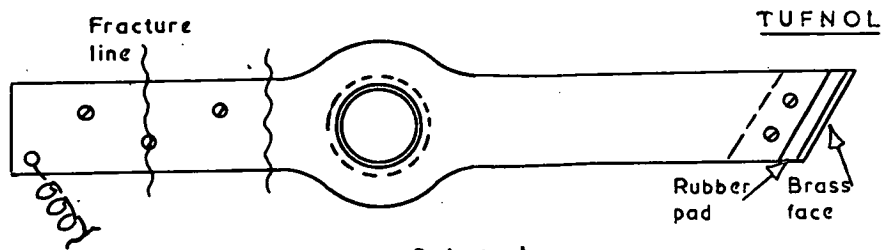


FIGURE. 3.6.4. b.

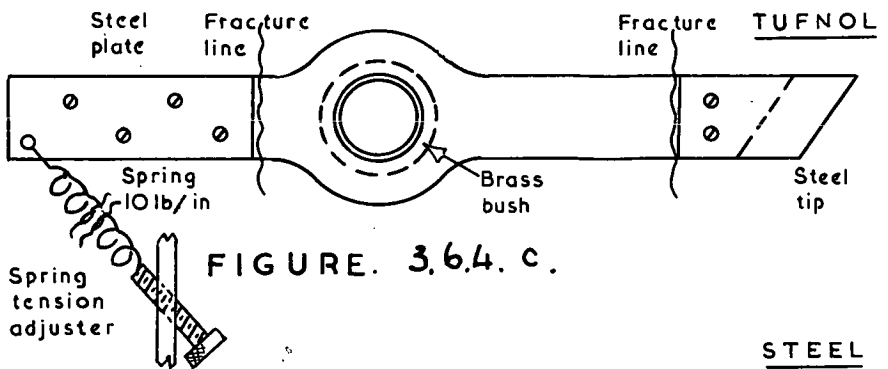


FIGURE. 3.6.4. c.

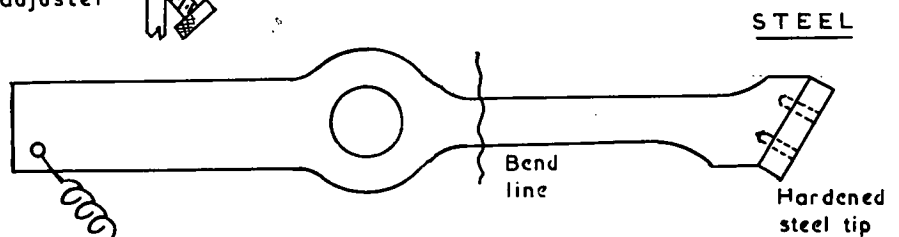
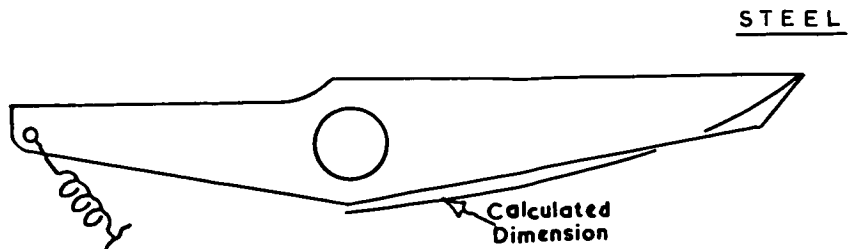
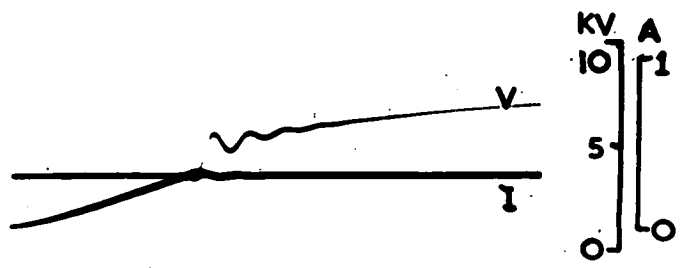


FIGURE. 3.6.4. d.

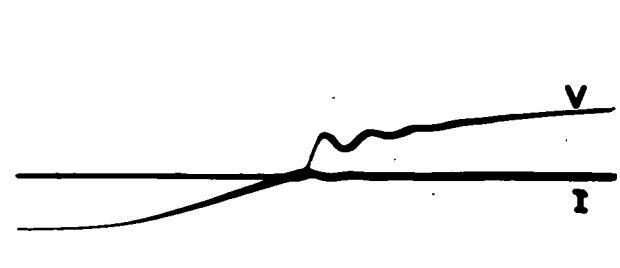


SCALE: HALF FULL SIZE

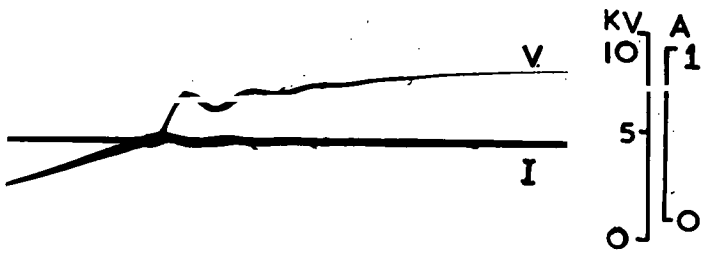
FIGURE. 3.6.4. e.



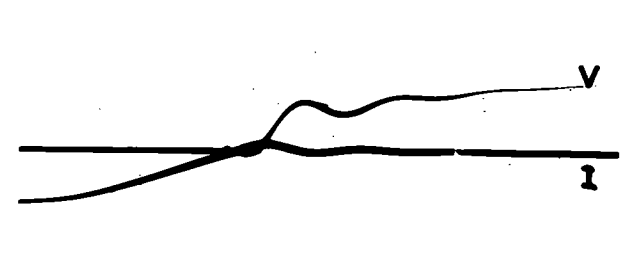
0.01 μ F



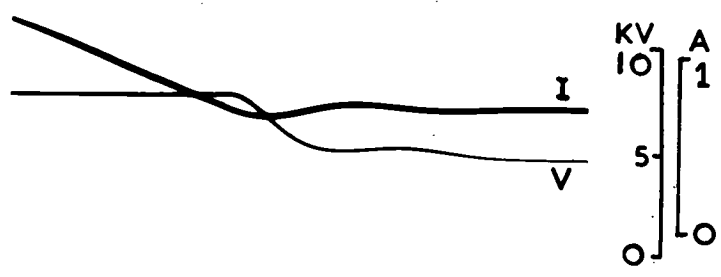
0.02 μ F



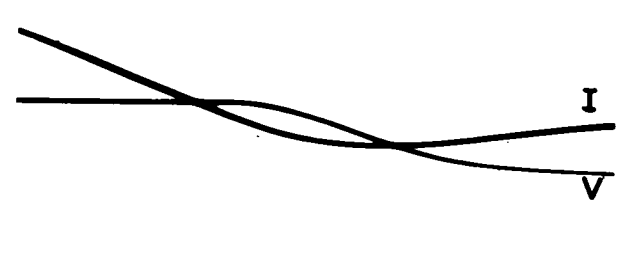
0.05 μ F



0.1 μ F



0.4 μ F



3.0 μ F

RECOVERY VOLTAGE TRANSIENTS

FIGURE 3.7.3.

TEST AND CONTROL CIRCUIT DIAGRAM OF SWITCHGEAR LABORATORY

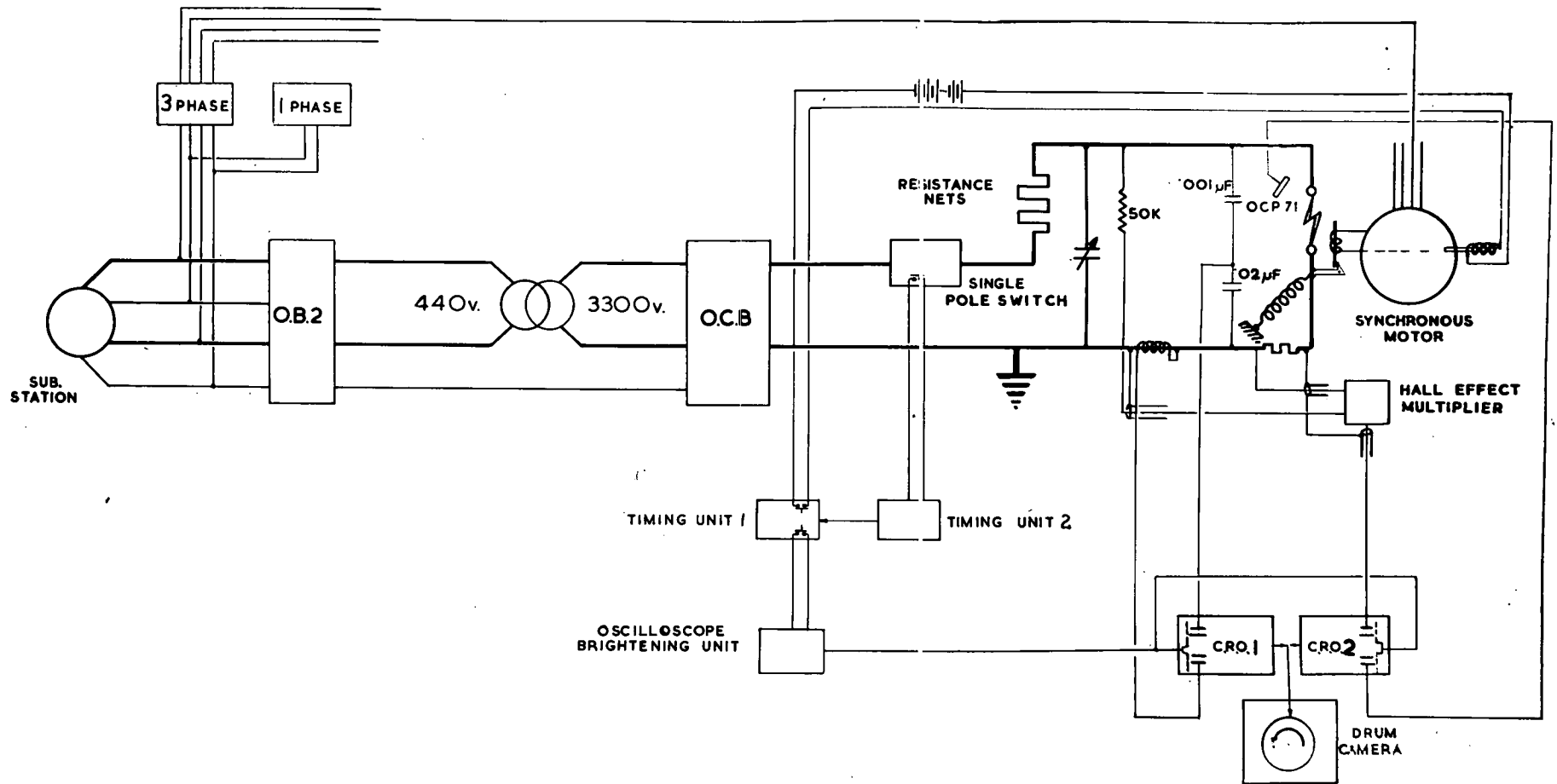


FIGURE 3.8.1.

No. 1 TIMING UNIT

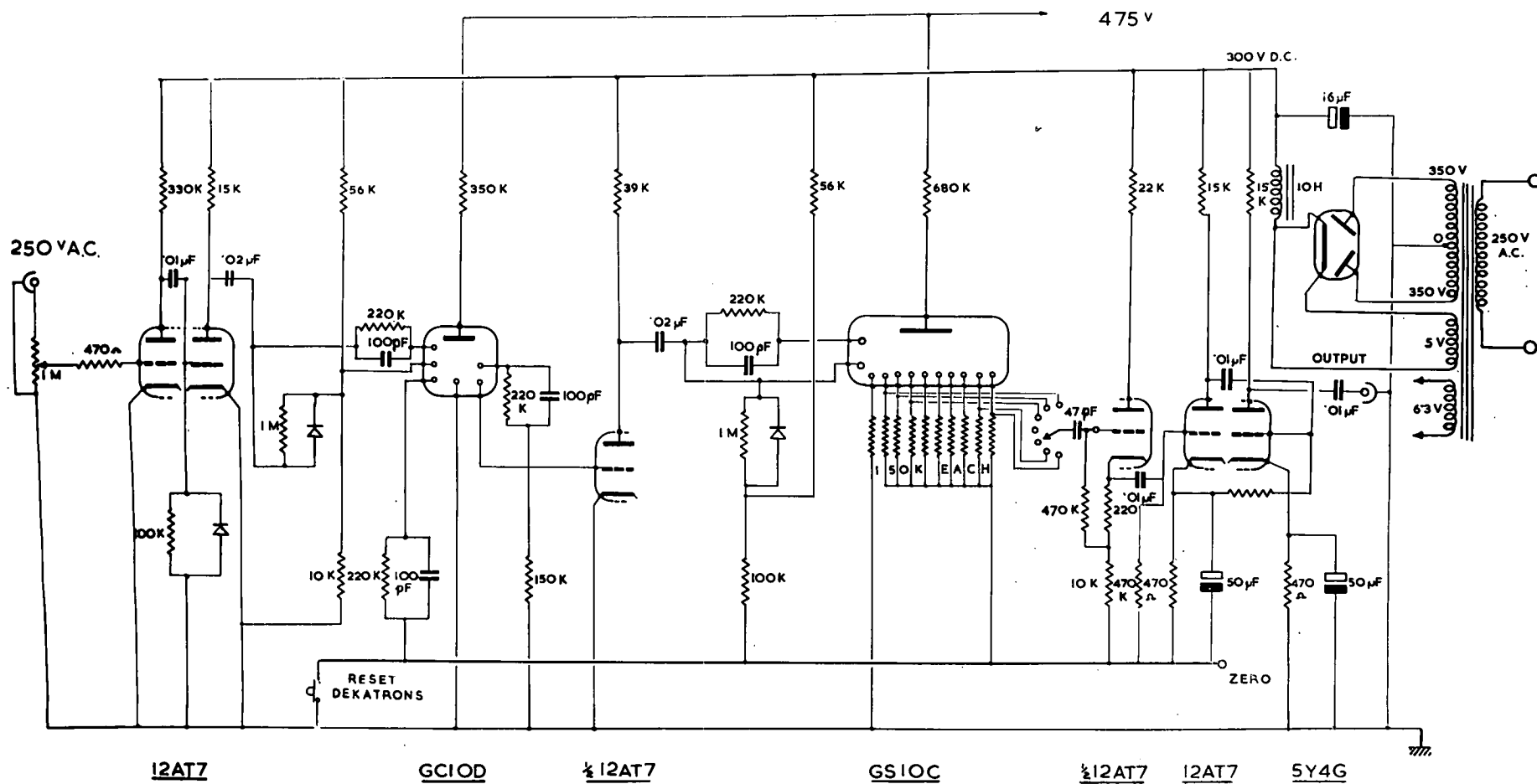


FIGURE 3.9.1

N22 RELAY UNIT

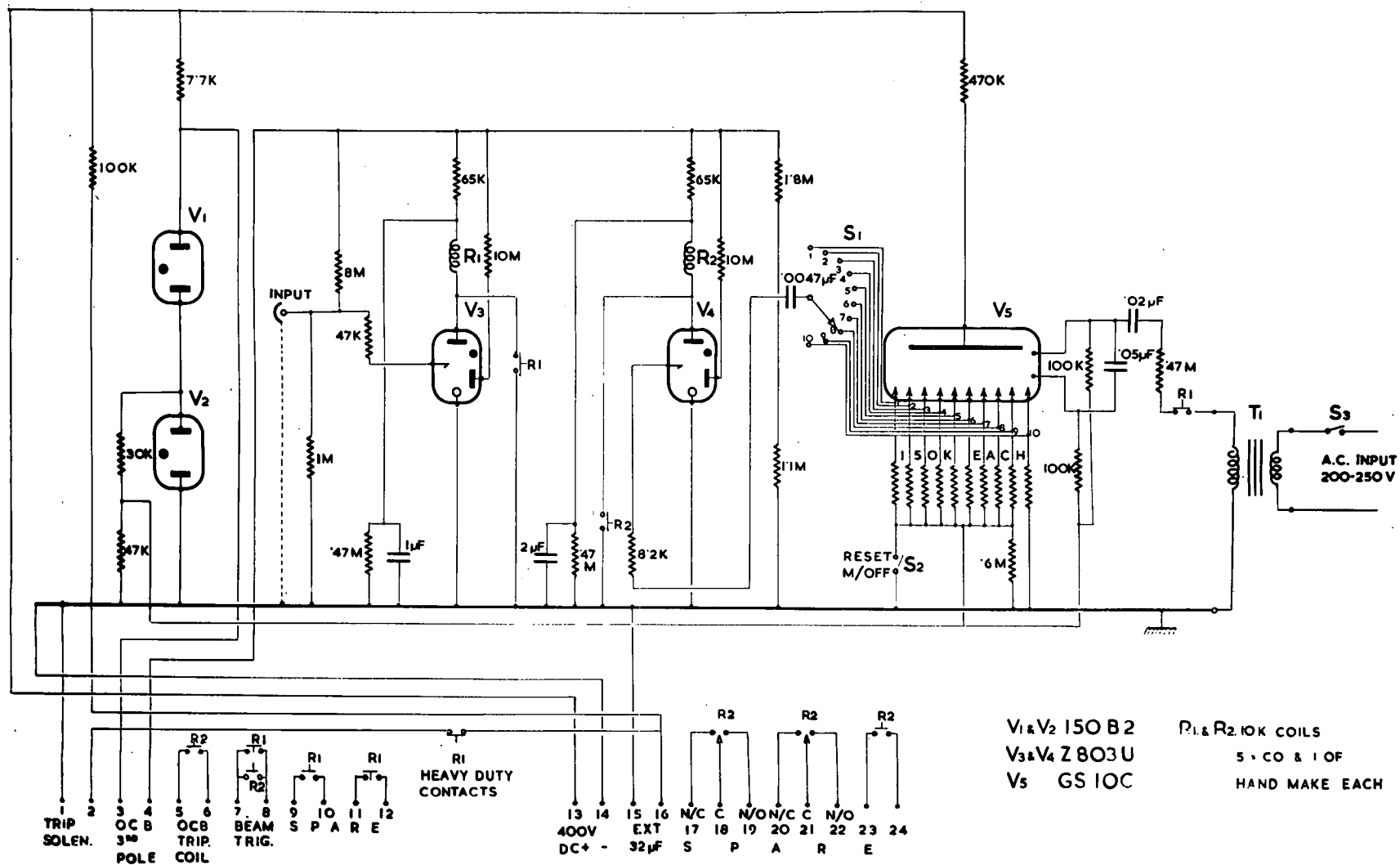


FIGURE 3.9.2.

DIFFERENTIATING CIRCUIT & OSCILLOSCOPE BRIGHTNESS TIMING UNIT FOR USE WITH T.U.2.

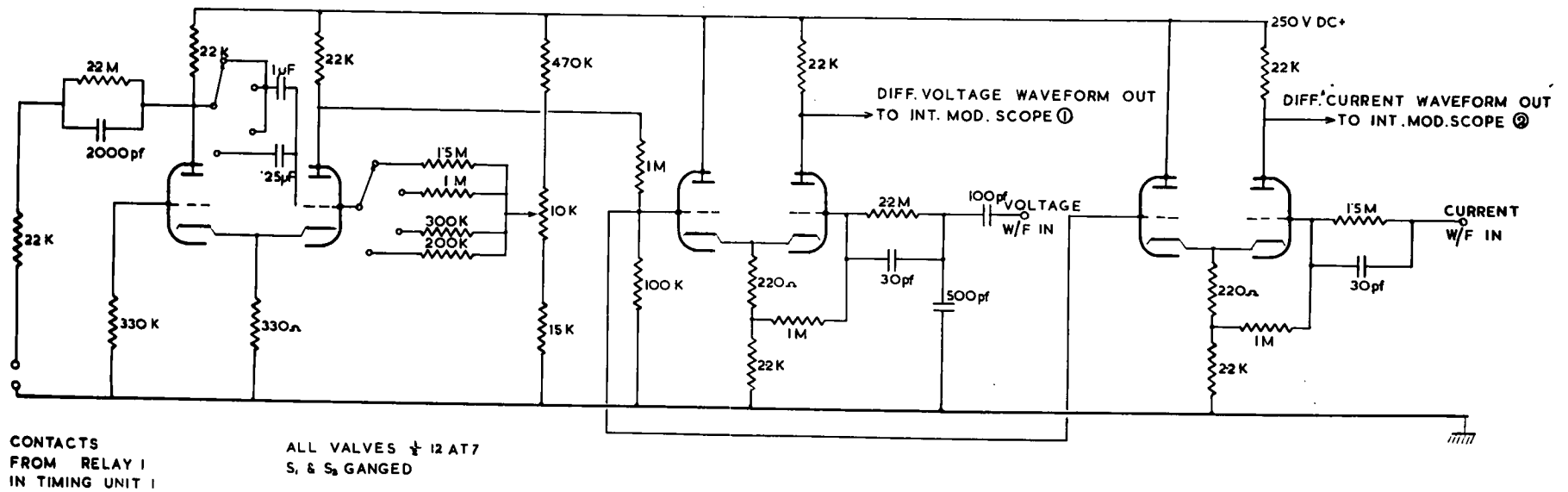
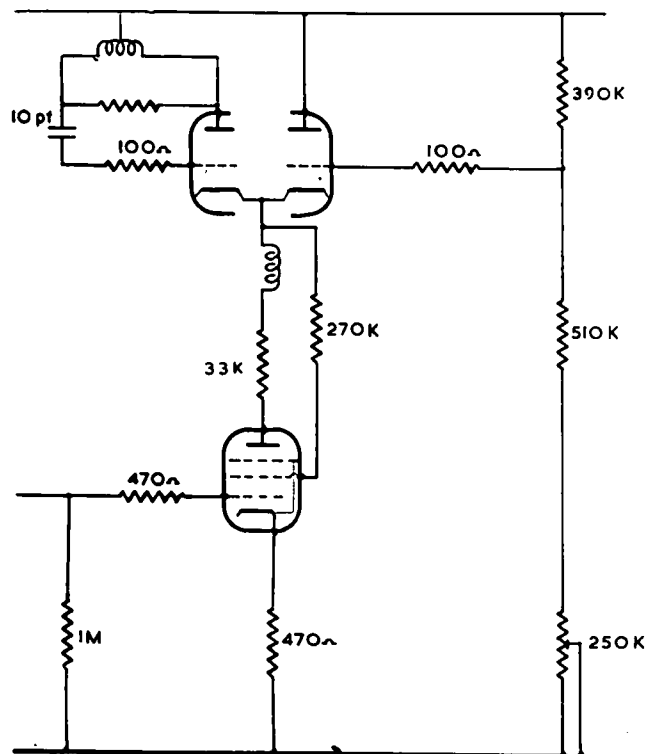


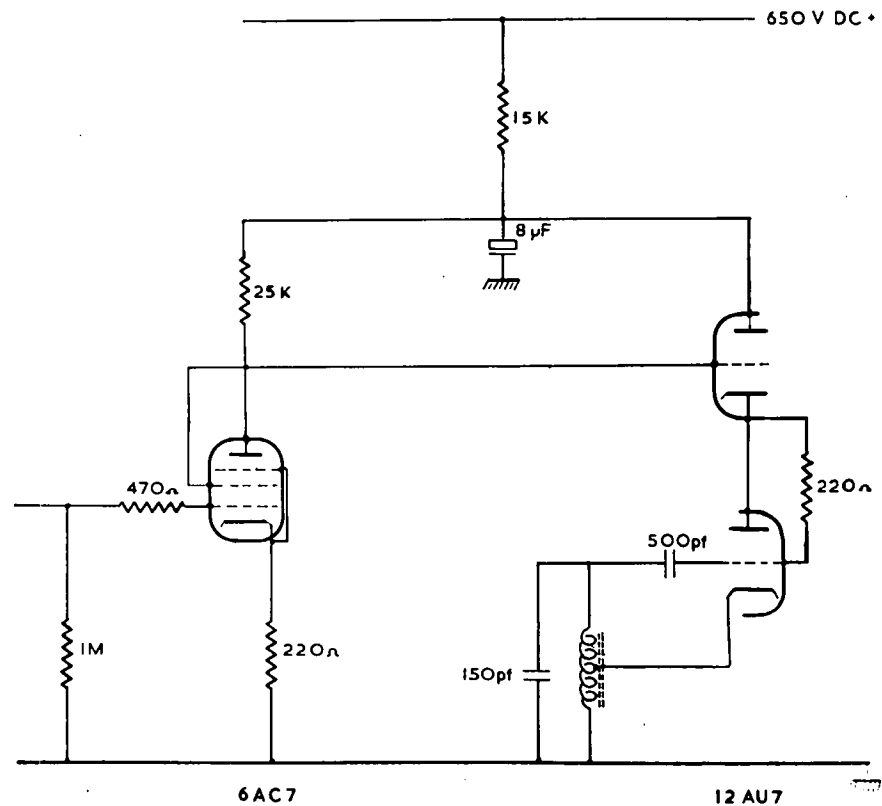
FIGURE 3.9.3.

INTENSITY MODULATION CIRCUIT MODIFICATION

COSSOR 1049 Mk3.



ORIGINAL



MODIFIED

FIGURE 3.9.4.

ARC PARAMETER MEASUREMENT CIRCUIT

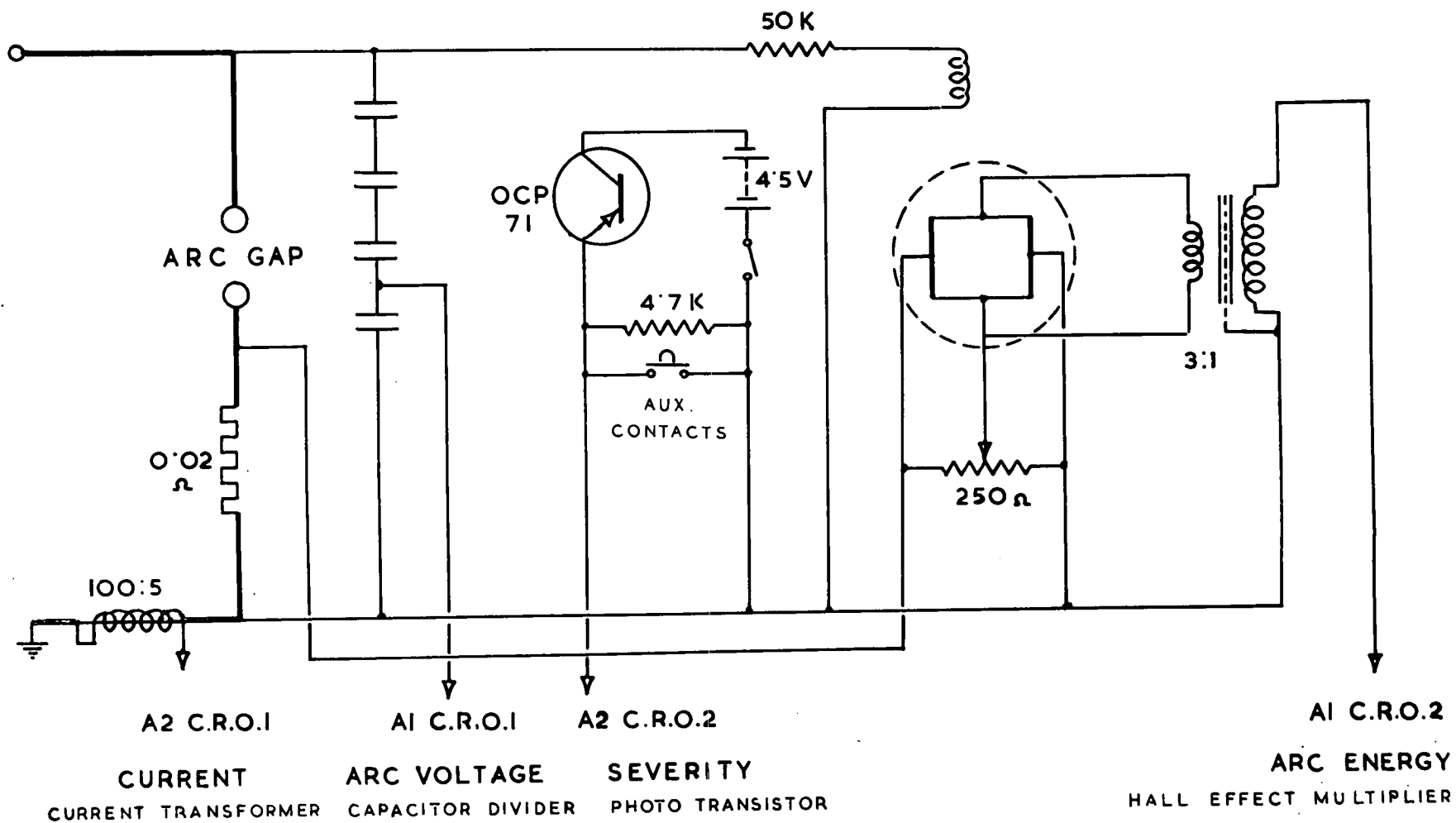
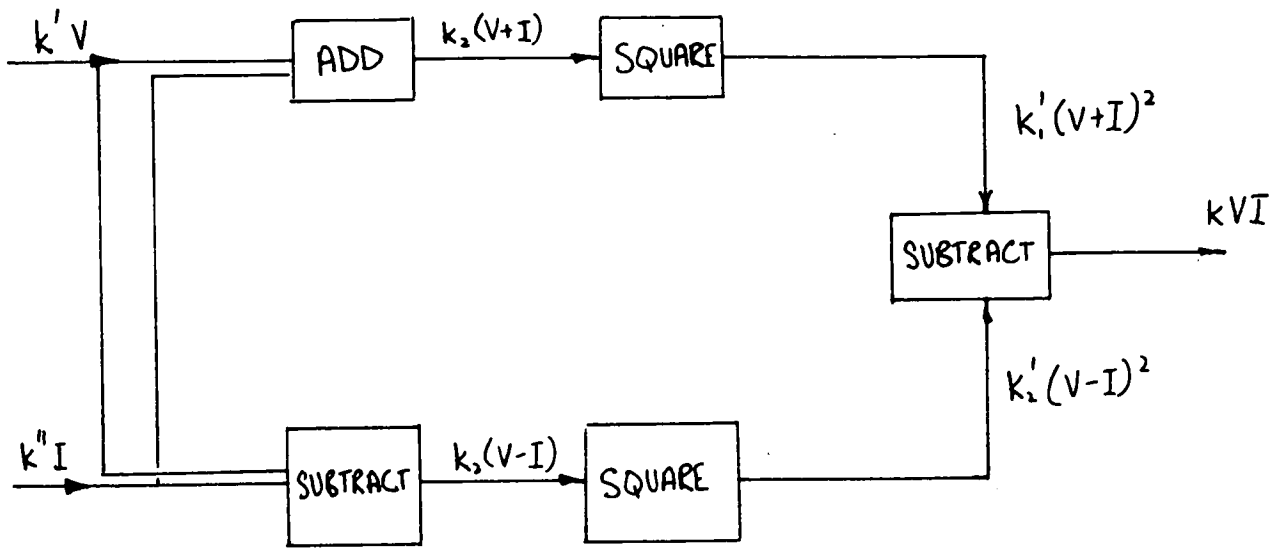
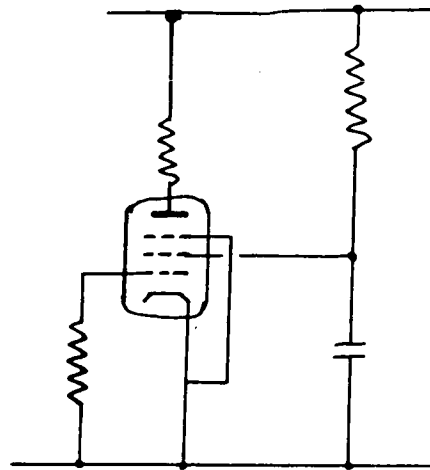


FIGURE 4.1.1



BLOCK DIAGRAM OF MULTIPLYING CIRCUIT

FIGURE 4.3.1.a.



SQUARING CIRCUIT

FIGURE 4.3.1.b.

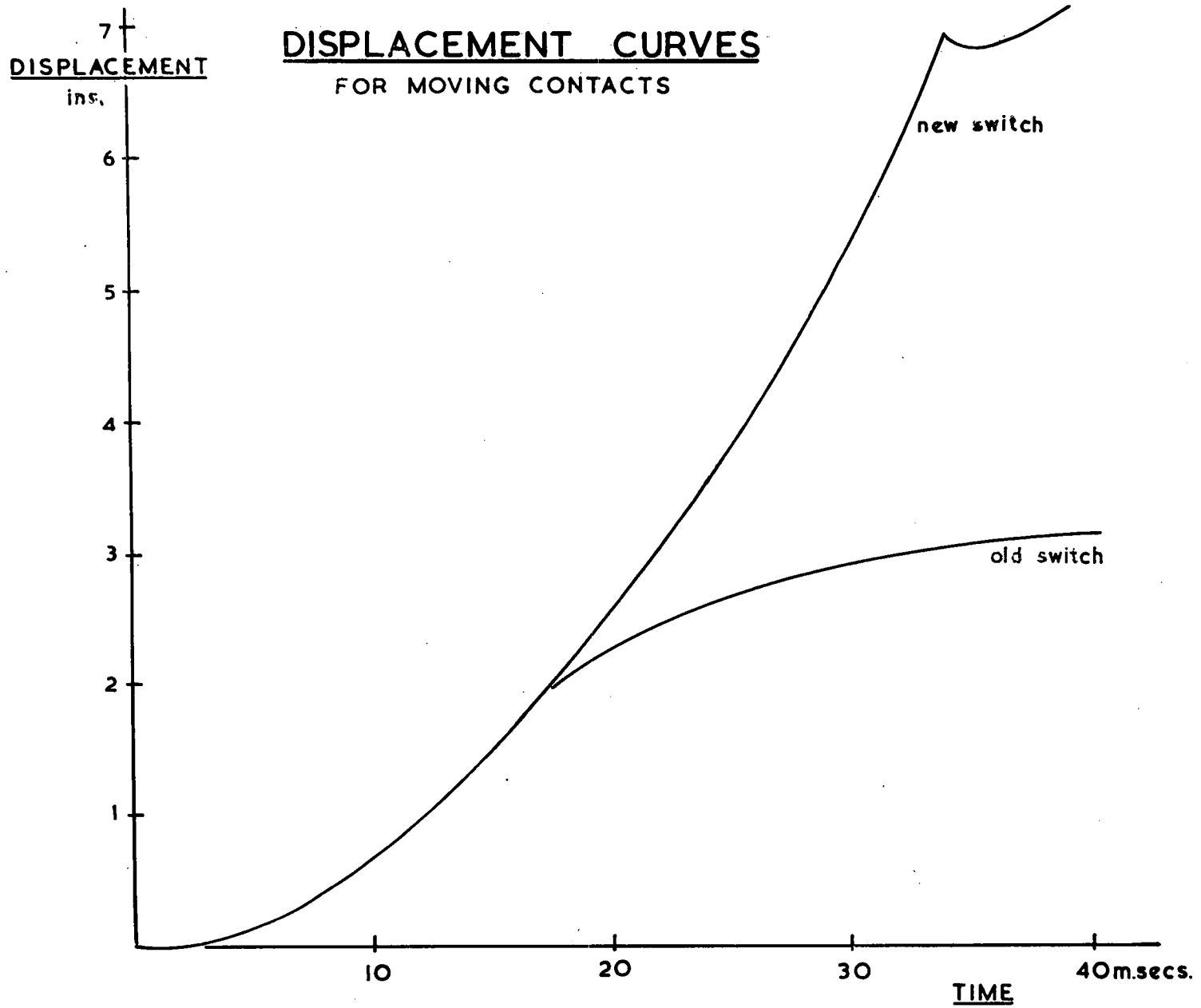


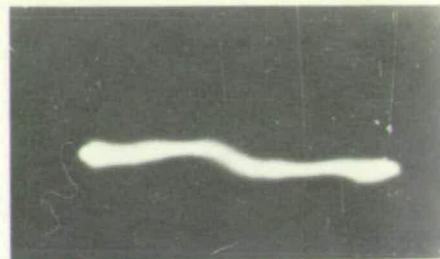
FIGURE 4.5.1.



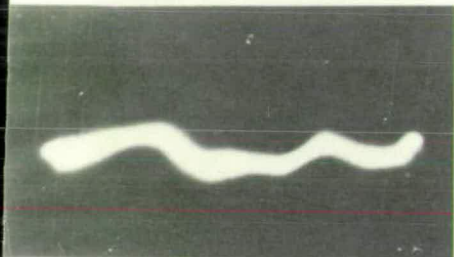
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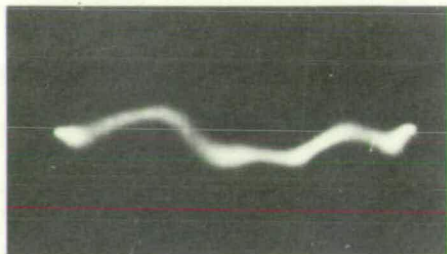
2



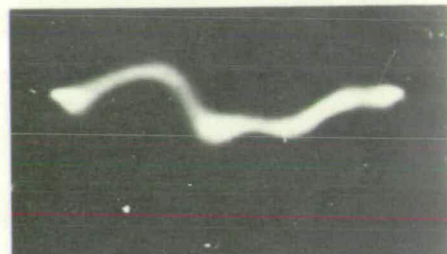
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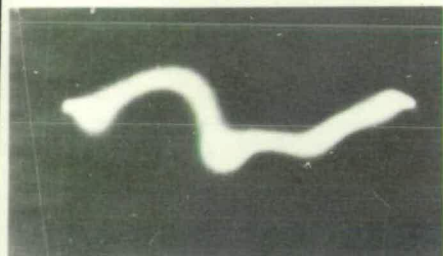
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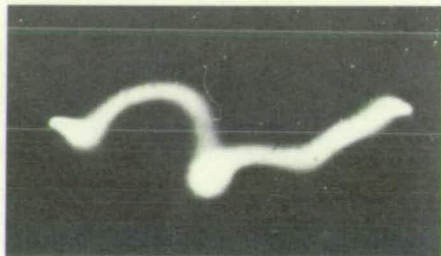
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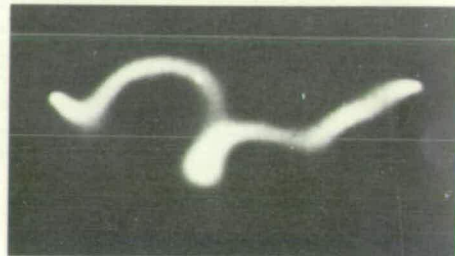
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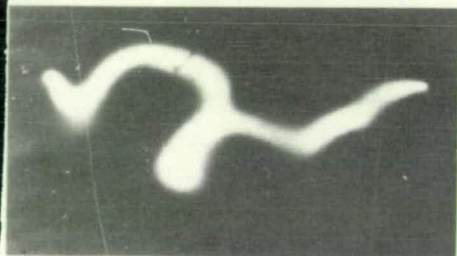
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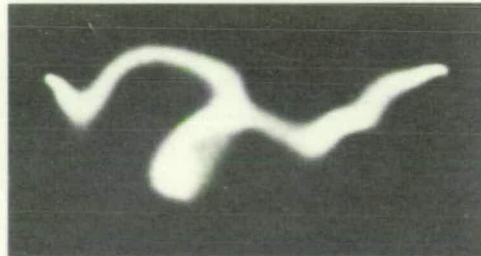
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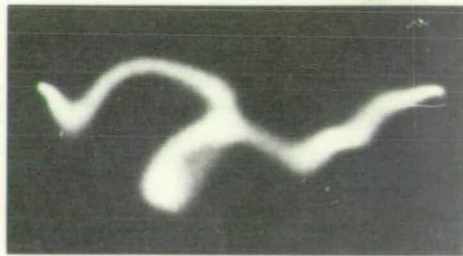
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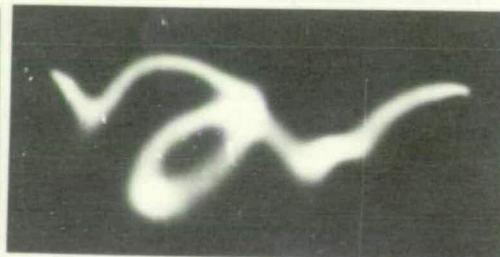
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12



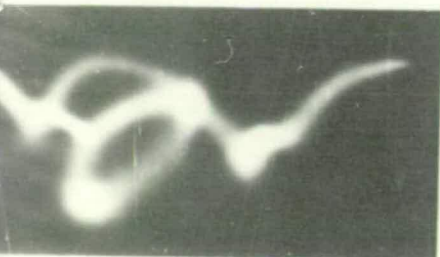
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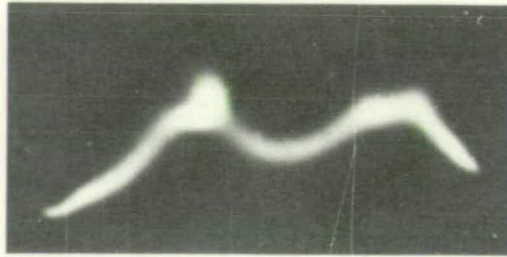
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15



16



17

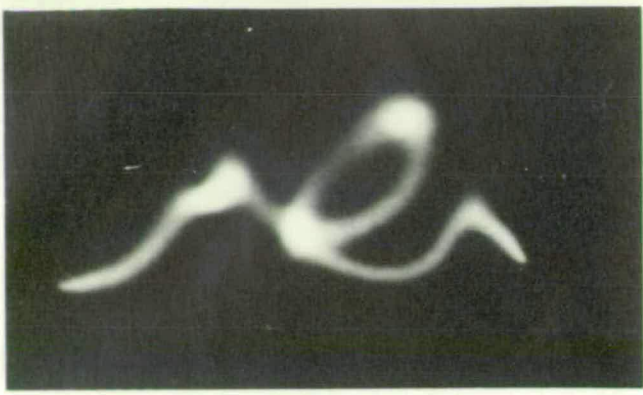


18

FIGURE 4.6.1.

(P.T.O)

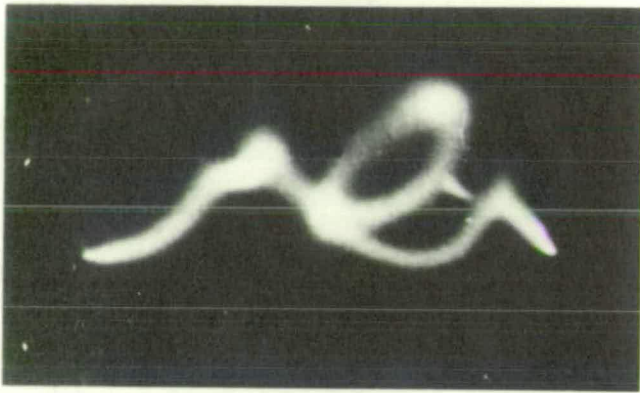
Please note that, due to a Photographer's error,
each photograph should be rotated through 180° ,
except no. 17 which is correct.



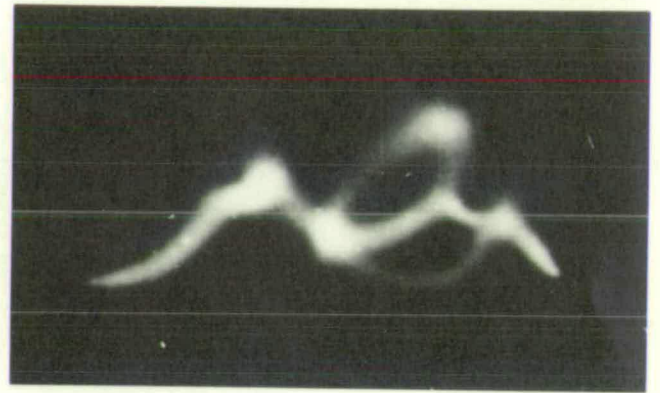
(a)



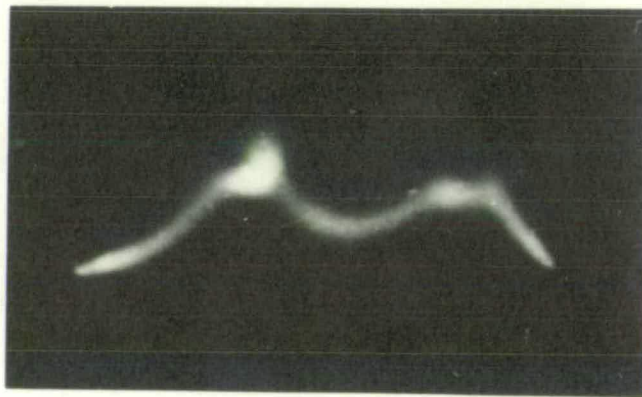
(b)



(c)



(d)



(e)

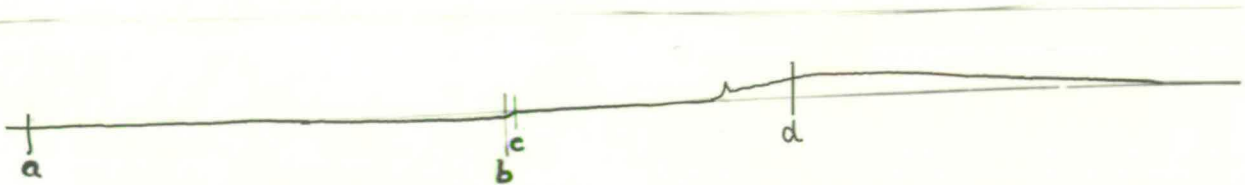
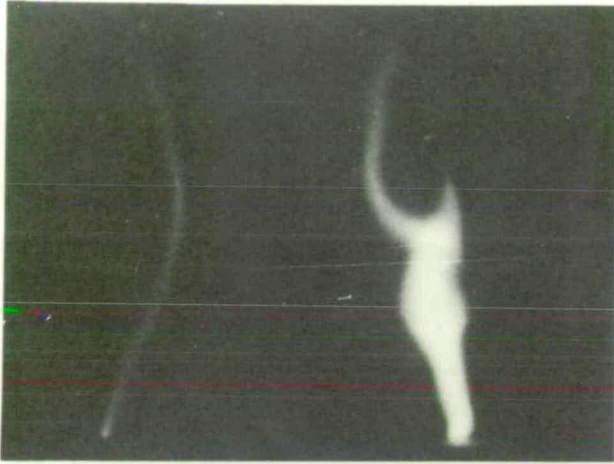
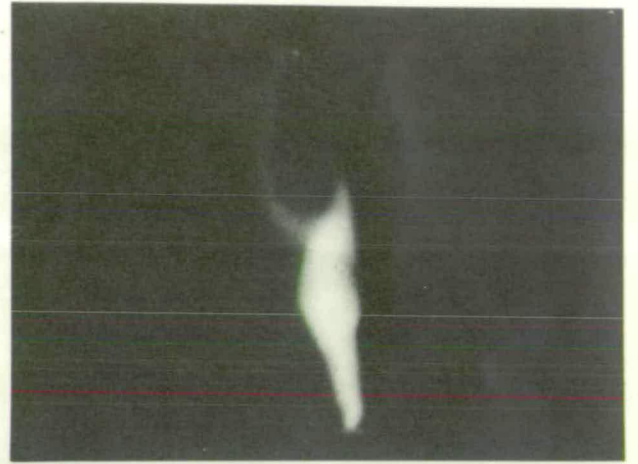


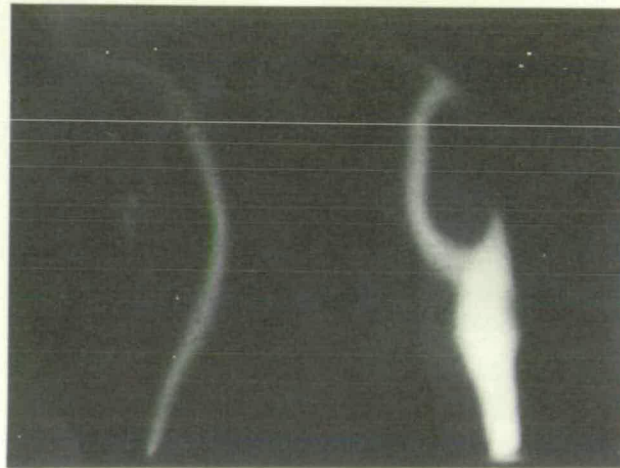
FIGURE 4.6.2.



(a) 3 msec before CURRENT ZERO



(b) CURRENT ZERO



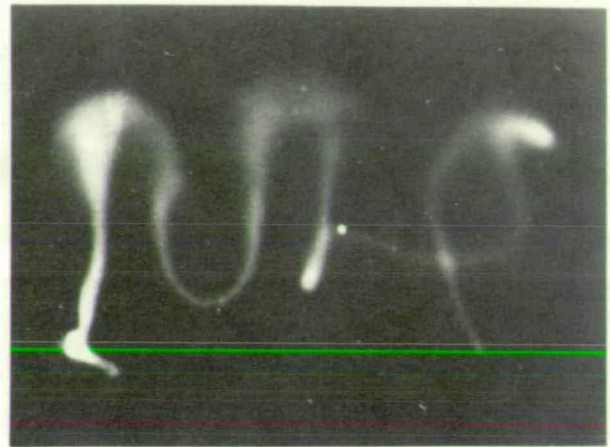
(c) 4 msec after CURRENT ZERO

ARC BURNING ON COPPER (LEFT ROOT) AND STEEL (RIGHT ROOT)

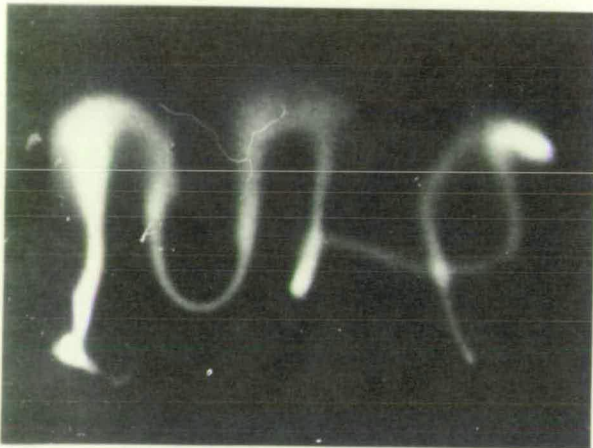
FIGURE 4.6.3.



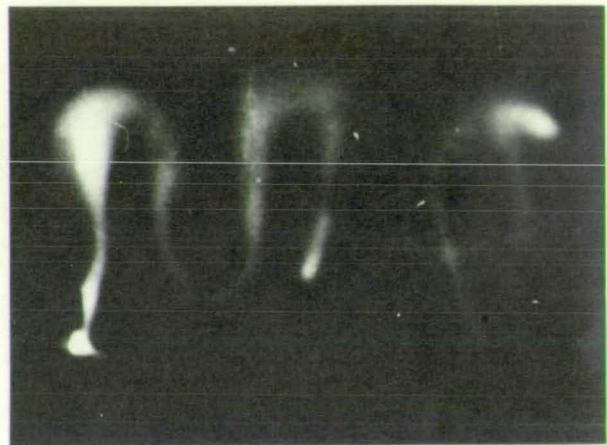
(a) 2msecs after Current Zero



(b) 3½ msecs after Current Zero



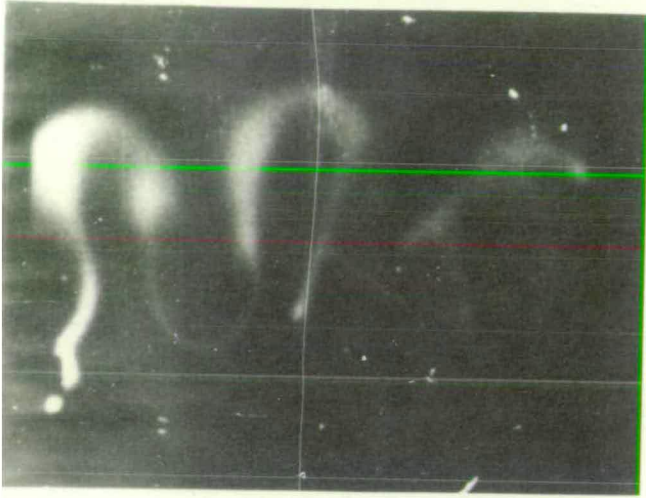
(c) Current Maximum



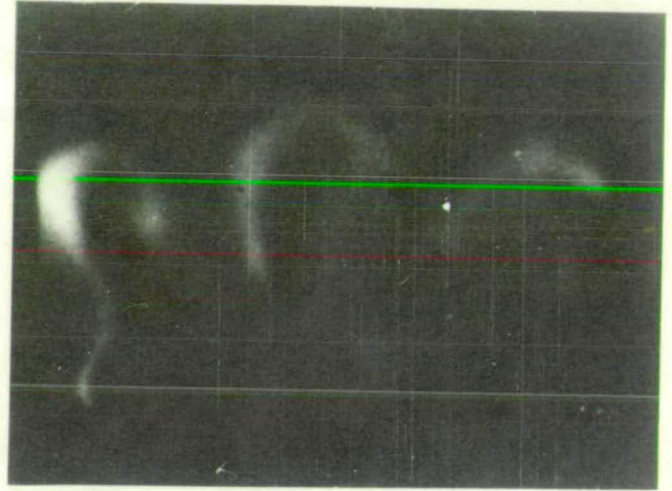
(d) 2msecs before Current Zero

SECONDARY ARC

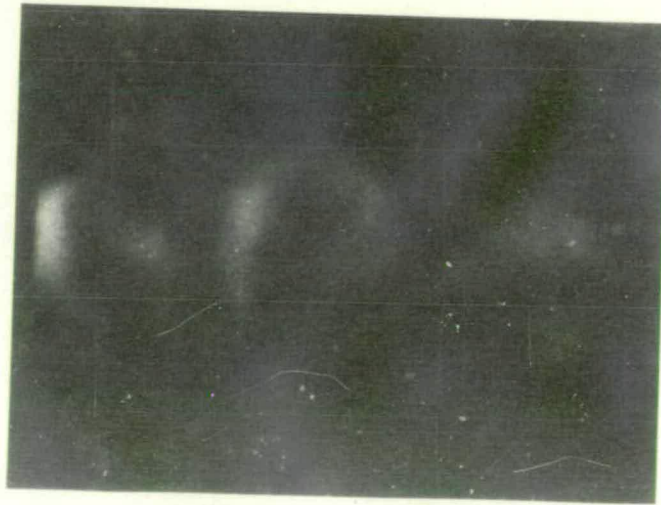
FIGURE 4.6.4.



(a) Extinction + 10 msec



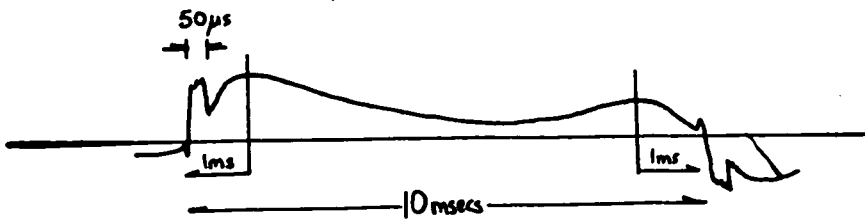
(b) + 20 msec



(c) + 60 msec

DECAY OF ARC CHANNEL

(11) FIGURE 4.6.5.



TYPICAL ARC VOLTAGE WAVEFORM
FIGURE 5.2.1

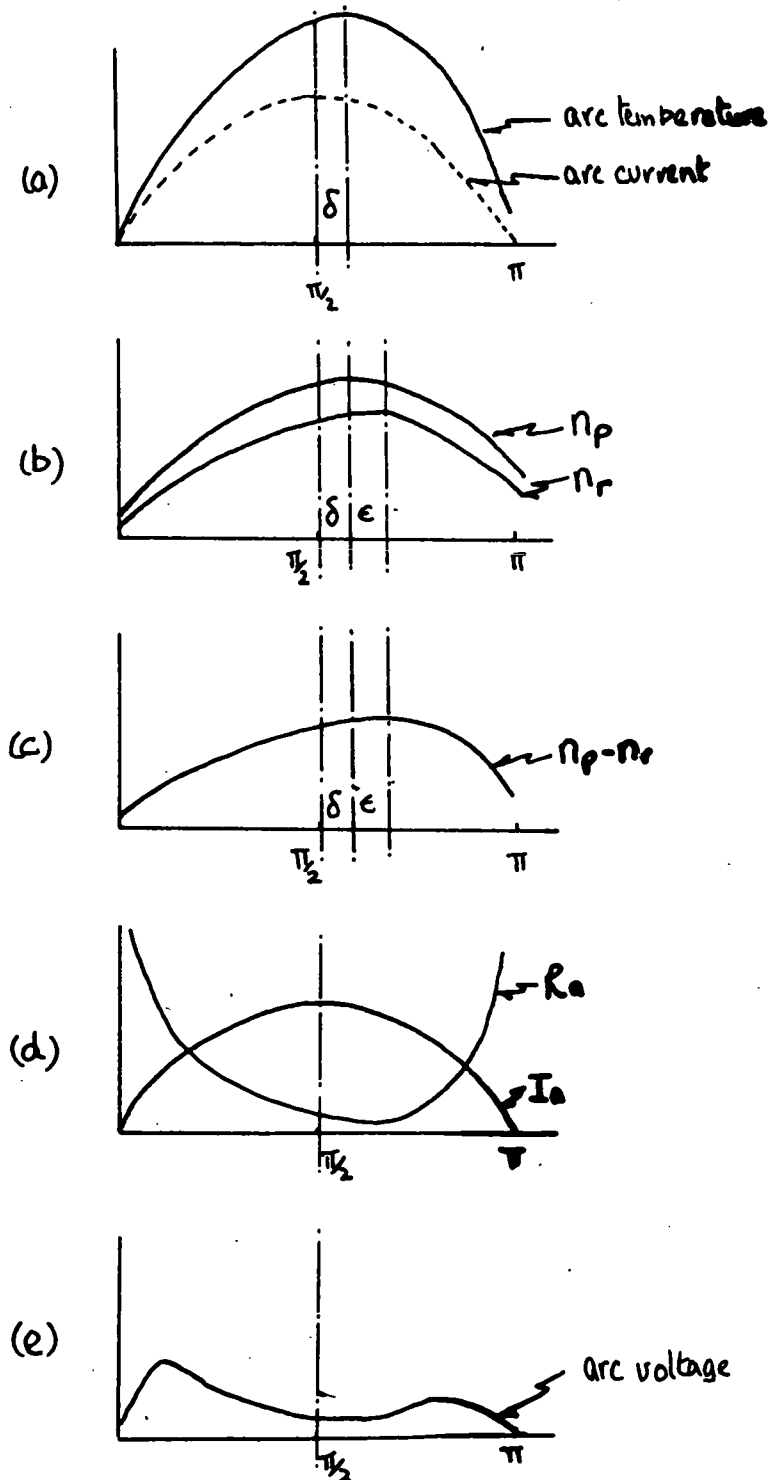
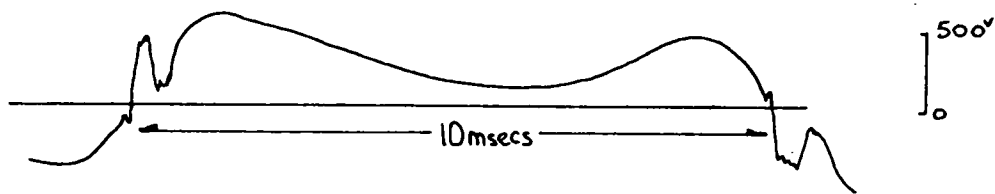


FIGURE 5.2.2.



TYPICAL ARC VOLTAGE WAVE FORM
WITH FORCED EXTINCTION

FIGURE 5.23.

WHEN ARC EXTINCTION IS ACCOMPLISHED BY VIRTUE OF ITS LENGTH, IT IS FOUND THAT THE PEAK ARC VOLTAGE IS APPROXIMATELY ONE-THIRD OF THE OPEN CIRCUIT VOLTAGE.

ARC POWER

CURRENT = 17 amps
VOLTAGE = 2400 volts

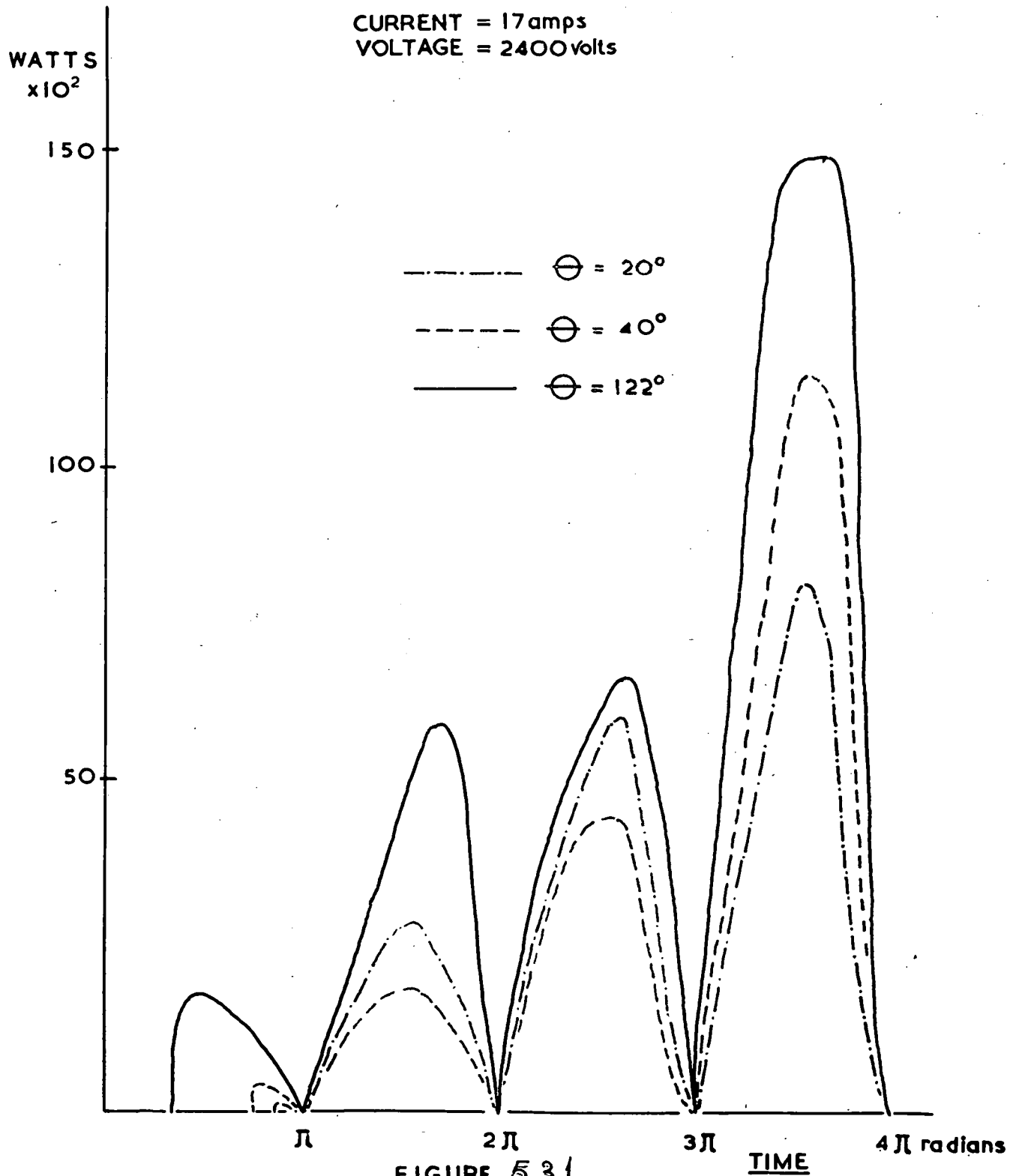


FIGURE 5.3.1

TIME

ARC ENERGY ~ PHASE

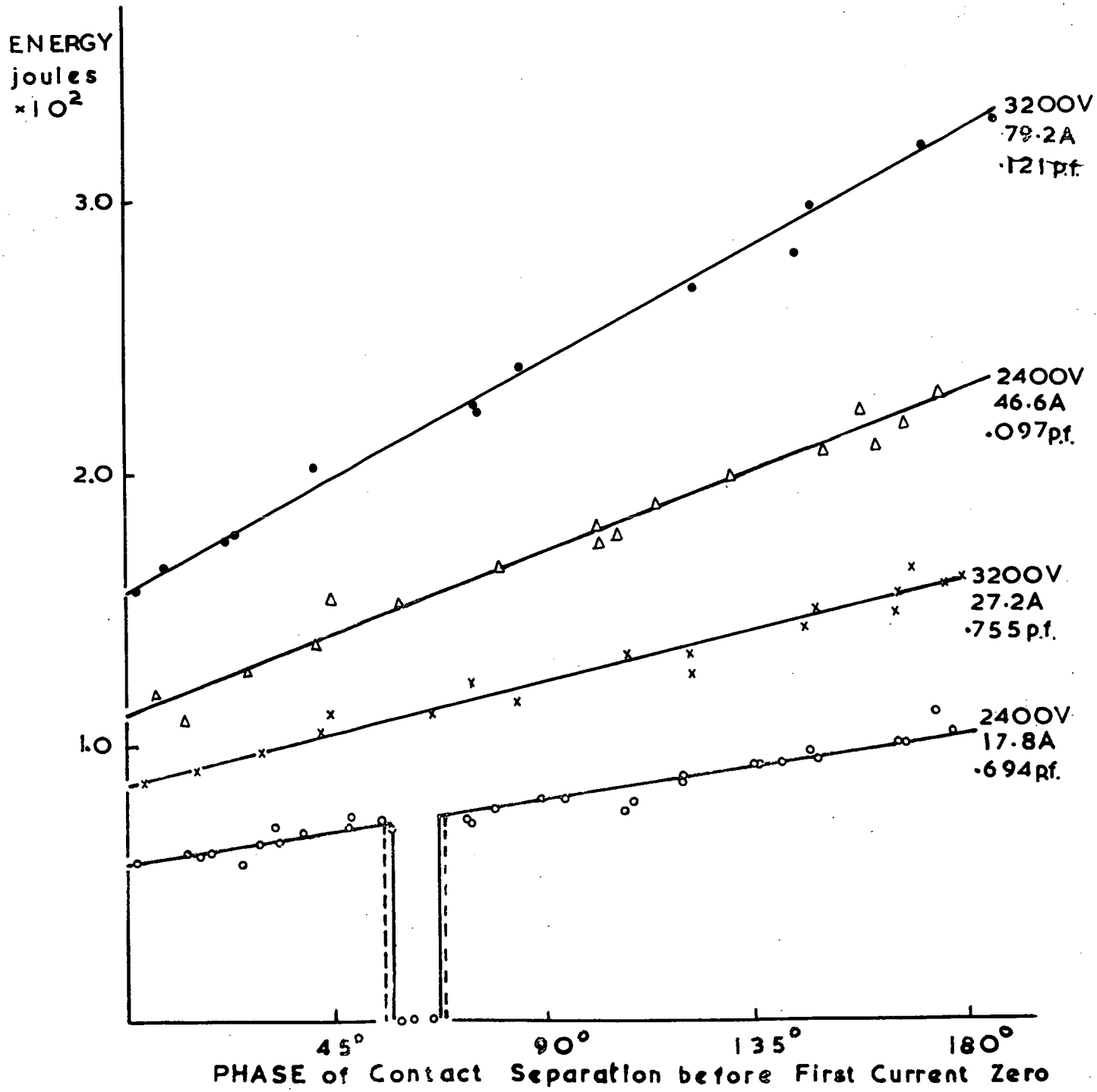


FIGURE 5.3.2.

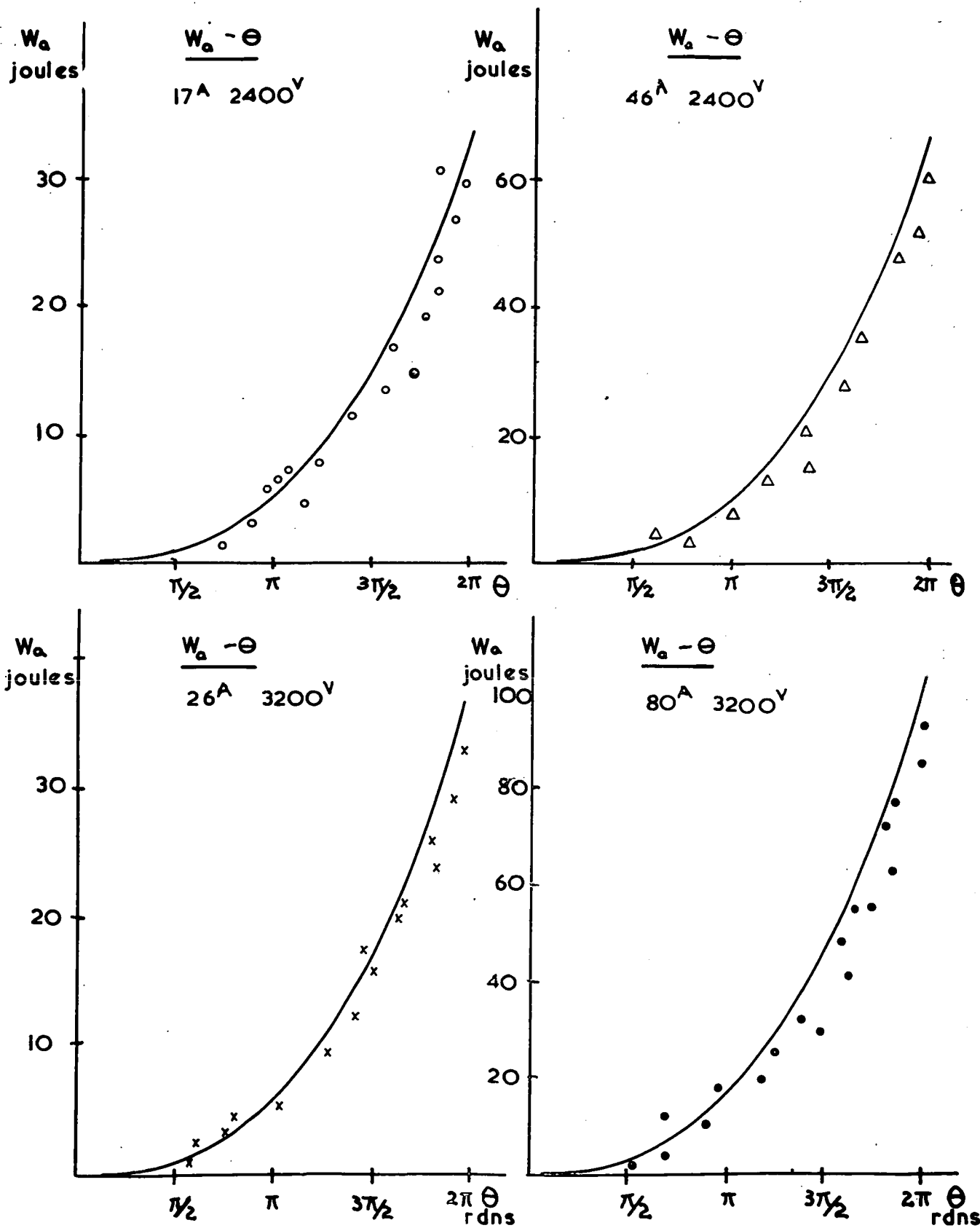


FIGURE 5.3.3.

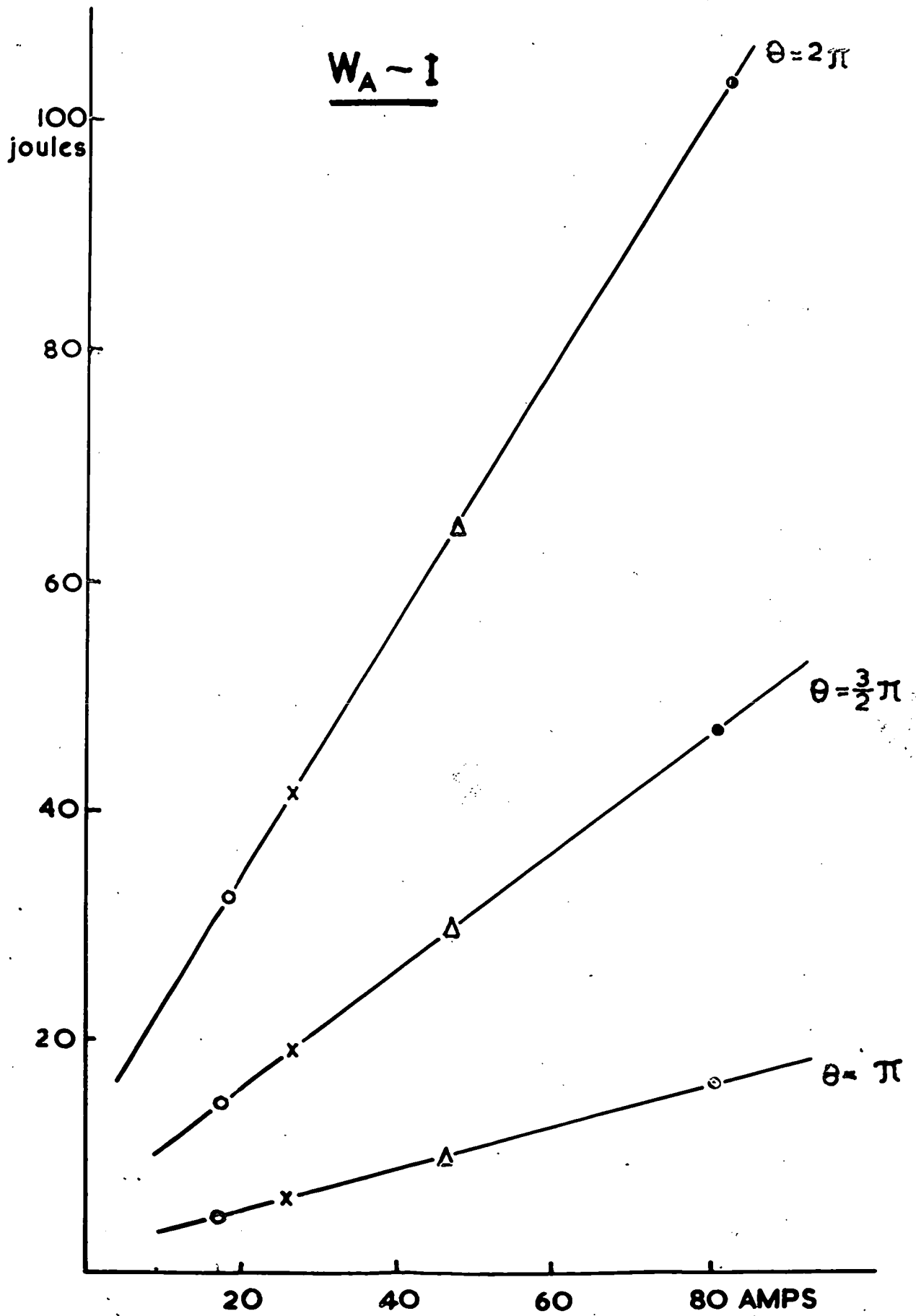
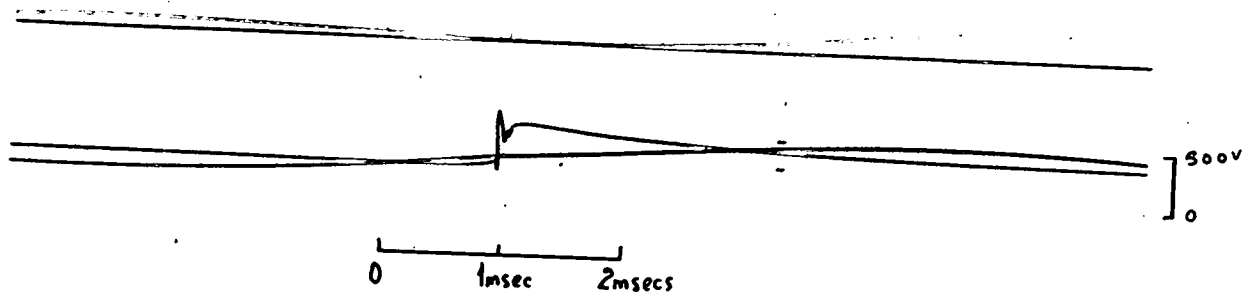
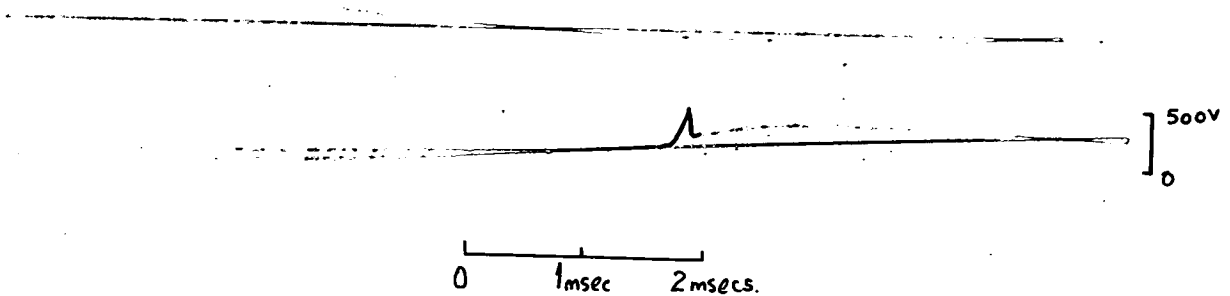


FIGURE 5.3.4.



ZERO PAUSE REGION

FIGURE 5.4.1.



ZERO PAUSE REGION 0.0.5 μ F added Capacitance

FIGURE 5.4.2.

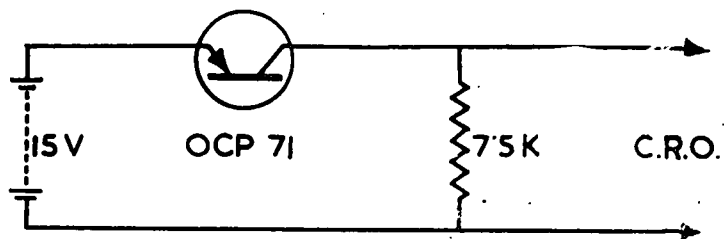


FIGURE 5.5.1.a

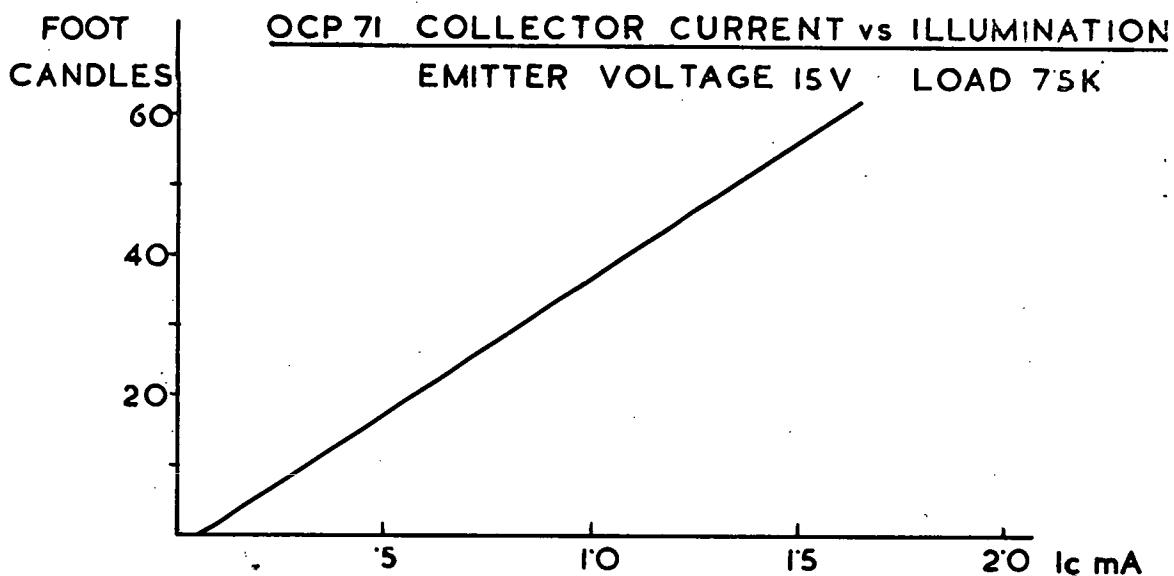


FIGURE 5.5.1.b

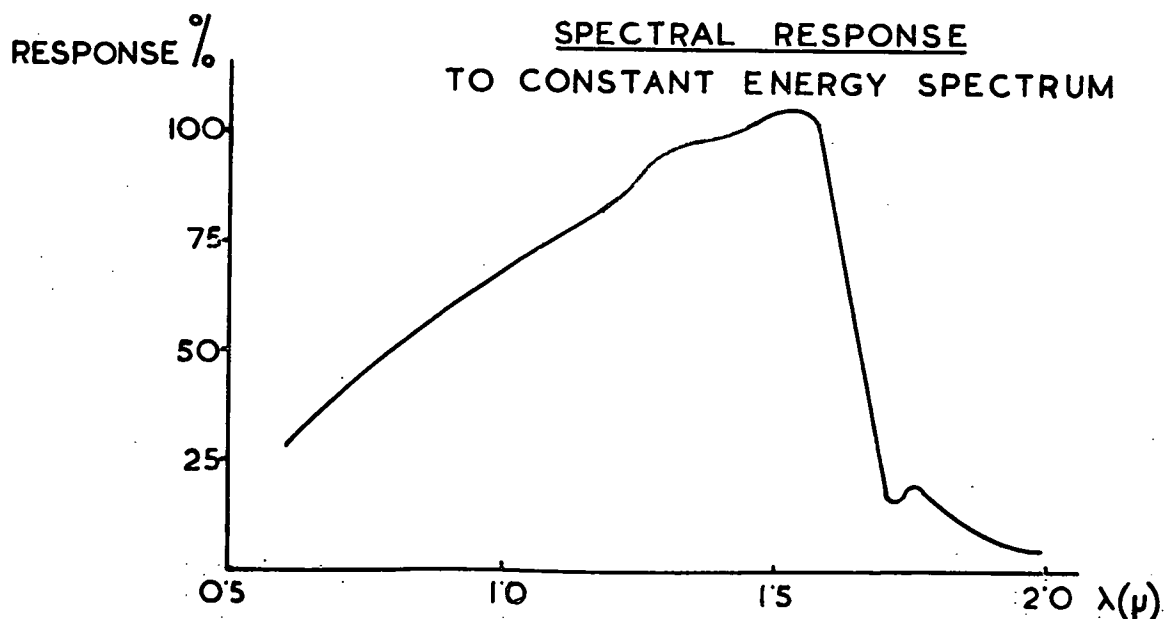


FIGURE 5.5.1.c

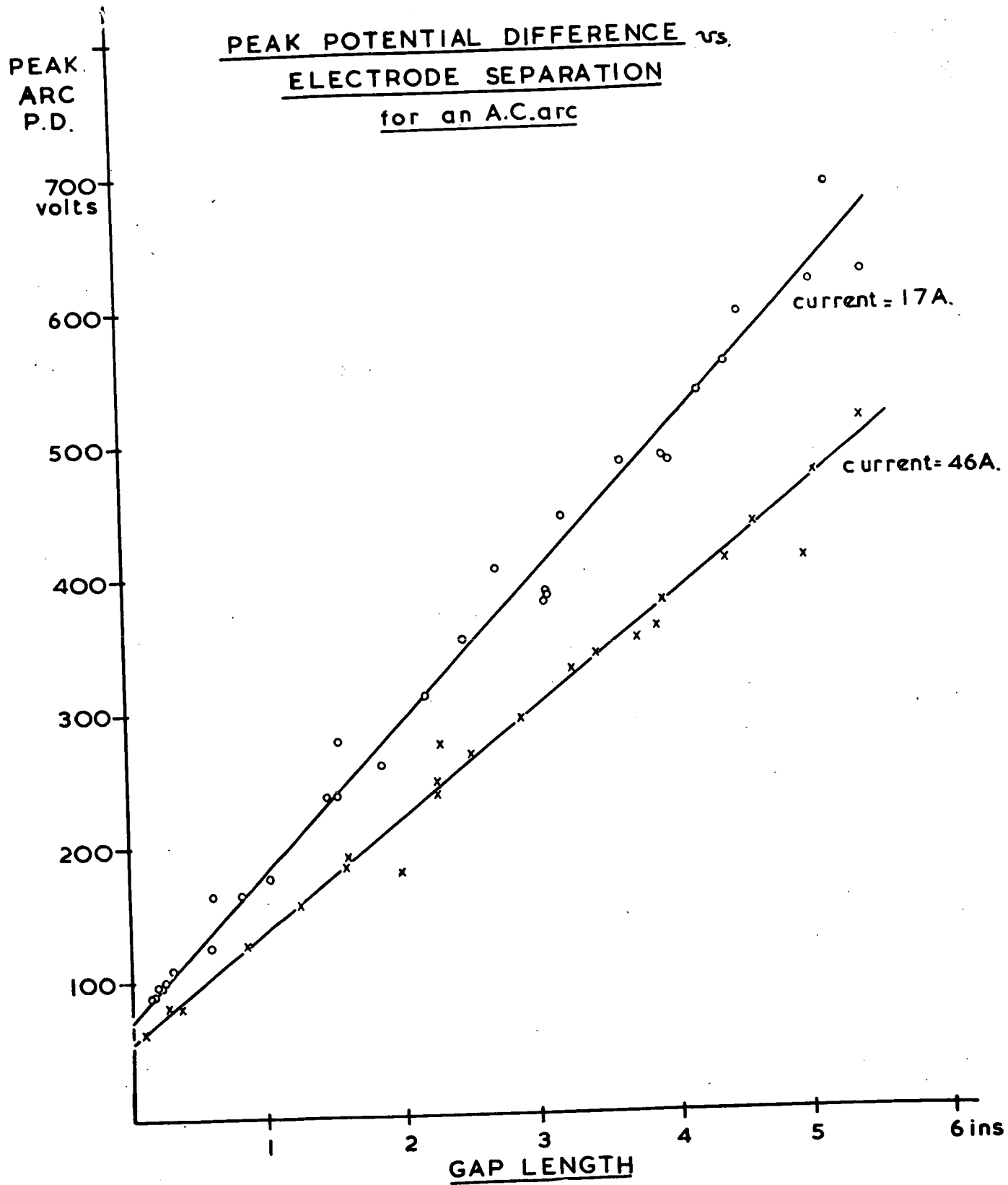


FIGURE 561

RANGE of PHASE ANGLES
giving EXTINCTION for different R.R.R.V

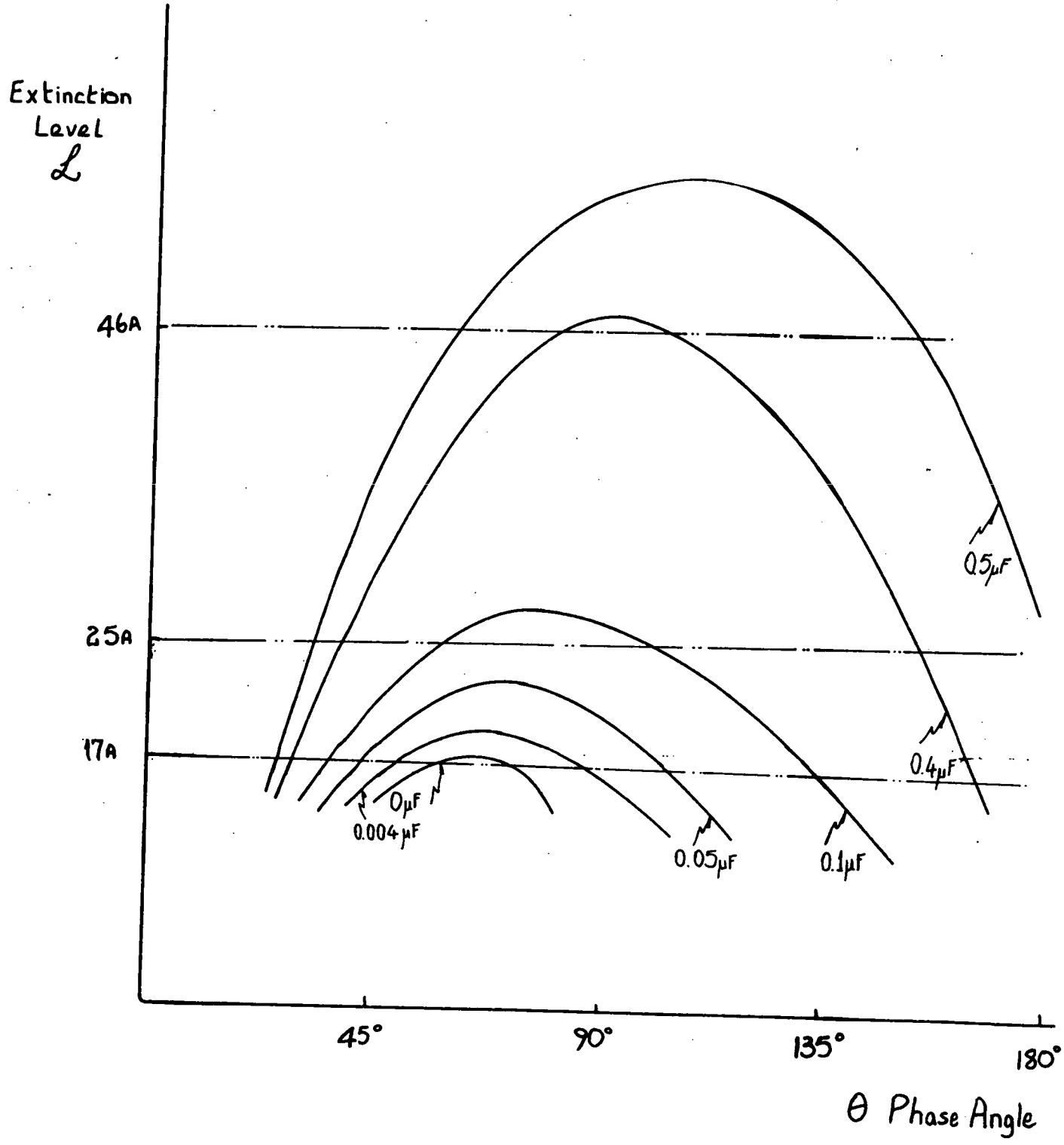
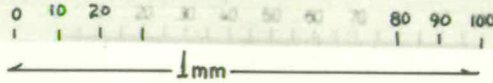
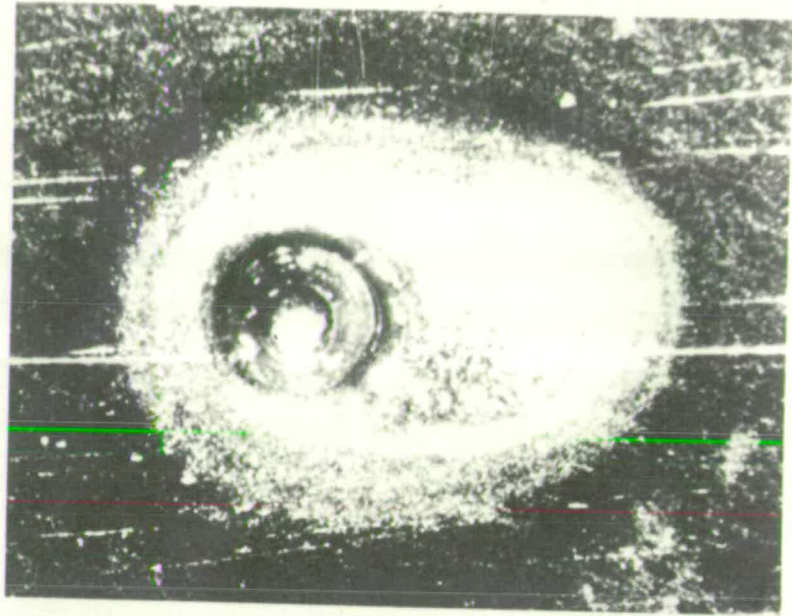
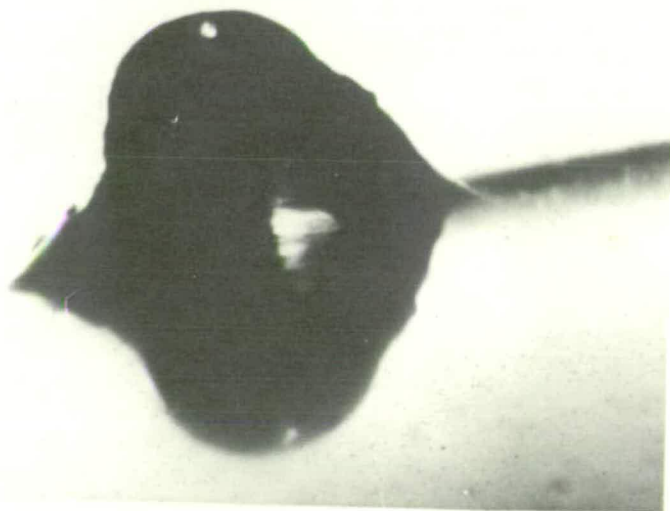


FIGURE 5.7.1.



Plan View of ARC ROOT
FIGURE 5.8.1.a



Elevation of ARC ROOT.
FIGURE 5.8.1.b.

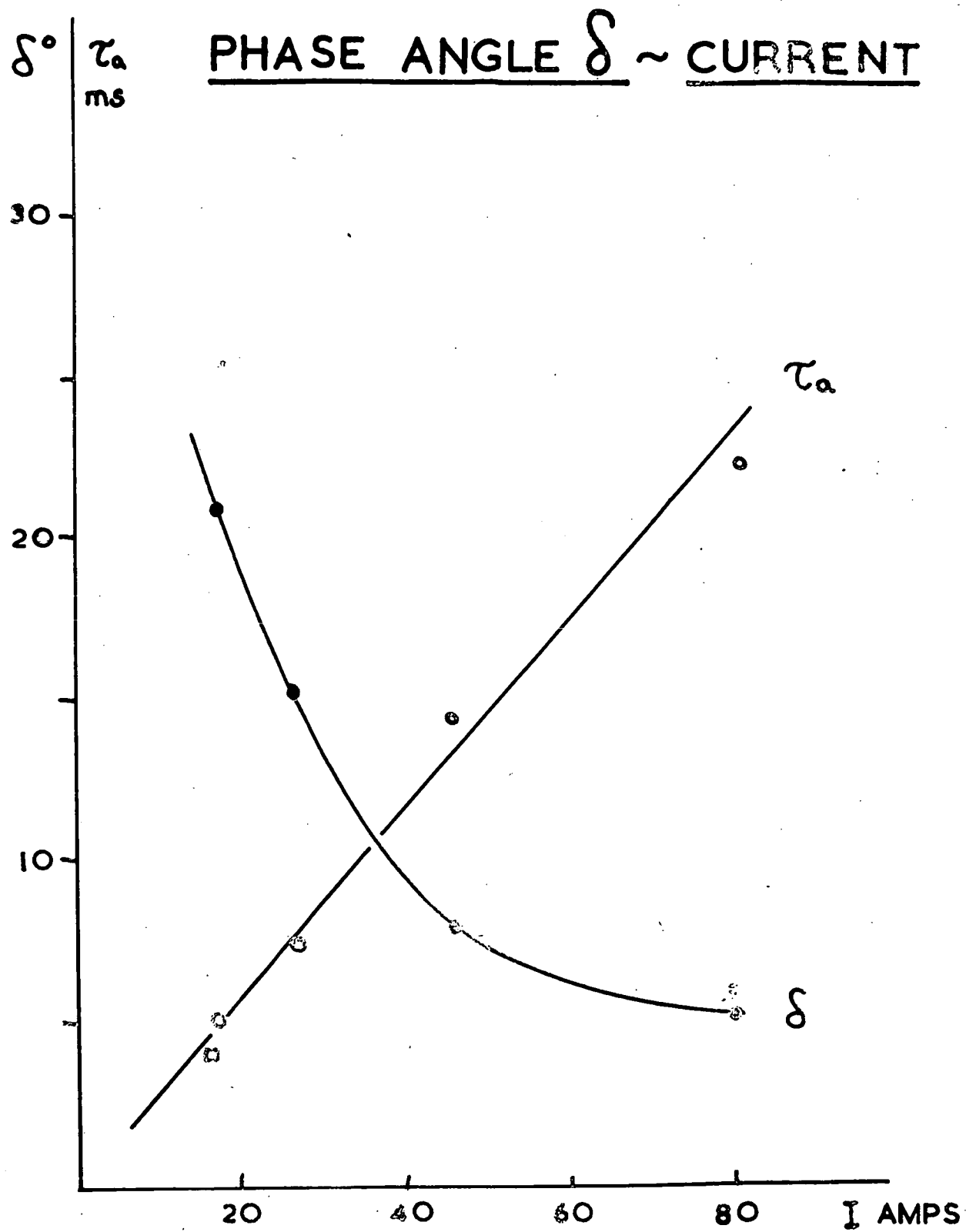


FIGURE 5.9.1

APPROX.
RADIUS

ARC RADIUS~CURRENT

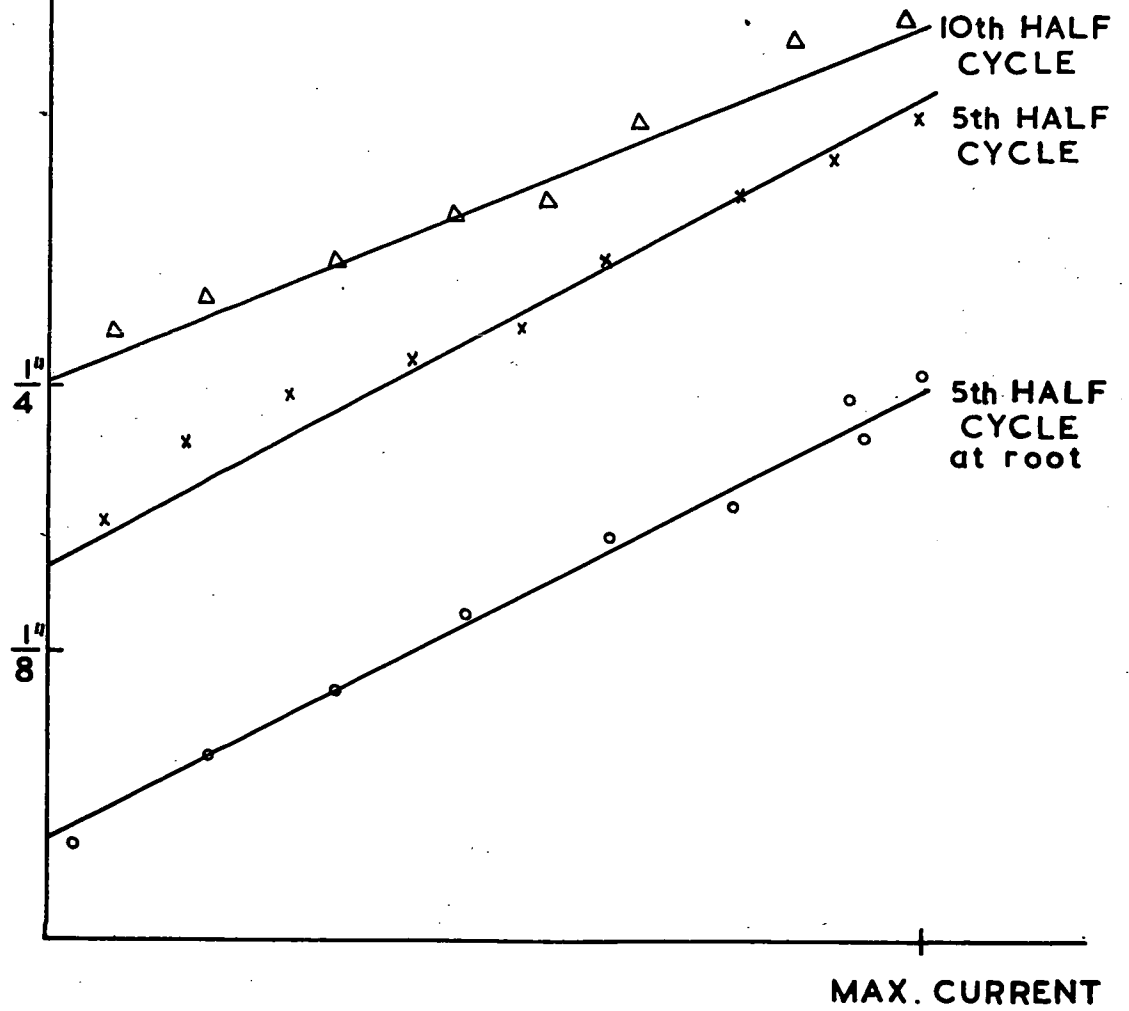
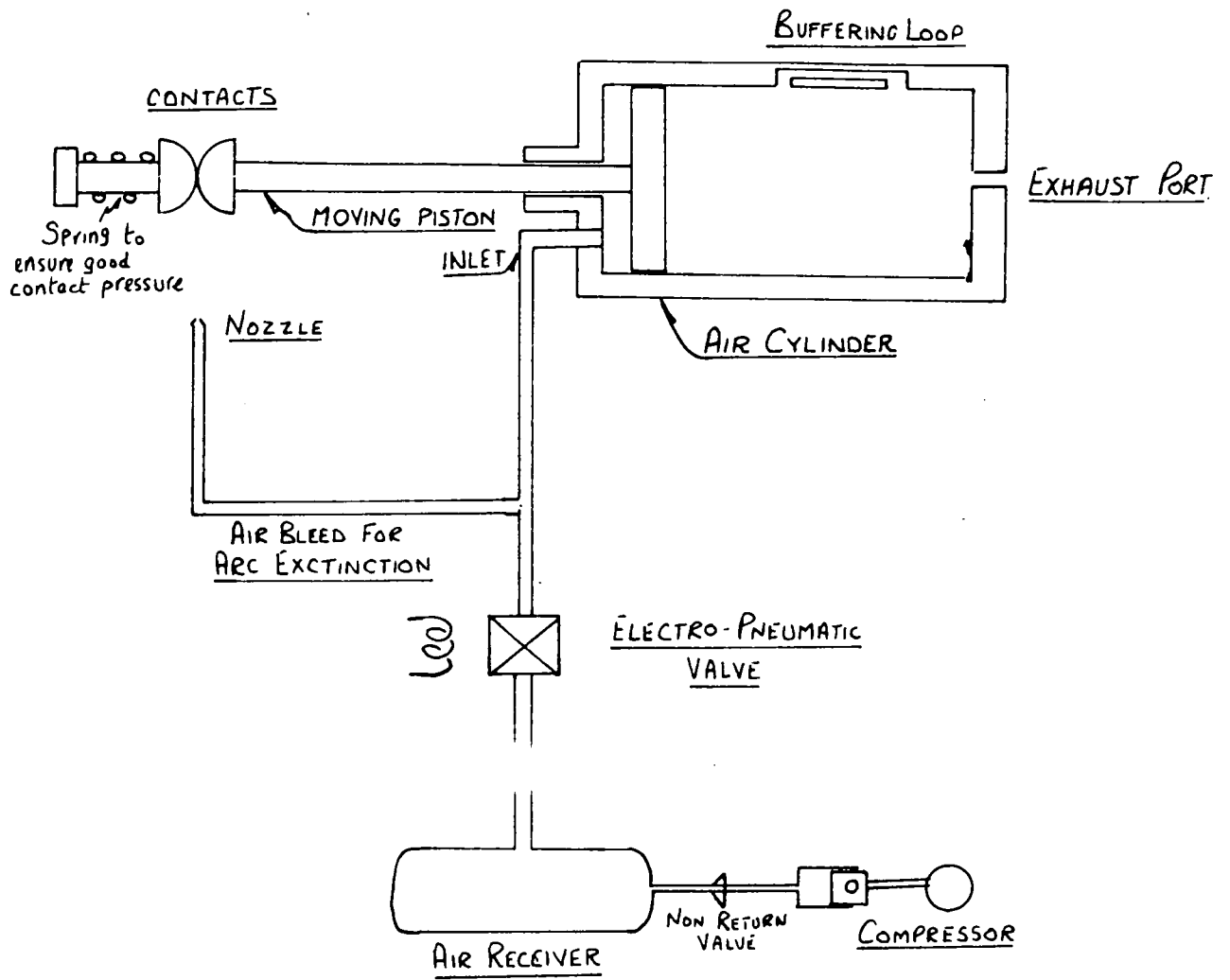
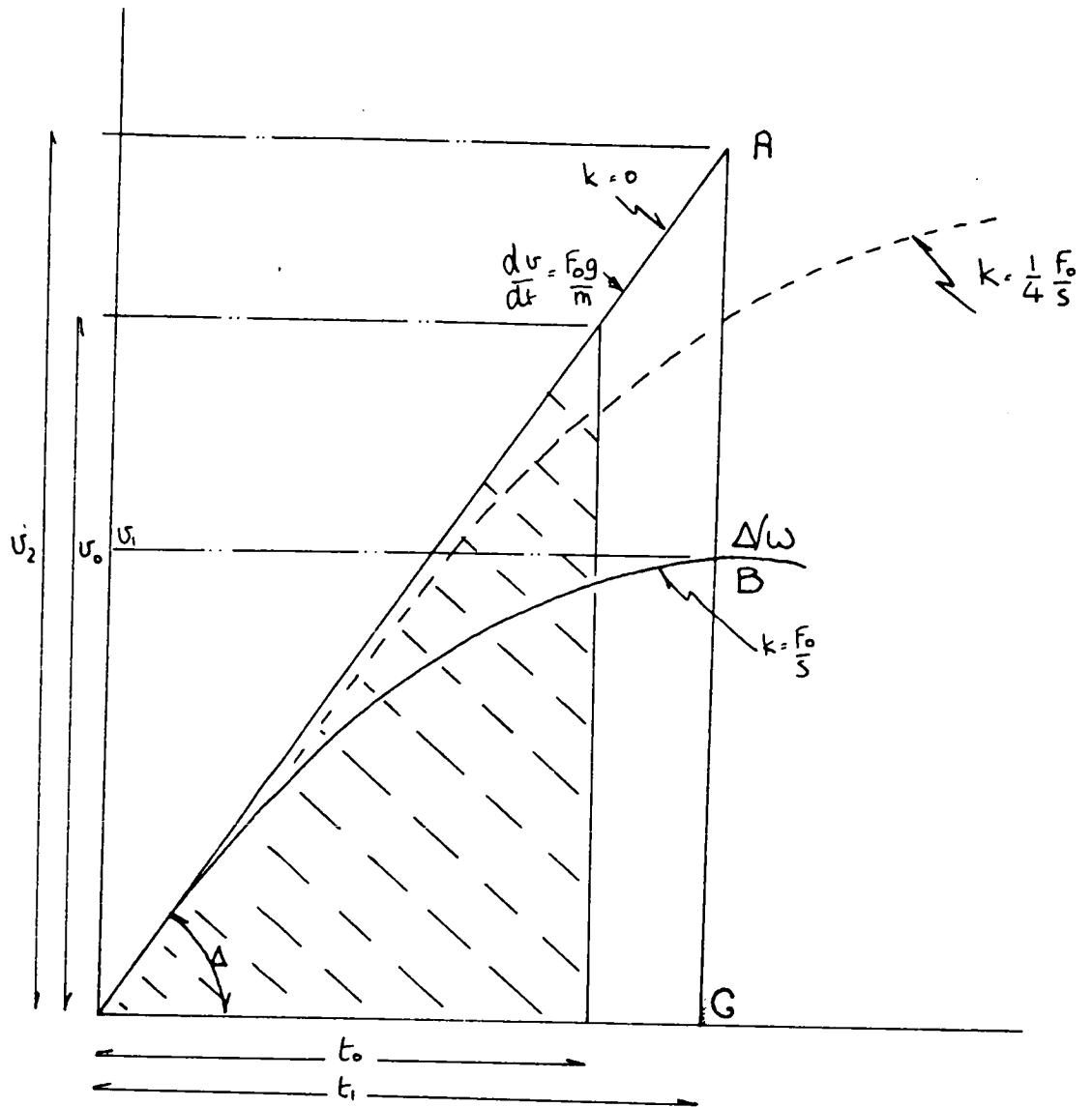


FIGURE 5.10.1.



SCHEMATIC DIAGRAM OF AIR OPERATED
EXPERIMENTAL SWITCH

FIGURE 6.3.1.



TIME ~ VELOCITY CURVES FOR SPRING SYSTEMS

FIGURE A.1.