

ARC CONTROL
IN
AIR CIRCUIT-BREAKER WITH STRONG MAGNETIC FIELD

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ABSTRACT

The decay of a horizontal A.C. arc between the electrodes of a horn gap was studied. With the arc initiated at the smallest gap between the electrodes, buoyancy force causes the arc column to rise from bottom, accompanied with increase in length. The losses from arc column, mainly due to conduction-convection phenomena in air, cause decay and consequent extinction of arc. The process being inherently slow, arc was struck in presence of transverse magnetic field of a blow-out coil, energised by arc current. Buoyancy force, being augmented by electromagnetic force, subjected the arc column to rapid motion through air causing increased rate of heat-loss and a fast thermal clearance.

Results are given of experiments on arc duration under the action of buoyancy force exclusively and also when an electromagnetic force acts in conjunction with buoyancy force. Magnetic field was found to have a marked influence in causing a fast recovery consistently. The consistency of results in presence of magnetic field was indicated by an appreciable decrease in standard deviation of arc duration along with the significant decrease in arc duration itself. Arc duration has been shown to be inversely proportional to maximum transverse magnetic flux density at adequate magnetic field strength for the magnitude of current to be interrupted. An empirical formula relating arc duration to maximum transverse magnetic flux density and current to be interrupted has been obtained in terms of two constants on the basis of experimental results.

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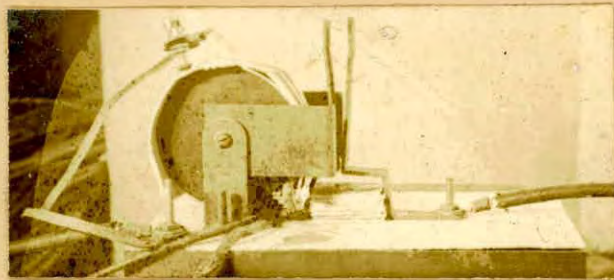
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LIST OF SYMBOLS

A	Area ; Constant
a	Constant
B	Magnetic flux density ; Constant
B_m	Maximum magnetic flux density
b	Constant
C	Capacitance
c	Constant
d	Constant
E	Voltage
E_n	Line to neutral Voltage
e	Base of natural logarithms, 2.718
F	Force
f	Frequency
g	Acceleration of gravity
I	Current
i	Instantaneous value of current
K	Thermal conductivity; Constant
k	Constant
L	Inductance
l	Length
log	logarithm to the base 10
M	Constant
m	Experimental or sample mean (arithmetic average)
N	Constant ; Number of turn
n	Constant
p	gas pressure
R	Resistance
R_c	Critical damping resistance

$RRRV$ Rate of rise of restriking voltage
 r_0 Instantaneous arc resistance
 r Radius
 s Experimental or sample standard deviation
 T Temperature ; Period of one cycle
 t Time ; Arc duration
 V Voltage
 V_a Arc voltage
 e_s, V_r Recovery voltage
 V_L Voltage gradient
 v Velocity
 W Energy
 $\dot{W}$ Energy flow rate
 x length
 x, y, z Coordinate axes
 Δ (Delta) Incremental or differential sign
 θ (theta) Angle ; Time constant
 ρ (rho) Gas density
 Σ (Sigma) Summation
 σ (sigma) Electrical conductivity
 ϕ (phi) Magnetic flux
 ω (omega) Angular frequency



Arc-control unit

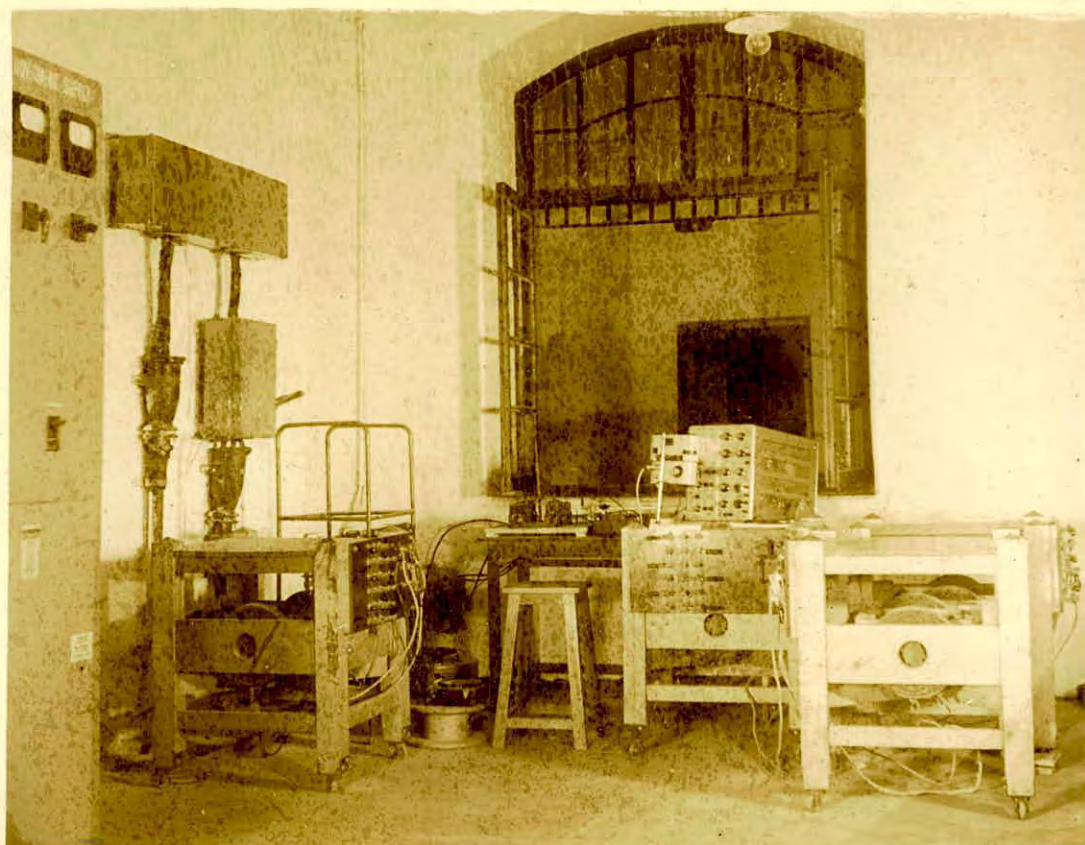
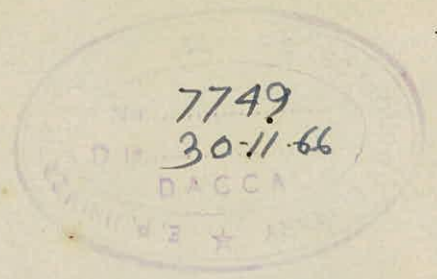


Fig I Experimental set-up



Chapter - 1

INTRODUCTION

The interruption of gaseous conduction or arc discharge, which ensues between separating contacts in a circuit-interrupter is a field of considerable investigation. Efficient circuit-breakers of large breaking-capacity, capable of operating on extra-high voltage circuits have been built. But these breakers, which are either of oil-break or gas-blast type have been developed more on the basis of some tried and tested practice than on the basis of any theory of gaseous conduction. The complex and varied nature of gaseous conduction occurring in different types of circuit-breakers has been found to be extremely difficult to analyse satisfactorily. As far as known to us, air-break circuit-breakers exist in the low and medium voltage range only, even though air is a very good insulator at normal pressure. Certain designs of air-break circuit-breakers are in the range of several KV; but their size do not compare very favourably with an equivalent design of an oil-break type.

The behaviour of an arc column as a flexible conductor, which can be deflected, or even 'blown-out' by a transverse magnetic field has been known since the last century. This property of an arc column has found application in air-break circuit-breakers as blow-out coils, which stretch the arc columns so as to aid deionisation. Magnetic control of the movement of arc column is utilised in various forms in circuit interrupters. A D.C. arc can be deflected by the field of a permanent magnet. But an A.C. arc carrying an alternating

current can only be deflected by an alternating magnetic field. The magnetic field is produced by a magnetic circuit, energised by the arc current itself.

The present work has been directed in evaluating the efficacy of this method of circuit interruption under conditions of severity of a power circuit. A circuit-interrupter as a protective device has to be 100% efficient. The deionisation of arc column, in this work, was mainly in the region away from the electrodes i.e. major part of the recovered dielectric strength was in the positive column of the arc. It was considered desirable to make an attempt to relate the effectiveness of this method of clearing an arc, quantitatively in terms of the magnitude of the arc current and the magnetic field strength. Since the arc duration i.e. the arc 'clearing time' is not a unique function either of the current to be interrupted, or of the imposed magnetic field, due to the nature of the physical phenomena involved in arcing, as well as certain other parameters of random nature, it was also realised that a statistical method of analysis of results would ^{be} of greater value in this investigation.

Greater effort in the direction of extinction of an arc in air may well open up new techniques, which may in turn lead to the development of air-break circuit-breakers of larger breaking-capacity capable of operating on circuits of higher voltages.

Chapter - 2

THE ARC

The discovery of Volta's pile in 1800 led to three classes of experiments with electric current. One of the classes dealt with heat producing effect of electric current, more particularly with the spark obtained on making and breaking a circuit. These experiments led to the discovery of arc but it is difficult to say where and by whom it was first obtained.

Sir Humphrey Davy's laboratory notes for the years 1805 to 1812 show ' a bright spark ' was obtained in the laboratory of the Royal Institution when the tips of two pieces of charcoal, connected across 200 batteries " each composed of 10 double plates arranged in cells of porcelain " were brought within $1/30$ or $1/40$ of an inch of each other. When the points were separated from each other " a constant discharge took place through heated air, in a space at least equal to four inches, producing a most brilliant ascending arch of light ". In 1820 , following Arago, Davy came to the conclusion that the arc behaves like a flexible conductor, both attracting a magnet and being attracted by it. It was on this occasion that he gave the name of " arc " to the electric flame, which he had earlier described as an " arch of light ". W. Petroff²⁵ of Russia also discovered the arc discharge at about the same time as Davy.

In the nineteenth century numerous investigation on D.C. carbon arcs

were carried out by different workers. In 1852 an interesting experiment was performed by Quet, who showed that a vertical carbon arc could be blown out by the horizontal magnetic field of an electro-magnet. This is the basis of present day blow-out coils employed in air-break circuit-breaks.

Towards the end of the last century Mrs. Hertha Ayrton made extensive research on the mechanism of and phenomena associated with the electric arc. A few of her notable conclusions are given below:

(i) Curves representing arc voltages against arc currents for various lengths of carbon arcs show an inverse characteristic and are split up into three zones, namely silent arcs, unstable arcs and hissing arcs (Fig. 1).

(ii) In the silent region the relationship between arc voltage V_a and arc current i for an arc-length l is well represented by Ayrton equation-

$$V_a = a + bl + \frac{c + dl}{i}$$

where , a , b , c and d are constants.

(iii) The curves connecting the arc voltage and arc-length for various constant currents are straight lines confirming Edlund's equation (1867) -

$R = a + bl$, where R is the apparent arc resistance, l is the arc-length and a and b are constants for a constant current (Fig. 2).

The work of Mrs. Ayrton and other workers before her deals with D.C.

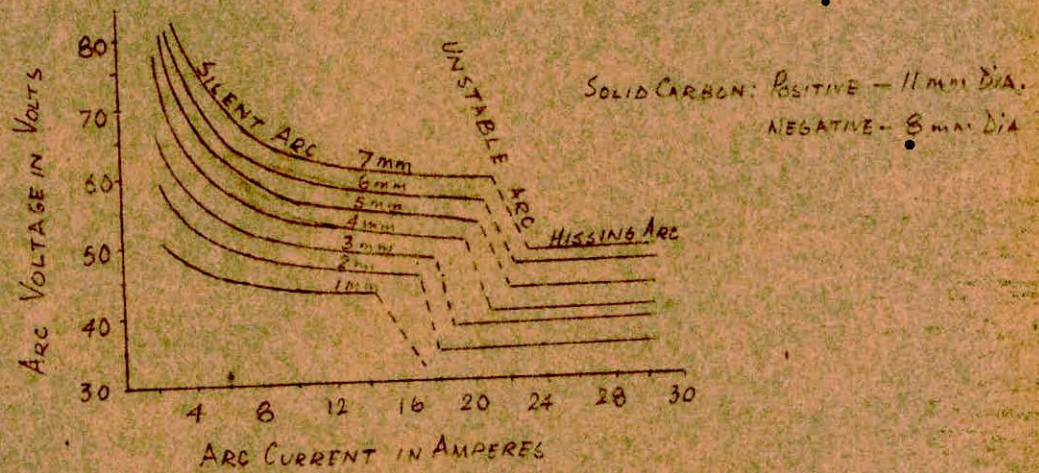


FIG.1. Volt-Ampere Characteristics of Carbon arcs in air.

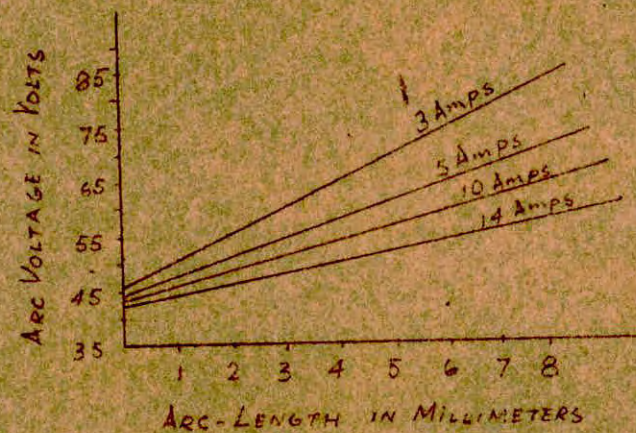


FIG.2. Arc voltage and arc-length relationships for various constant currents

arcs of short length and small power. But in the present day power system engineering circuit - breaker designers are faced with control and extinction of high power A.C. arcs associated with three-phase supplies at very high voltages.

2.2 INITIATION OF ARCING IN CIRCUIT-BREAKER.

The entire cycle of discharge occurring between separating contacts in a circuit-breaker is termed as 'arc'. As the last point of contact separation is reached, the current density increases to such a magnitude as to produce a local rise of temperature. The temperature of such a point has been estimated by Slepian² to be given by -

$$T = \frac{V^2}{33.5 K \rho}$$

where V = Voltage between the contacts - Volts

K = thermal conductivity - Cal/cm²/oc/cm

ρ = resistivity of the material - ohm - m

For $V = 1$, $\rho = 10^{-5}$ and $K = 1.0$, a temperature of 3000 °C may be reached at the last point of contact. This temperature is high enough to cause metal vaporisation. The voltage stress appearing across the vapour gap is then sufficient to cause ionisation of vapour and thus initiating condition for gaseous discharge. Alternatively a large number of electrons can

be liberated from the atomic shells either by thermionic emission or by field emission from the last point of contact. The former requires temperature much higher than 1000°C while the latter, a field of the order of 10^8 volts/cm. On ordinary smooth metal surface (10^{-5} cm is the finest roughness that can be seen) there can be little points where the local field may be materially higher.

2.3 ARC : THE GASEOUS ELECTRICAL CONDUCTOR.

2.3.1 Discharges in Gas Gap.

In the gas gap between two electrodes there will always be some free electrons. With the application of a small D.C. voltage, the free electrons will flow through the gas, the flow being impeded by collisions with the neutral gas atoms. (Fig. 3a). Soon all the electrons and ions produced by external agency will be involved and the current will stabilise at approximately a constant value, independent of voltage over a limited range. So far the current is negligibly small and the gas is an insulator.

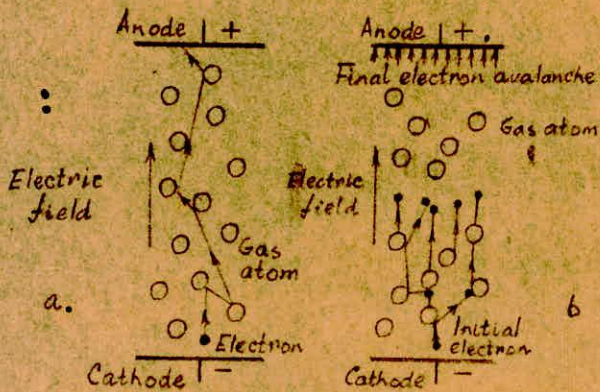
If the voltage is increased still further, a few electrons will attain high kinetic energy, able to ionise atoms by collision and thereby release further electrons and ions i.e. the current will commence to increase again. Additionally some electrons will be produced by positive ions

bombarding the cathode ; this is the region known as Townsend discharge.

Upto this point the discharge is not self - sustaining as removal of ionising agency cuts off the supply of electrons and the current ceases (Fig. 4).

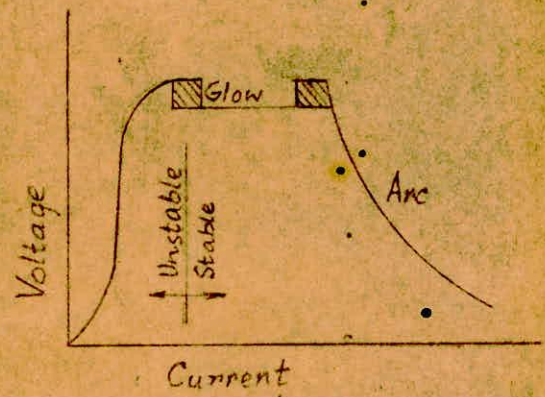
On the other hand, with higher applied voltage between the electrodes, the free electrons will soon attain ionising velocities. These high-energy electrons will on collision with neutral gas atoms, free positive ions and electrons, which can then function similarly. The process is cumulative, producing an electron avalanche and finally a spark discharge (Fig. 3 b).

The gas under this condition is conductive and can easily be maintained in a state of stable conduction. Subsequent to a spark discharge if the current is limited to a low value by the circuit impedance a glow discharge with nearly constant voltage characteristic will be produced. Above a critical value of current a decreasing (negative slope) voltage-current characteristic is obtained, and this finally leads to the formation of an arc (Fig. 4) . Usually glow discharge occurs in gases in low-pressure range (0.1 - 100 mm of Hg) where in the supply of electrons is limited. In high-pressure range it is difficult to distinguish it from the arcs. But glow regime may have important bearing in understanding post-arc phenomena in A.C circuit interruption.

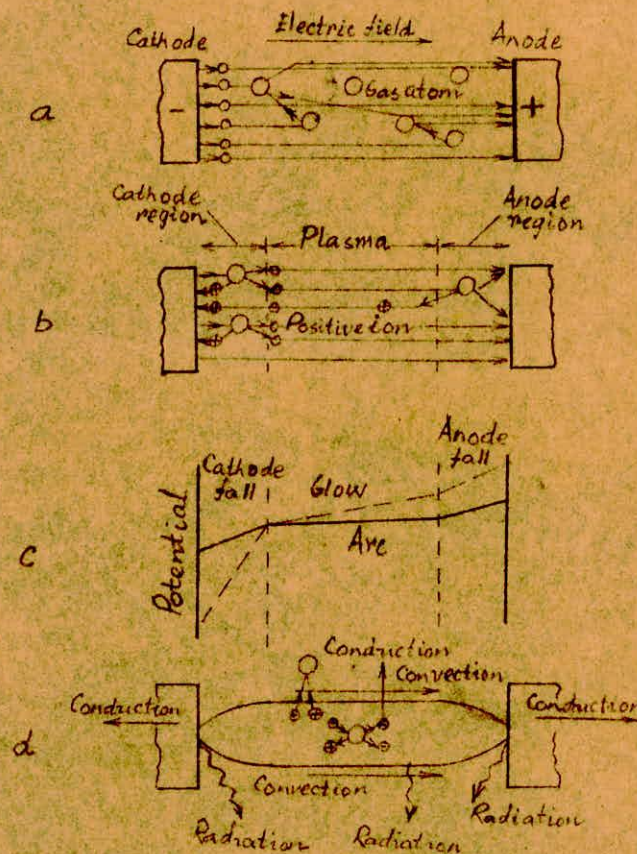


¹ Fig. 3. Electron conduction in a gas.

- (a) Electron-atom collision with no ionisation.
 (b) Electron-atom collision with ionisation and production of electron avalanche.



³ Fig. 4. Voltage current relationship during discharge.



² Fig. 5. Electric conduction in a gas.
 Production of discharge regions and potential distribution.

^{1,2} From Journal I.E.E., 2, 712, 1956.

³ From Ref. 4, p 245.

2.3.2 Production of Discharge Regions.³

Let us consider again a gas gap between two electrodes as a part of a simple D.C. circuit. In the simplest state, the current is solely due to motion of free electrons present in the gap (Fig. 5a). This system, however, lacks a fundamental requisite of a self-sustaining discharge, namely a mechanism able to produce required electron emission from cathode. Cathodic emission can be brought about by field stress, temperature or light radiation. Both glow and arc discharge require the production of positive ions in a region close to cathode. Because of some initial ionising collision between accelerated free electrons and neutral gas atoms a positive space charge builds up across cathode region (Fig. 5b) producing a voltage drop, termed the cathode fall. Under the influence of this local field stress the positive ions are impelled on the cathode surface producing more electrons. In the glow discharge the current density is low ($\sim 10 \text{ amp/cm}^2$) and the cathode fall high ($\sim 300 \text{ volts}$), so that positive ion bombardment of cathode surface is possible. In an arc the current density is high ($\sim 10^4 \text{ amp/cm}^2$), so that the ions, with low cathode-fall voltage ($\sim 10 \text{ volts}$) can produce high temperature at the cathode with consequent thermionic emission in refractory materials such as carbon, tungsten and molybdenum. For low-boiling-point materials like sodium, mercury and copper, the mechanism

of electrons emission is not clearly understood. It is considered that for arcs, with continuously moving roots, field emission can still play a major part. But for arcs with fixed roots, thermal emission should be a major factor as for example, copper vapour will be 80% ionised at 1900°K and arc temperature rises to about $10,000^{\circ}\text{K}$.

As shown in Fig.5b, which illustrates the flow of currents and not charge concentration, the electrons emerge into a region known as the plasma. The plasma is almost electrically neutral, so that the positive-ion and electron concentration must be equal. The required positive-ions for neutralisation are produced by collision in the anode region, where a negative space charge and anode voltage drop exists. The discharge thus comprise three regions, namely cathode-fall space, plasma and anode-fall space. The potential distribution in these regions is illustrated in Fig.5c, which shows the potential gradient is high at both ends compared to the main arc region of plasma.

2.3.3 Losses from the Discharge.³

In circuit-breaking, losses from the discharge are important, as successful circuit-interruption requires that the energy losses from the discharge must exceed the energy input into the discharge. The mobility of positive-ion being small, the electron current constitute the main source of current. Thus the losses depend almost entirely on the result of the elec-

tron collisions. (1) As a result of many non-ionising collisions with electrons, the gas atoms gain considerable amount of energy and the temperature of plasma in an arc discharge can rise to 4000 - 10,000 °K. These high temperatures produce both radial and axial conduction losses and give rise to convection phenomena and loss as depicted in Fig. 5d. (2) Atomic excitation occur from electron collision so that the discharge emit light and loses energy by radiation. (3) Energy losses also occur at the electrodes. (4) Of the other possible losses which may occur, Fig. 5d shows those due to ionisation and dissociation within the discharge and their subsequent recombination outside. For a stable discharge ionisation^{losses}/by diffusion must be balanced by new ionisation within the discharge, and such a process is depicted in the diagram. These losses, which occur in varying degree in different types of circuit-breakers indicate the intricacy of the arc interruption problem.

2.4 ARC BURNING VOLTAGE.^{4,5,6}

The relationship between the arc burning voltage and arc current should be of the form -

$$V_a = \frac{B}{\sqrt{i}} \quad (1)$$

since the arc has a decreasing volt-ampere characteristic (Fig. 8).

The arc column comprises of a main region of plasma with anode-fall space

and cathode-fall space at ends. The gradients at ends are practically independent of arc length and so the expression for arc voltage should be modified to -

$$V_a = A + \frac{B}{i} \quad (2)$$

Actually, the relationship at atmospheric pressure has been found by Nottingham to be -

$$V_a = A + \frac{B}{i^N} \quad (3)$$

where A, B = constants dependent on electrode material and arc length

i = current in ampere

$N = 2.62 \times 10^{-4} T$ = constant which is approximately a linear function of anode material absolute boiling temperature (T), and is approximately 1 for carbon, 1.3 for tungsten and 0.65 for CuO .

Above atmospheric pressure, the burning voltage is increased, the relationship being of the type

$$V_a = M \log p + N \quad (4)$$

Where M, N are constants, p is the gas pressure and arc current and length are assumed as being constant. Arc in pure hydrogen do not follow this law above 100 atmospheres pressure being unstable probably due to the turbulent convection of the gas.

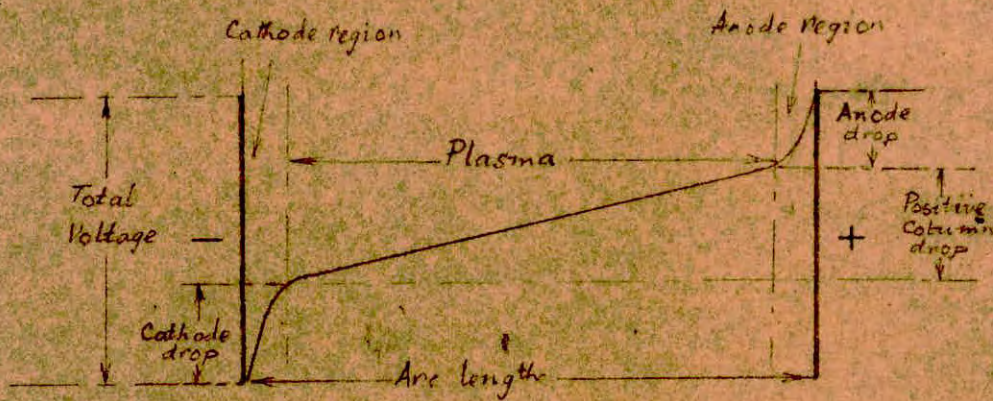


Fig. 6. Voltage distribution of electric arc.

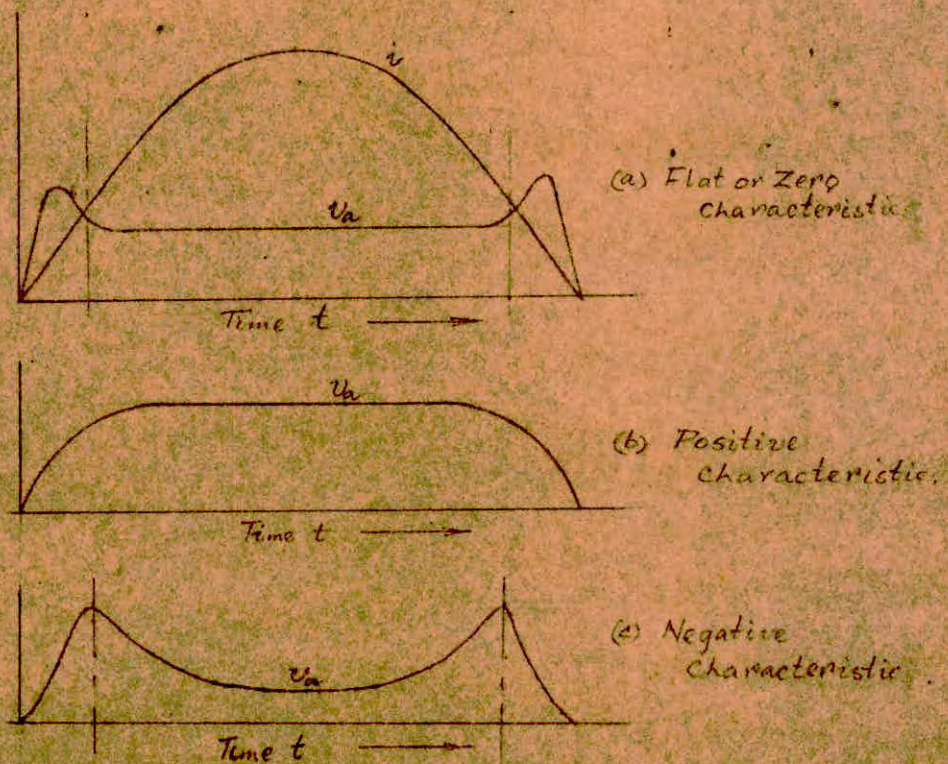


Fig. 7. Forms of arc voltage during half-cycle of current



Fig. 8. Typical Volt-Ampere characteristic of arc.

1 From Ref. 7, p. 49.

The form of arc voltage drop, as the current passes through its sinusoidal form, depends on the type of breaker ; but in general, the shape takes ^{one} ~~due~~ or other of the forms shown in Fig.7.

A plot of instantaneous values of arc voltage against corresponding values of current, gives the arc characteristics, but more accurately arc characteristic does not depend on the current but on the rate of changeⁿ of current ; that is static and dynamic characteristics must be distinguished. However, during most of the half-cycle the quantity $di/dt/i$ is small and a plot of V_a against i gives the static characteristic nearly enough. Static characteristics are said to be positive, zero or negative depending on whether dv/di is positive, zero or negative. Near current zero when $\frac{di}{dt}/i$ becomes large, this will no longer be true. Consequently the arc gap has a higher breakdown voltage near a current zero decaying with increasing current to either form a or c . In general arc has a negative volt-ampere characteristic (Fig.8) as is given by equation (1) and (3). With a confined arc, it is evident from equation (4) the arc voltage may be increasing instead of decreasing due to pressure build up within the arc chamber consequent on the high temperature.

In A.C. circuit the current varies cyclically going through zero twice in every cycle. The anode of first-half cycle becomes the cathode of next-half cycle and the phenomena is repeated periodically with the arc reigniting after every current zero. At a current zero the energy input into the arc must be zero and so it would appear, the arc resistance momentarily jumps to infinity forming an insulating gap. Actually due to thermal inertia of arc column, the gas gap remains in an ionised state at current zero giving arc a finite value of resistance, which leads to reignition. Reignition is of two types, which are described as thermal reignition and spark reignition. The thermal type is exemplified by discharges with thermionically emitting materials like carbon. The anode of the carbon arc is maintained at a much higher temperature than the cathode so that when it becomes the cathode of the following half-cycle, it is ready to emit a copious supply of electrons to carry the current, and no appreciable rise of voltage is required to initiate the arc in reverse direction. With discharge in hydrogen between copper electrodes, on the other hand, conditions are quite different. The current remains zero for a period of the order of 100 - 200 μ sec. and a relatively insulating gap is formed, which can only be broken down by a high reignition voltage in the form of a spark discharge. In air and nitrogen, conditions seems to be varied and a transition from spark

breakdown to thermal breakdown may occur. In general spark type of re-ignition
are marked with higher breakdown voltage than that of thermal type.

Chapter - 3

ARC EXTINCTION

3.1 INTRODUCTION

The extinction of an A.C. arc in a circuit breaker is fundamentally different from the extinction of a D.C. arc. A D.C. arc is to be lengthened or the arc space is to be so deionised that the arc burning voltage necessary to support the current rises to a value above the applied circuit voltage. The current then reduces to zero and the arc is extinguished. An A.C. arc burns with a low voltage drop across it and influences the course of current in a minor way. In A.C. circuit, current reduces to zero value twice in every cycle. There is no energy input into the arc at such a zero pause and arc extinguishes at or near such a moment.

The interruption of a fault current is one of the major duties of a circuit-breaker. As system faults are mainly inductive, current lags the system voltage by 90° approximately i.e. at a current zero the arc gap will have to support the peak of the circuit voltage. This is a more onerous duty than when the power factor of a circuit is unity i.e. current and voltage passes through zero at the same moment.

3.2 INTERRUPTION OF A SIMPLE A.C. CIRCUIT

In order to study arc extinction phenomena, it is convenient to consider interruption of a simple A.C. circuit with a generator, an inductance L , a

condenser C, representing say the line capacitance and the circuit-breaker S, as shown in Fig. 9(a). Initially the breaker is closed when the fault has occurred. Let the generator voltage be

$$e_g = E \sin \omega t$$

then the fault current

$$i_f = \frac{E \sin \omega t}{\omega L \angle 90^\circ} = I_f \cos \omega t$$

If the breaker opens at some time t before current zero, an arc will be drawn out between contact gap burning with a low voltage v_a , which is in phase with current. Arc voltage v_a being very small, current will still lag the generated voltage e_g by nearly 90° . Assuming now an ideal condition, in which in a small time embracing current zero arc gap momentarily changes from a comparatively good conductor to a comparatively good insulator, a transient voltage of reverse polarity will appear across the gap having a value

$$e_R = E_s \left(\cos \omega t - \cos \frac{t}{\sqrt{LC}} \right)$$

This is an oscillatory voltage (Fig. 9b) termed as the restriking voltage transient. The first term (e_s) represents the fundamental frequency voltage, called the recovery voltage. This voltage appears across the gap after final arc extinction. The second term represents a natural frequency voltage, which oscillates about the voltage level of e_s with a frequency

$$f = \frac{1}{2\pi \sqrt{LC}}$$

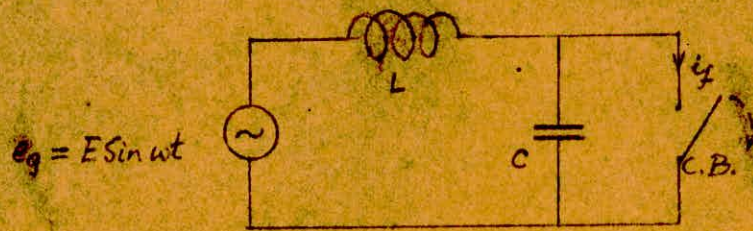


FIG. 9.(a) A simple A.C. circuit.

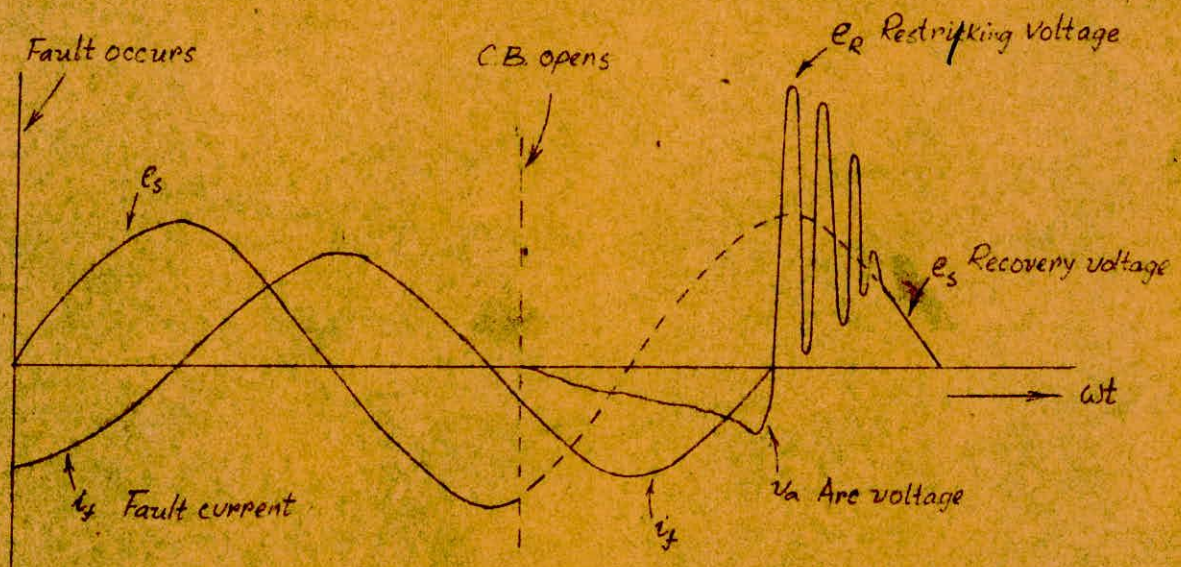


FIG. 9.(b) Voltage and current waves during circuit interruption.

and has a peak value equal to that of e_s . The total voltage swing is therefore $2 E_s$ from zero i.e. $2 \sqrt{2} V_s$ when V_s is the r.m.s voltage.

The arc space will have to stand the high transient voltage, till recovery voltage is established across the electrodes of the breaker. Evidently whether or not arc extinction will take place depends on the restriking voltage transient and particularly its rate of rise. The natural frequency of a power circuit vary say from 5 to 100 Kc/s. The period of the latter wave is only 10 microseconds. It may thus be generalised that the time available for the transition from conducting to an insulating gas space vary from 2.5 microseconds, i.e. the time required to reach the first peak to several thousands microseconds depending on the character of the external circuit. Arc extinction thus depends on the reaction between the behaviours of the gas space and that of the external circuit.

3.3 THEORIES OF ARC EXTINCTION

Most of the theories of arc extinction have originated from investigations into the circuit-breaker performance, so that these theories are mainly concerned with A.C. conditions and the behaviour of an arc at a current zero. Out of the various theories so far proposed, two are very widely known and referred to in analysing the behaviour of a circuit-breaker. The first one is due to J. Slepian of United States (Westing house) who in the period 1928-30,

proposed a theory which is known as the Dielectric Recovery Theory. He analysed the problem of arc extinctions as dependent on two factors, the rate of recovery of the dielectric strength of the arc space and the rate of rise of restriking voltage of the external circuit. In 1939, A.M. Cassie of Electrical Research Association, Britain proposed another theory from consideration of the energy content of the arc space and is known as Energy Balance Theory. These two theories seems to have made considerable impact on the problem and will be outlined here.

3.3.1 Dielectric Recovery Theory:

Slepian^{8,9} visualised the arc extinction phenomena as a rapid transition from an highly conducting to a comparatively non-conducting arc space embracing a current zero. The transition depends on the reaction between two opposing forces which are called into play. The first is the rate at which the arc space recovers its dielectric strength due to disappearance of ions and the other is the rate of change of circuit voltage, which tends to reignite the arc. The theory assumes that at every instant after current zero, the arc space recovers a certain dielectric strength, which can be represented by a unique curve such as curve (a) in fig. 10. If the restriking voltage is given by curve (b) , which always lies below the dielectric recovery curve(a),

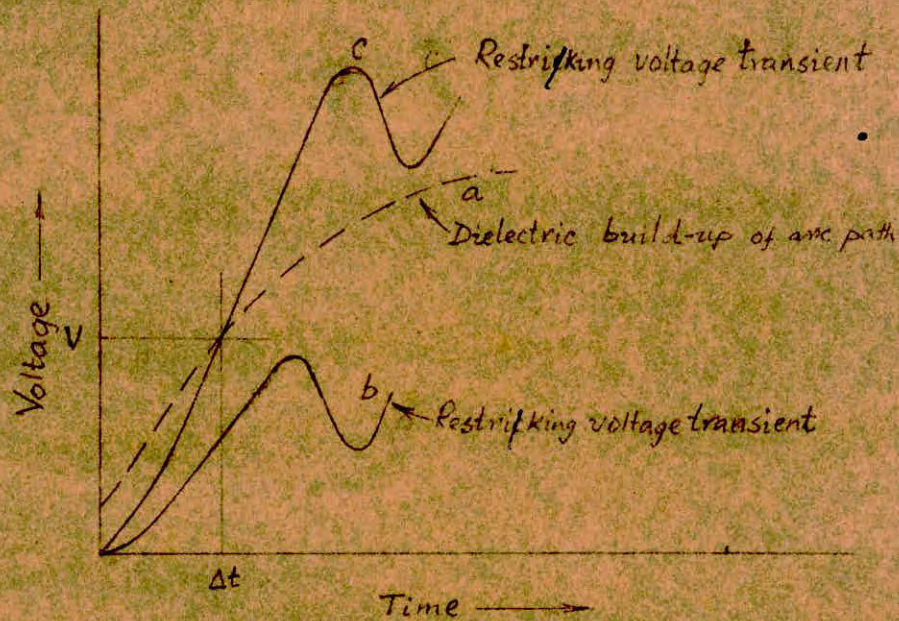


FIG. 10. Dielectric recovery theory of arc extinction.

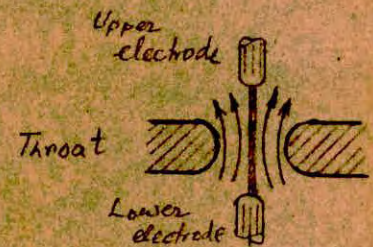
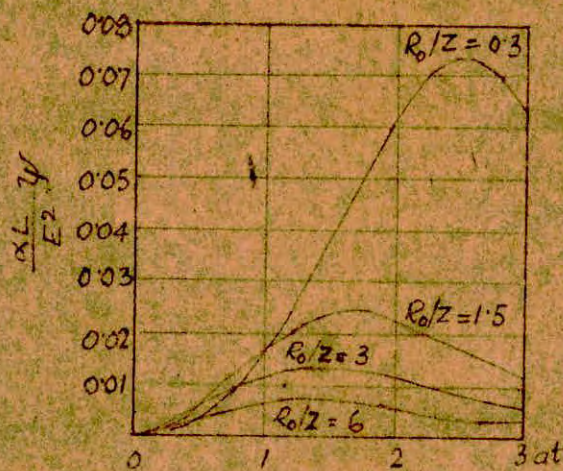


Fig 11(b) Arc in a nozzle

Fig 11(a) Variation of arc power with initial resistance.

1 From Ref. 7, p. 71.

2 From Ref. 7 p. 53.

then the arc will be extinguished. If however the restriking voltage is given by curve (c), reignition will occur at voltage V and time Δt after current zero. In the words of Slepian, "the extinction^{or}/reignition of an A.C arc following a current zero depended⁵ on the outcome of a kind of race between contending factors", - the dielectric recovery of arc space and the restriking voltage transient.

A prerequisite for the application of this theory is the determination of a critical dielectric recovery curve for the arc space under investigation. The theoretical determination of such curves for different types of circuit-breakers with varied arc conditions ^{is a} ~~are~~ considerable ^{difficult} problems ^{itself} in themselves. Slepian's own attempt at assessing the dielectric strength of an ionised gas between closely spaced electrodes in the open gave the value as

$$V = 1.9 \times 10^9 \times \left(\frac{273}{T + 273} \right)^5 \times t$$

where T is the absolute temperature and t is time in seconds. With brass electrodes, if its boiling temperature, 1200°C is taken as the temperature in the cathode region, then-

$$\frac{dv}{dt} = 0.4 \times 10^6 \text{ volts/sec.}$$

If the melting point of 940°C is taken, the

$$\frac{dv}{dt} = 1.1 \times 10^6 \text{ volts/sec.}$$

The theoretical values of the rate of recovery of dielectric strength are well below the experimental value of 25×10^6 volts/sec.

The formulation of this theory is based on the assumption that dielectric recovery of arc gap and restriking voltage are two independent time-varying quantities. Actually the dielectric recovery is not an independent process as at every instant it can be modified by the existing circuit voltage. However Slepian's contribution is considerable as he really first distinguished between the recovery and restriking forces. With experimental values of the recovery of gas gap in a particular type of circuit-breaker, this simple ~~six~~ criterion of arc extinction can still be of great value.

3.3.2 Energy-Balance Theory :

The existence of post-arc conductivity in circuit-breakers excludes the idea of simple dielectric recovery curve. Gas-blast breakers with high post-arc currents are found to clear a circuit successfully. Also high rate of rise of restriking voltage does not have marked bearing on the performance of these breakers. These considerations led A.M. Cassie^{10,11} to propose a theory of arc extinction phenomena in terms of energy exchange in gas gap during the interrupting period.

A sudden change in arc current is not accompanied with a corresponding change in voltage given by Static V_i characteristic of an arc. The reason is traced in the 'heat content' of the gap. Arc is a column of heated, dissociated ionised gas. Because of the thermal lag or 'hysteresis' of arc column, its resistance or conductivity does not depart from its previous value with the momentary change in current. The behaviour of arc can thus be better understood in terms of a time-dependent equation in R .

Assuming a constant temperature through the positive column of arc, which excludes the electrode phenomena, varying area of arc cross-section, and main losses being due to forced convection, Cassie formulated an equation in R in 1938:

$$\frac{dR}{dt} = kR \left(1 - \frac{e^2}{e_0^2} \right) \quad (1)$$

where $e_0 = \text{const.}$

In terms of instantaneous current, the equation reduces to:

$$\frac{dR}{dt} = kR - \frac{k}{e_0^2} R^3 \quad (2)$$

This is an energy-balance equation as the first term on right represents the rate of heat loss and the second term, the heat input.

In about 1943, Mayr^{12,13} also deduced a similar equation in R , assuming losses due to thermal conduction only. The equation is:

$$\frac{dR}{dt} = \frac{N_0}{Q_0} R - \frac{1}{Q_0} e^2 \quad (3)$$

where in again the first and second term on right represent heat loss and gain.

M_0 is the rate of heat loss from arc column per unit length and Q_0 is a constant.

If the current in an arc were stopped suddenly, then equation (2) reduces to:

$$\frac{dR}{dt} = \text{const. } R = \frac{1}{\theta} R.$$

$$\text{or } R = R_0 e^{t/\theta} \quad (4)$$

i.e. resistance of arc column increases exponentially with a time constant

Reignition after a current zero can occur in either of two alternative process. If the post-arc current is less than say 10^{-4} A, i.e. all conductivity has practically ceased, then only spark or corona break down can take place governed by something like Paschen's law i.e. breakdown strength $\propto \int \rho dx$. This may be referred to as hard zero.

In the other process there is post-arc conductivity, and the mechanism becomes one of energy balance, in which rate of energy input exceeds the loss. Slepian¹⁴, faced with this situation gave a new definition for the electric strength of the gap - the voltage, applied at any instant, which is just sufficient to keep the specific conductivity or specific resistance, of the plasma constant. This voltage may be used for assessing balance, for which an indication of arc resistance at current zero is also necessary. If the current linearly falls to zero, then it can be shown that arc resistance at current zero

is :

$$R_0 = \frac{2 e_0}{\omega \theta I} \quad (5)$$

where e_0 , the voltage gradient in the arc ; I peak value of current and ω = angular frequency.

The arc column will be contracting in diameter because of axial flow of gas but this will not cause arc temperature to drop. ^{Fig 11(b)} The arc column will of course be loosing heat by thermal conduction, which can be called diffusion loss causing the axial temperature to drop. The specific electrical conductivity does depend on temperature. Now to make the diffusion loss and to hold the temperature constant, a voltage V_d be applied to the column, the diffusion loss

$$W = \frac{V_d^2}{R} \quad \text{watts} \quad (6)$$

Hence $V_d = \text{const } \sqrt{R}$, since W is roughly constant.

Therefore a change in V_d increases as the square root of change is resistance due to deformation only. This voltage V_d is the dielectric strength of the gap as defined by Slepian.

The voltage appearing across the gap is no longer the simple restriking voltage transient but one which has been modified by the conductivity of the circuit. Now the problem is one of balance between energy V^2/R entering the residual column from the circuit and the energy W , being lost due to diffusion. If V^2/R exceeds W after current zero, an 'energy breakdown' of the gap occur.

In the reverse process, R increases exponentially and the restriking voltage rises. The energy input V_R^2 increases to a maximum and then fall off again, this maximum being less than W . The variation of V_R^2 after current zero for a typical circuit is shown in Fig. 11.(a)

Chapter - 4

CIRCUIT CONDITIONS IN RELATION TO CIRCUIT INTERRUPTION

The duty imposed on a circuit-breaker depends on a number of factors which have been termed conditions of severity. They include circuit power factor, current asymmetry, earthing conditions, recovery voltage and restriking voltage. B.S. 116 defines 'recovery voltage' as 'the normal frequency rms. voltage that reappears between the poles of a circuit-breaker after final arc extinction' and 'restriking voltage' as 'the transient voltage that exists at, or in close proximity to, each zero current pause during the arcing time; the important characteristics are its amplitude and its rate-of-rise (expressed in $V/\mu s$) at the time of final arc extinction.' But in American terminology 'recovery voltage' covers the complete voltage phenomena at circuit interruption.

The easiest duty is the interruption of load current when besides the small value of current the power factor is high eg 0.8. But in a short circuit the impedance is almost inductive but low giving a low power factor (.15 or less). This is a more severe condition as besides the large current to be interrupted the arc gap has to support nearly the peak of generated voltage at a current zero (Fig.9b), when the arc current is interrupted, the voltage at the breaker contact changes rapidly to nearly twice the circuit voltage. The frequency of this oscillatory voltage kx in the simplest case is -

$$f = \frac{1}{2\pi} \sqrt{\frac{1}{LC}} \times 10^{-3} \text{ KC/s.}$$

which is the system natural frequency. A high " rate of rise of restriking voltage " or RRRV increase the possibility of arc restablising across the gap.

The amplitude of recovery voltage about which oscillation occur modifies RRRV proportionately. A 3-phase fault that is insulated from earth, either at neutral or fault, produces recovery voltage in the first phase to clear (i.e. $1.5 E_n$) which are more severe than those produced by single phase or 3 phase earth faults on systems with earthed neutrals, where the recovery voltage is E_n . A further modification in the recovery voltage is introduced by asymmetry in the fault current. Depending on the position of fault in a system and the values of system parameters, multiple-frequency restriking voltages transients may be produced.

4.3 INTERRUPTION OF SMALL INDUCTIVE CURRENT

When interrupting magnetising current of a transformer (secondary open-circuited) or very small (reactive) fault current, a powerful arc-control device may force out the current before a normal current zero. The system energy at the instant of interruption is then transferred to parallel capacity⁷ such that

$$\frac{1}{2} C (e'')^2 = \frac{1}{2} L i_o'^2$$

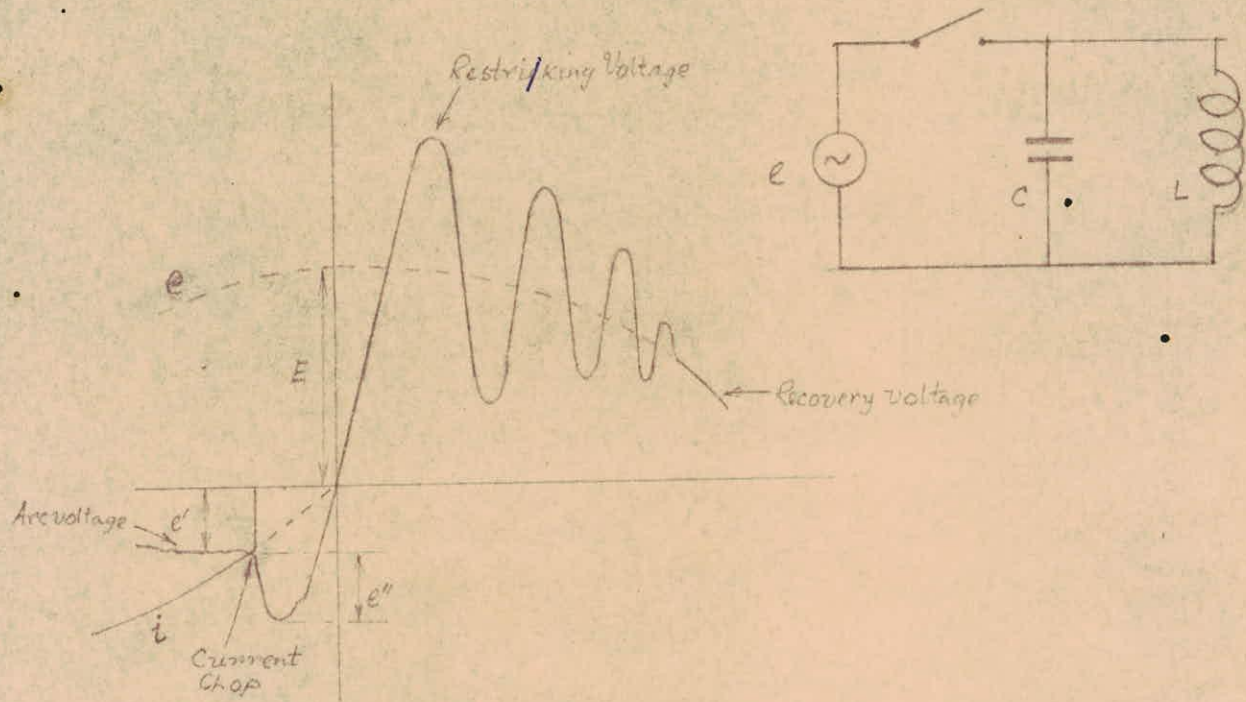


FIG. 12. Interruption of small inductive current showing current chopping & overvoltage swing.

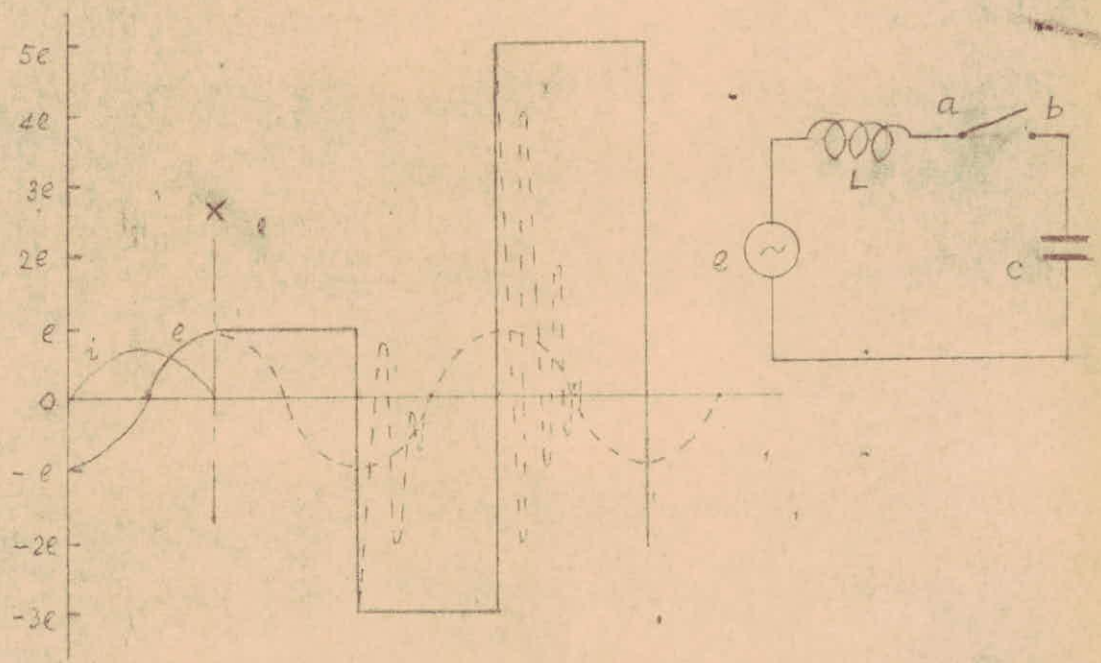


FIG. 13. Interruption of capacitive current showing voltage multiplying.

$$\text{or } e'' = i_0 \sqrt{\frac{L}{C}}$$

where i_0 = current at cut-off.

With a high cut-off current and low system capacitance (Fig. 12) e'' can be very high. The amplitude of oscillation is now $E + e' + e''$. This phenomena is known as " current chopping " which is usually accompanied with high over voltage producing sometimes multiple restriks with a half-cycle.

4.4 INTERRUPTION OF CAPACITIVE CURRENT ¹⁵

The disconnection of open-ended line or cable imposed on a breaker the duty of interruption of charging current, which leads the source voltage by approximately 90° . If the arc goes out at a current-zero (time x in Fig.13) when the voltage is at its peak value, the line end b remains fully charged at the positive potential $+e$. Thereafter generator voltage changes sinusoidally to $-e$ (end a) at the next peak, while the other end has a potential $+e$, so that there is twice peak to neutral voltage $2e$ ($2\sqrt{2} E_n$) across the break contacts a transient voltage of this magnitude ($2e$) will be oscillating at natural frequency of L and C about the negative maximum peak giving the maximum voltage to earth as $-3e$ ($-3\sqrt{2} E_n$). If the arc gap is able to stand this high voltage, the voltage doubling process may be repeated at the next peak giving $4e$ ($4\sqrt{2} E_n$) between contacts and $5e$ ($5\sqrt{2} E_n$) from line to earth.

The voltage doubling process is limited by leakage losses or a breakdown of

system insulation. The probability of the voltage reaching $4e$ is only 0.00001.

4.5 EFFECT OF RESTRICTING VOLTAGE ON AIR-BREAK CIRCUIT-BREAKER PERFORMANCE

The ^{is}restance of a breaker has a damping effect on the restriking voltage, the main effect being reduction of R.R.R.V. The critical damping resistance ¹⁶ is-

$$R_c = \frac{1}{2} \sqrt{\frac{L}{C}}$$

If the post-zero breaker resistance(R) is ~~ex~~equal to or less than R_c , the voltage change between breaker contacts after current zero follows an exponential form i.e. effective damping has taken place. If $R \gg R_c$, an oscillating voltage appears i.e. restriking voltage has not been effectively damped.

In air-break circuit-breakers, the process of arc interruption involves, the length^{en}ing and cooling of arc thereby increasing arc resistance considerably. This reduces the phase angle between current and voltage, so that the voltage^{at}/current zero is low and restriking voltage tends to be correspondingly small. Moreover, the post-zero resistance of these breakers is very low due to the presence of ionised gas in arc-space so that any restriking voltage is rapidly damped. Restricting voltage has thus little effect on air-break circuit-breakers.

In With oil ^{current} breakers and air-blast circuit-breakers the post-zero resistance is considerably high and consequently these breakers have little damping effect on restriking voltage.

Chapter - 5

AIR-BREAK CIRCUIT-BREAKERS

The air-break circuit-breaker has air immersed contacts and arc is initiated and extinguished in air medium. Arc is drawn to much greater lengths in air-break circuit-breakers than the short arcs associated with oil-break and air-blast circuit-breakers. The lengthening of arc raises the arc-resistance to a high value and thus helps to extinguish the arc. The air-break circuit-breaker is essentially a high resistance breaker while the two other main types of breakers, the oil-break type and air-blast type, can be grouped together as ' low resistance ' breaker because of shorter arcs associated with them.

Modern air-break circuit-breakers incorporate an arc-control device or arc-chute, which are made to perform three inter-related functions -

(1) to confine the arc within a restricted space, (2) to provide magnetic control of arc movement and (3) lastly to provide rapid cooling^{of} arc gases. The arc-control unit is mounted just above the arcing contacts. The arc is driven by various magnetic means, into the chute, where in contact with arc-splitters or cooling baffles or such other devices it is lengthened and cooled until it is extinguished.

5.3 TYPES OF AIR-BREAK CIRCUIT-BREAKER.

Arc-chute breakers can be divided into two types depending mainly on the method of construction of arc-control unit. In the cold-cathode type, the chute is made up from a stack of thin metal plates and in the refractory type, the chute contains a stack of refractory plates, each of which usually contains a magnetic insert.

The cold-cathode type operates basically on the same principles as an air-immersed de-ion breaker,¹⁸ which is an American invention. Normally the cathode anode drop of a pair of hot electrodes is about 20 volts but if the electrodes can be kept cool, the cathode-anode drop rises near a current zero to approximately 300- volts. In breakers of this type, the steel plates are given an inverted U - shape and the arc current is used to energize these magnetic circuits (Fig. 14). The electro-magnetic forces generated thereby drives the arc column into the stack of plates. This breaks up a long arc into a series of short arcs. The rapid motion of arc through the de-ion structure holds down the arc temperature. Each of the short arcs recovers a strength of several hundred volts. Thus by using a large number plates, a breaker may be constructed which can interrupt a circuit of considerable voltage.

In the refractory type, arc is mainly elongated and to provide large elongation, chute plates are so designed that arc has to move in a zig-zag path

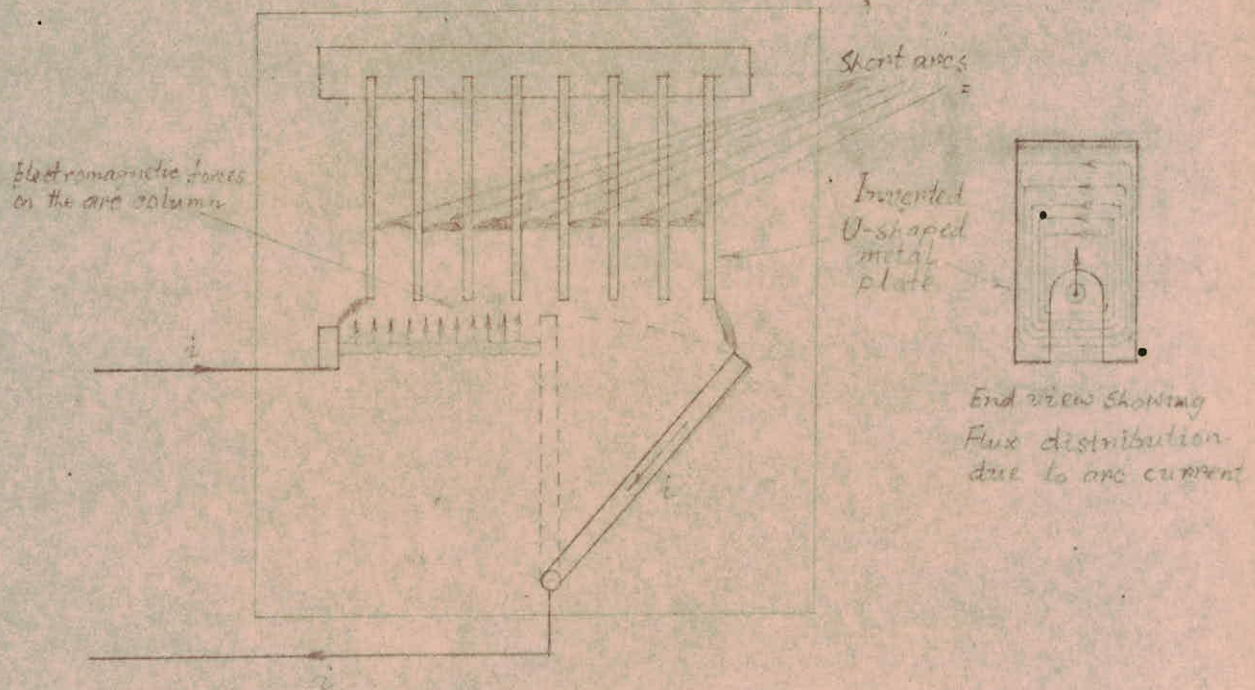


FIG 14. Principle of 'deion' arc-break circuit breaker.

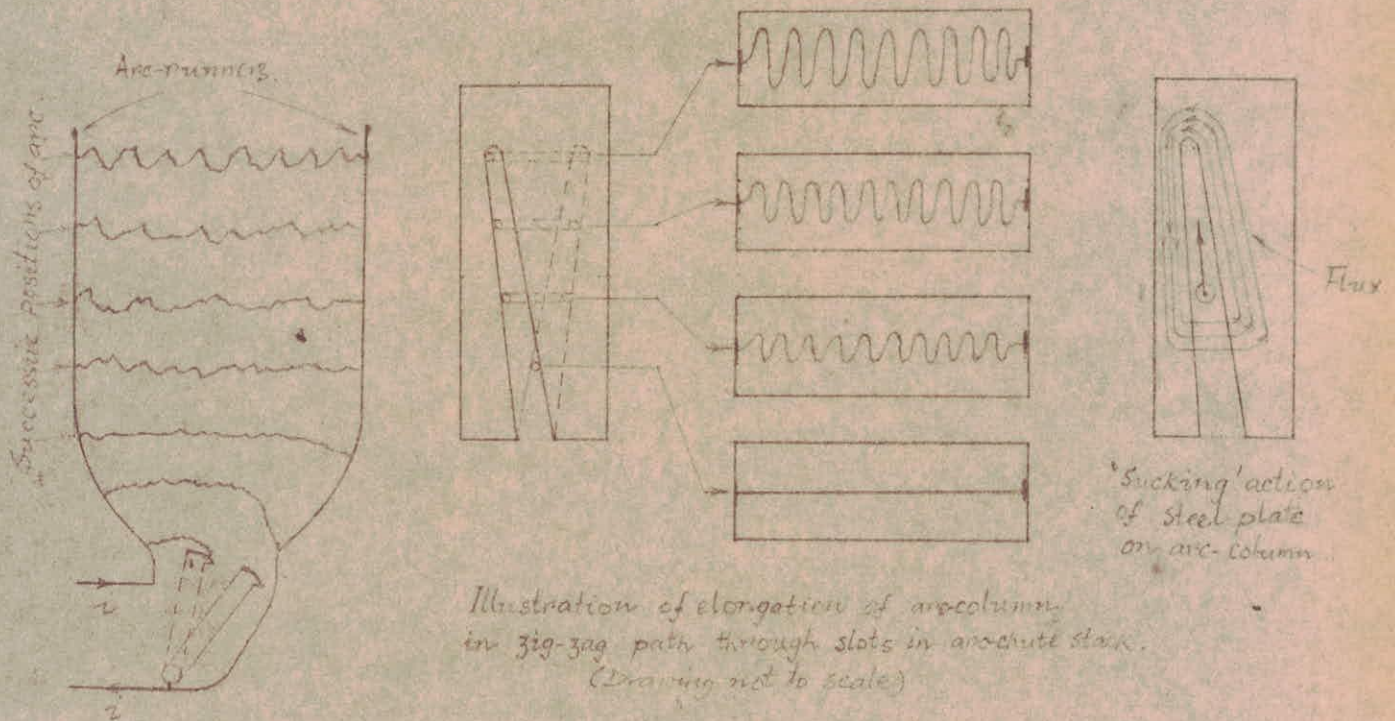


FIG 15. Principle of 'refractory' arc-chute breaker.

through them. In one typical arrangement¹⁹, the plates contain slots which are inclined alternatively left and right (Fig. 15). Initially the arc is transferred (by convection air-current) from arcing contacts to diverging arcing horns or arc-runners. The arc current loop so formed energizes the iron plates, embedded in the chute plates of insulation. The magnetic field established thereby 'sucks' the arc column into the chute plates. As the arc root travels vertically over the runners, the length of the zig-zag path through the plates increases. The large elongation increases the arc-resistance and the voltage dropped in the arc path reaches a value at which arc becomes unstable and is extinguished at the next current zero.

Chapter - 6

ARC CONTROL IN AIR

The principles and methods followed in certain types of interrupters to initiate decay in an arc discharge in air so as to extinguish it are outlined. These methods of arc control are analysed in a later section and the dominant factors which contribute to a fast gap recovery are separated. The experimental investigation which is based on these methods of arc control so as to evaluate their efficacy is given at the end.

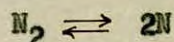
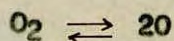
The principles usually, employed to cool and deionise the hot gases of an arc column in air and to produce instability of the arc are :-

- 1) Arc Cooling.
- 2) Arc Lengthening.

1) Arc Cooling : Arc loses heat by conduction phenomena in air. Air has a high thermal conductivity at arc temperature ($4000^{\circ}\text{C} - 6000^{\circ}\text{C}$) and consequently conduction loss to surrounding wall of cold gas is high. This conduction loss is increased because of the temperature gradient of several thousand degrees per millimeter, that exists in the region surrounding the arc core.

At the high temperature of arc, a portion of gas molecules may dissociate into

atomic state by absorbing energy from arc. Thus for air, the process -



or as suggested by V. Engel and Steenback the process -



may occur in equilibrium. The diffusion of the ions into cold gas boundary and their recombination outside results in liberation of the energy.

The deionisation process contracts the arc-core, and arc-resistance which is inversely proportional to d^2 (where d = diameter of arc-core) builds up to a considerable magnitude just before a current zero. For successful circuit interruption, the arc-resistance should increase to a value at which circuit voltage can not cause any current flow through it.

2) Arc Lengthening : When an arc column is stretched, the arc length is considerably greater than the distance between fully opened contacts. An increase in arc length is accompanied with contraction in diameter of arc-core. These two changes act cumulatively to build up the resistance of the arc-path. The current decreases and voltage gradient of positive column increases according to the formula $V_L = \frac{B}{i^n}$. The voltage gradient of the column is the ratio $\Delta V / \Delta x$, where ΔV is the change in voltage associated with a change in arc length Δx . With increase in column gradient and in arc-length, the positive column drop continuous to build up until total arc-drop reaches the circuit voltage. With

the total circuit voltage dropped in the arc-path, the arc becomes unstable and dies out.

6.3 METHODS OF ARC - CONTROL USED.

In view of the principles outlined in the last section, the two methods of arc control employed in the experiments, reported in this work were -

- 1) The arc -runner
and
- 2) The magnetic blow-out coil.

1) The arc-runner;

The arc-runners or the arcing-horns are the electrodes over which arc-column is made to travel by the buoyant forces²¹ acting on the column. Owing to high temperature of arc-column relative to surrounding medium, the column is subjected to strong convection currents in air. These convection currents causes the arc to rise from bottom through successive positions such as 2 to 5 (Fig. 16). The column, as it lengthens, moves rapidly through cool surrounding gas, which aid surface deionisation and further increases the arc voltages. The anode and cathode spots tends to lag behind the main column because of cooling action of metal electrodes and the tendency of cathode root to cling to the point of high electron emission. The action of arc-runners is

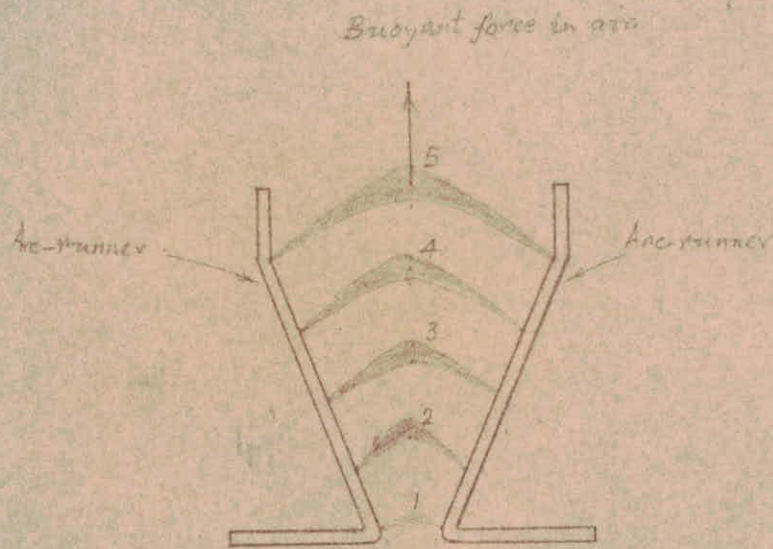
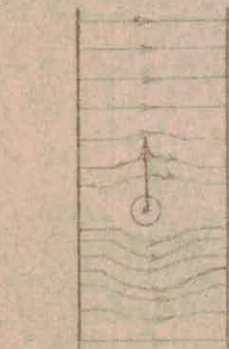
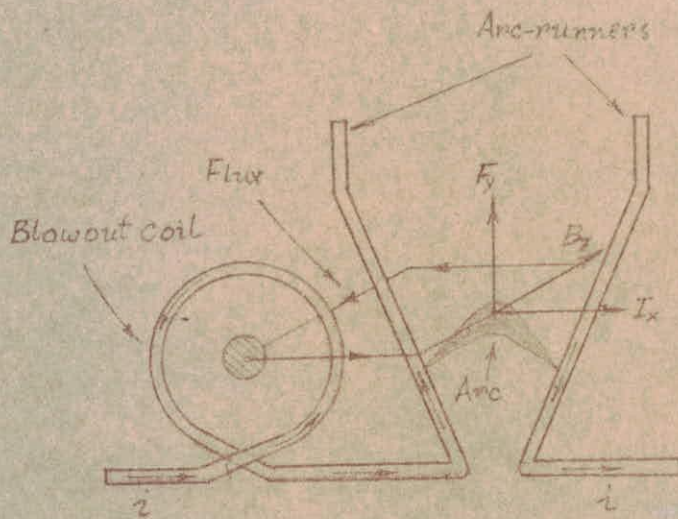


FIG. 16. The action of arc-runners



End view showing resultant flux

FIG. 17. The action of magnetic blow-out coil

inherently slow and high current arc unaided by any magnetic drive will tend to burn low and arc will not be extinguished. The angle of spacing of electrodes is important as with too wide an angle the arc will not rise up. The arc is forced up the electrodes by thermal effects in air and this type of clearance is called thermal clearance.

2) The Magnetic Blow-out coil:

If an extra drive is provided by the application of transverse magnetic field on arc-space, the arc-column is subjected to rapid motion through coil air. Deionisation of arc-space is much faster because of increased conduction-convection losses to gas boundary. The arc-core contracts as arc-column lengthens and arc resistance builds up at a faster rate. The arc voltage increases rapidly to circuit voltage and current dies out.

The magnetic blow-out coils function by means of the magnetic field established by the current that is to be interrupted. The coil is automatically switched into the circuit only during the period of arcing and in this respect its action is similar to that of a series motor. The differential force on an arc-column of length dl , carrying a current i and subjected to a magnetic field of flux density B , is given by -

$$dF = Bi \, dl \, \sin \theta_{i-B}$$

where θ_{i-B} is the angle between i and B .

The force results in the direction of the advance of a right-handed screw if the current is pictured as rotated into the magnetic field. If $\theta_{i-B} = 90^\circ$, then -

$$dF = Bdl i$$

Since the magnetic field is produced by the current to be interrupted, we have for small currents -

$$\begin{aligned} \text{Force on the arc} &= \text{Flux density} \times \text{current} \\ B(i) \times i \\ i^2 \end{aligned}$$

At higher current if the magnetic circuit is saturated, the force on the arc will be more nearly proportional to the first power of current.

The action of blow-out coil is illustrated in Fig. 17. If the current is in x - direction and the magnetic field, in z - direction, then the force acts in y - direction perpendicular to the plane of i and B. Reversal of current coincides with the reversal of transverse magnetic field so that the motion is still upwards, and operation is effective with alternating currents. But the direction of winding is important ; the direction should be such as to produce an upward magnetic force always.

The rate and direction of arc movement is also dependent on another parameter i.e. the gas pressure. The direction of arc movement outlined above

is that given by Ampere's law. The Amperian or forward motion of arc occurs at atmospheric pressure, but at low pressure the arc moves in opposite or retrograde²² direction. As the experiment was carried out at atmospheric pressure, the arc was not subjected to any retrograde forces.

6.4 THEORETICAL CONSIDERATIONS ON EXTINCTION OF AN A.C. ARC IN AIR

The positive column of an arc has in most cases, a well defined boundary with a high temperature arc core. The surrounding gas only a few millimeters from the core is practically at ambient temperature. Because of high temperature gradient of the order of several thousand degrees per millimeter in the region immediately surrounding the arc core, energy dissipation from this part of the arc can be initiated so as to cause instability and consequent extinction of arc.

The heat loss from the high temperature arc core of a horizontal arc at atmospheric pressure (Fig. 18) to cold gas boundary is mainly due to conduction - convection²³ phenomena in air. Losses²⁴ due to radiation and diffusion of ions form a very small percentage of total loss. If at time $t = 0$ the arc column has a length x , then after a short interval of time dt , the length increases to $x + \Delta x$ while the column rises through a vertical distance Δy . The rate of heat flow into a laminar boundary layer of radius r and thickness dr in the interval dt , is -

$$\left(2\pi r dr c_p \Delta T \rho \right) (v) \left(x + \frac{\Delta x}{2} \right)$$

where v = average convection velocity from y to $y + y$
 c_p = specific heat at constant pressure
 ΔT = temperature at r above ambient temperature
 ρ = gas density

The electrical power input into the arc during the interval is

$$v_a i$$

where v_a = instantaneous arc voltage

i = instantaneous arc current

If v_a is assumed to be sensibly constant during the interval then the rate of heat input is -

$$\frac{1}{4.18} \times \frac{v_a^2}{r_o} = \frac{1}{4.18} \times \frac{v_a^2 \delta \pi r^2}{(x + \frac{\Delta x}{2})}$$

where r_o = instantaneous arc resistance

δ = instantaneous electrical conductivity

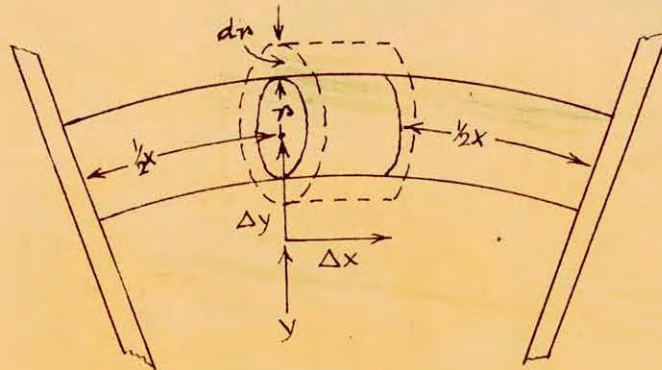


Fig. 18 Sketch of elementary arc column showing laminar boundary layer

The heat storage rate in the arc column during the interval is -

$$\left(\pi r^2 \cdot c_p \cdot T \cdot \rho \right) \left(\frac{\Delta x/2}{\Delta t} \right) = \left(\pi r^2 \cdot c_p \cdot T \cdot \rho \right) \left(\frac{v_a}{a} \right)$$

where T = average temperature of arc core

ρ_c = gas density in the arc core

$a = \frac{y}{x/2}$ = constant depending on the angle given to arc runners.

The energy balance equation in the positive column for the small interval of time.

Rate of Energy Input = Rate of Energy loss = Rate of Energy stored

$$\dot{W}_{\text{input}} - \dot{W}_{\text{loss}} = \dot{W}_{\text{stored}}$$

$$\frac{1}{4.18} \pi \frac{v_a^2 6 \pi r^2}{(x + \frac{\Delta x}{2})} - (2 \pi r dr c_p^{\Delta T} \rho)(v) \frac{(x + \frac{\Delta x}{2})}{2} = (\pi r^2 c_p^{\Delta T} \rho_c) \left(\frac{v}{a} \right)$$

With a large T , the product t is constant and heat loss does not depend on temperature. A contraction in diameter of arc core will cause large changes in the first and third term than in the second term. Therefore the significant variable in the second term is the length x and convection velocity v . The velocity v is not an independent variable but is caused by a buoyancy force of $g(\rho - \rho_c)$ per unit volume in free convection in air. A large increase in velocity leading to increased rate of heat loss results when an electromagnetic force of ' B ' per unit length acts in conjunction with buoyancy force.

The third term $\dot{W}_{\text{stored}}$ accounts for the fact that arc resistance can not momentarily rise to infinity at a current-zero, when there is no energy input into arc. Instead $\dot{W}_{\text{stored}}$ gives arc a finite value of resistance r_0 , which maintains flow of current with the appearance of voltage after a current zero.

The energy input to the arc is marked by zero-pause phenomena while energy loss from arc is a continuous process. If the loss-rate has increased substantially at a current-zero then immediately after the current zero when input watts is considerably less, the excess heat loss will come from heat stored in arc column. The process will continue during every half-cycle until the stored energy is exhausted. At this stage arc resistance will have built-up sufficiently to force out the current at the next current-zero.

The rate of heat loss will therefore, determine the duration of ~~max~~-arcing and from the above consideration we have that the loss-rate mainly depends on average velocity v and increase in length. Therefore

$$\frac{dW}{dt} = Kv dx = Kv dx$$

where W = heat loss from arc column

K = constant mainly dependent on gas density and temperature.

v = average convection velocity

dx = increase in length dependent on the angle given to arc-runners.

6.5 EXPERIMENTAL INVESTIGATION

It was proposed to perform the following experiments -

- 1) To record the time of recovery of horn-gap at different currents with the arc initiated at the smallest gap between the electrodes of the horn-gap.
- 2) To initiate the arc in presence of transverse magnetic field of a blow-out coil, energised by arc current and to record the new values of arc

durations at the above currents.

3) To vary the flux-density in the arc-space with the circuit adjusted for a fixed short-circuit circuit-current and to record arc duration at each value of flux density.

Arc durations were to be evaluated from oscillographic records of arc voltage and current. The power factor of the circuit was to be fixed at a low value and short-circuit was to be made at full circuit voltage of 400-volts. In view of the possibility of scatter of data, a large number of experiments were proposed to be performed at each stage for statistical study.

Chapter - 7

EXPERIMENTAL METHODS AND APPARATUS

This section deals with the experimental set-up made for performing the proposed experiments. The apparatus and the methods used are also described.

The function of the unit as the name suggests is to control and extinguish an arc. The unit comprises the arc-runners and the blow-out coil (Fig. 19). Arc-runners were made from polished copper sheets. Copper being a good heat-conducting material facilitates rapid movement of arc-roots. Runners were of $\frac{1}{8}$ " x $\frac{3}{4}$ " in cross-section and they together formed a V-shape upto a height of 3 inches, above which they were parallel upto a height of 1 inch. The fixed gap between the electrodes at the bottom was $\frac{1}{8}$ ", which increased to 1" at the top. The arc-runners were mounted on a bakelite plate covered with asbestos sheet.

The blow-out coil had 110 turns of paper insulated flat copper wire, wound on a bakelite tube, with a soft iron core (1" in diameter) inside it. The coil was mounted on the left-hand side of the runners and the winding direction being anticlock wise from the front. When magnetic field was to be

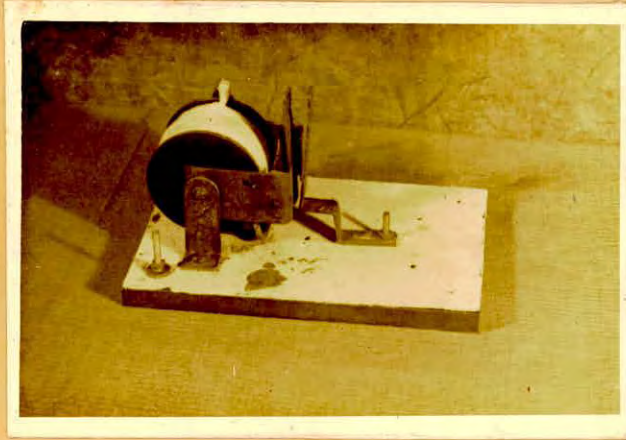


Fig 19 (a) Arc-control unit

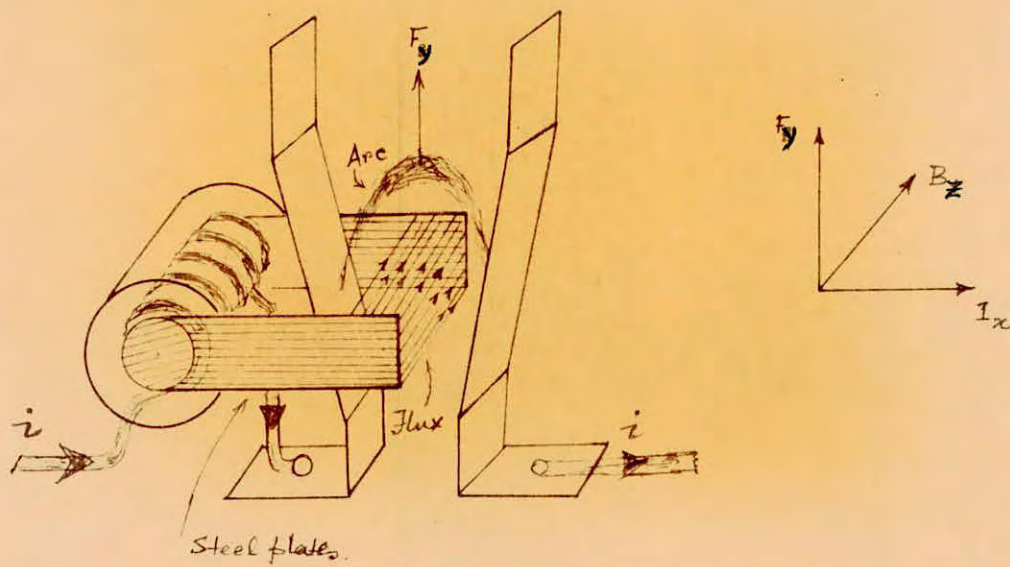


Fig 19 (b) Sketch illustrating the function of arc-control unit

applied in the arc-space, the coil was connected in series with the arc-runners. To increase the flux density in the arc-space, the reluctance of the magnetic circuit was decreased by fixing two 1/16" mild steel plates (4" x 2") at the two ends of the core. This arrangement also facilitates variation of magnetic field in arc-space by simply changing the pair of steel plates with another pair of different size.

7.3 TEST CIRCUIT

A view of the experimental set-up is shown in Fig.1. The schematic diagram of the experimental set-up is given in Fig.20 in which the test circuit is indicated by thick line. The supply for the short circuit test was taken from 400- volt A.C. Main through a manually operated circuit-breaker on the switchboard in the Test Laboratory. This is a Westing house De-ion Air-break breaker, which has a rating of 100 A at 650 V.

The short-circuit was made through a Make-break Mechanism (Fig.20-21) which holds the circuit under short circuit for $\frac{1}{2}$ sec. so as to limit the disturbance on the mains supply and also to protect the arc-control unit from probable destruction. The mechanism comprises two Westinghouse De-ion Air-break breakers mounted side by side on a common board with the ' ON ' end of one turned

to the ' OFF ' end of the other. A steel rod with two welded steel ' arms ' is hinged on the board between the two breakers. Two adjustable metal pieces on the two arms form two ' grips ' for the operating handles of the breakers. With the operation of the steel rod, C.B.1 closed the circuit while C.B.2 opens the circuit. By adjusting the position of the ' grip ' on C.B.2, the latter is made to open the circuit $\frac{1}{2}$ sec. later, during which time the circuit remains energized. The operation of the mechanism was tested with the help of a pen recorder, which showed it maintains a circuit for 25 - 35 cycles.

Sectionalised reactors and resistances, as shown in Fig. 20, were provided for regulation of the magnitude and power factor of the test current.

The 40-volts supply obtained through a variac was used to adjust the value of impedance for a certain test current. If the ammeter on this circuit shows a current of 10 A when 40-volt is applied, then with the application of 400-volt, the test current will be 100 A. Obviously, the 40-volt supply is disconnected before the 400-V test voltage is applied.

7.4

MEASURING CIRCUIT.

The major items of equipments employed for measurements were a shunt, a voltage divider, a cathode ray oscilloscope, an oscilloscope camera and a search coil (Fig.20).

- 1) Shunt - 100 A, 50 mV.: The test current was passed through it and the voltage

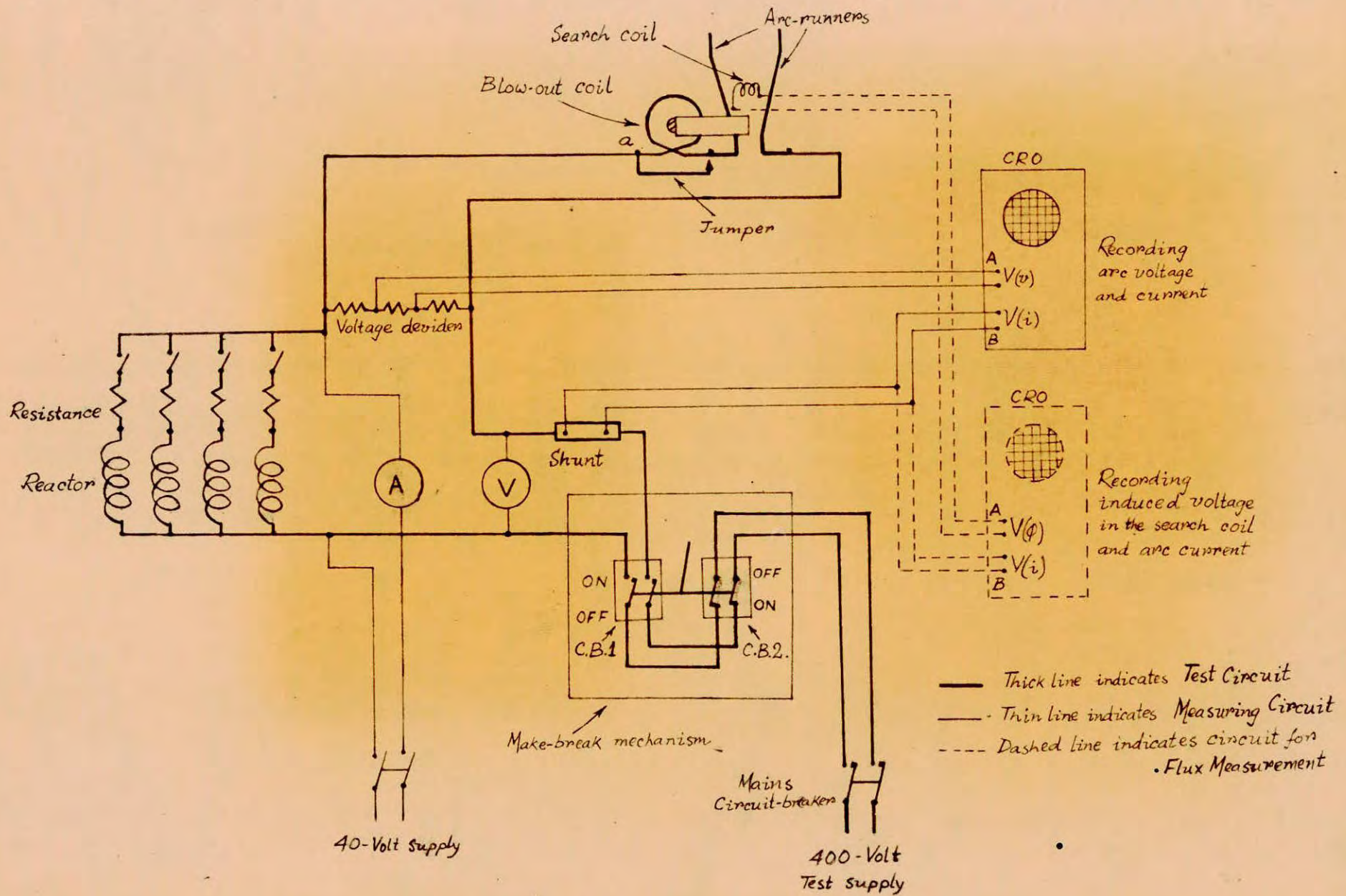


FIG. 20 Schematic diagram showing experimental set-up.

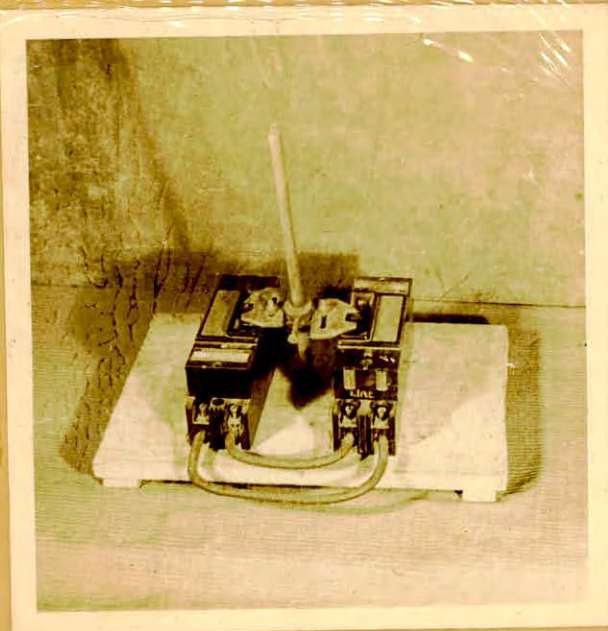


Fig 21 (a) Make-break mechanism

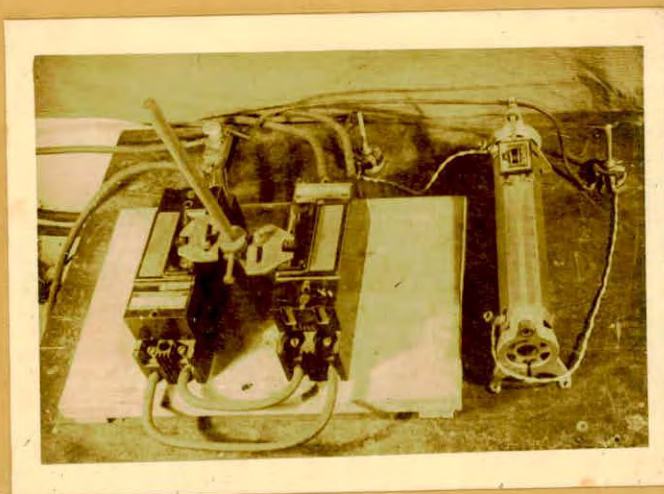


Fig 21 (b) Make-break mechanism, voltage divider and shunt

drop was applied to the deflector plates of the oscilloscope for obtaining the current trace.

2) Voltage-divider - The voltage-divider circuit ^{was} made of three resistors - 50 kilo-ohm, 50 kilo-ohm and 5 kilo-ohm. These high values were chosen, so that divider circuit may not distort the arc voltage appreciably. The voltage division-ratio is $r/(R + r)$, where $r = 5$ kilo-ohm and $R = 100$ kilo-ohm. The voltage applied to the deflector plates for obtaining the voltages trace was 19.1 volts.

3) Cathode ray oscilloscope - The experiment requires the simultaneous recording of two quantities arc voltage and arc current, for obtaining the duration of arcing. Also each experiment being of a short duration, flux density in arc-space was calculated from the oscillogram of the induced voltage in a search coil placed by the side of arc-runners. These were achieved by use of -

Tektronix - Type 545 A Oscilloscope along with
Type CA Dual- Trace Plug-in Unit.

4) Recording Camera - The traces on the screen of cathode ray oscilloscope were recorded on 35 m.m. negative film in -

Oscilloscope Camera
Type - A.C. 2/25
D.Shackman & Sons
London & Chesham.

5. Search coil:- The search coil, which was used for flux measurement had 500 turns of thin copper wire.

7.5 EXPERIMENTAL PROCEDURE.

The important steps followed in performing the experiments were as outlined below-

1) The series blow-out coil was connected in the circuit, when tests were made in presence of magnetic field in the arc space. The coil was disconnected at 'a' (Fig.20) and the arc-runners were directly connected to the line with the help of jumper, when tests were made without the application of magnetic field. The steel plates on the blow-out coil was turned back when the coil was not in use.

2) The impedance of the reactor bank was adjusted with the help of 40-volt supply to give desired short-circuit current when 400-volt test supply was applied. Before applying the test voltage, the 40-volt supply was disconnected.

3) The fixed gap at the bottom of arc-runners was shorted with fuse wires, which initiated the arc when short-circuit was made.

4) The terminals from voltage divider circuit was connected to channel A (Fig. 20). The arc voltage and the arc current being of varying amplitude a repetitive sweep in the oscilloscope produces a jumbled display of waveforms. The oscilloscope was, therefore, set for SINGLE SWEEP operation for

the first 10 or 25 cycles depending on the requirement of a particular test. Oscillographic records of the first 10 or 25 cycles following the application of test supply were obtained by proper selection of sweep speed.

5) The oscilloscope camera was focussed on the screen and the lens was left open. This completed all operations prior to application of short-circuit.

6) Next with the operation of make-break mechanism the circuit remained under short-circuited condition for about 0.7 sec. The appearance of voltage on channel 4, triggered the time-base into operation and arc voltage and arc current traces were recorded on film. The film was then advanced by one frame for the next test. Oscillograms of part I and 2 of the experimental investigation (sec. 6.5) were obtained by repeating the above procedure.

7) For part 3 of the experimental investigation, the flux density in arc space was varied by changing the pair of steel plates on the blow-out coil with another pair of different size. The steps 1 - 6 were then repeated.

7.6

FLUX MEASUREMENT EXPERIMENT

The flux measurement experiment was performed separately and the necessary changes in the test circuit (Fig. 20) is shown by dashed line - channel A of the oscilloscope was now connected to search coil, while channel

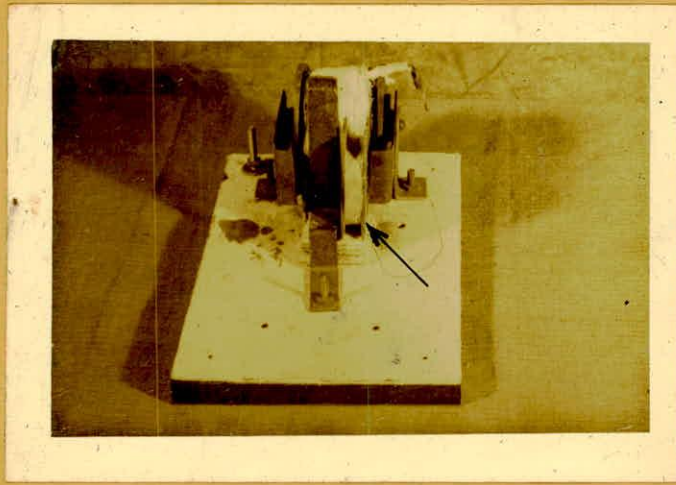


Fig 22 (a) Search coil placed in position for flux measurement

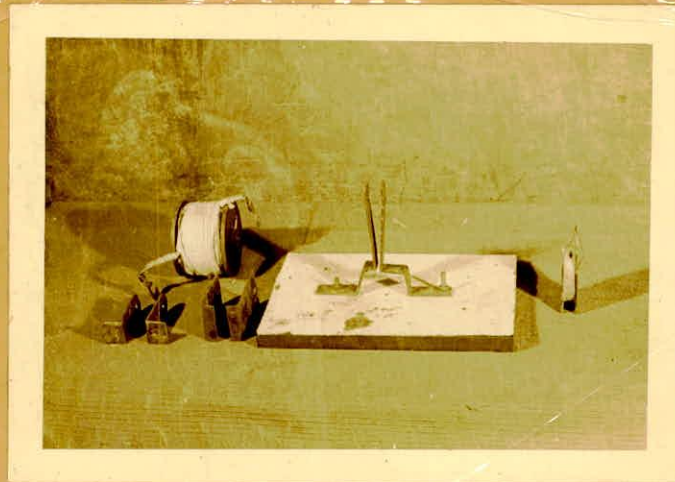


Fig 22 (b) Components of arc control unit and search coil shown on extreme right

B was connected to shunt as before. The search coil was placed close to arc-space with an asbestos steel in between it and the arc-runners as shown in Fig 22a. Tests were then carried ^{out} at different currents with the blow-out coil in the circuit. Oscillographic records of induced voltage in the search coil and corresponding arc currents were obtained by following steps 1-6 of sec.7.5. Induced voltage traces were then enlarged for graphical analysis. The flux-density in the arc-space was then evaluated in sec.8.4 of the next chapter from enlarged wave-forms shown in Fig. 31 - 33.

Chapter - 8

EXPERIMENTAL RESULTS

8.1 INTRODUCTION

All experimental observations were recorded by high speed oscillography since the duration of arcing lasts only a few cycles in many of the following experiments. Test data have been , therefore, collected from oscillographic records. The circuit conditions were kept constant, as far as practicable, but the duration of arcing depends on a number of factors, some of which are not easily controllable (See discussion). Consequently time taken by the arc-control unit to clear an arc were reproducible within a certain range of variation. A series of experiments were therefore performed at each stage to evaluate the overall behaviour by statistical study .

8.2 LIST OF OSCILLOGRAMS

a) The first set of experiments was performed in the absence of magnetic field. Each of the following oscillograms has a first 25-cycle representation. Abbreviation N/F indicates No Field i.e. blow-out coil was not used . Three typical oscillograms from this set is shown in Fig. 23.

Set I -

10	Oscillograms	- 30 Amp	N/F
10	"	- 50 Amp	N/F
10	"	- 76 Amp	N/F

b) The second set of experiments was performed in presence of magnetic field. Each of the following oscillograms has a first 10 cycle

representation. Abbreviation W/F indicates With Field i.e. Blow-out coil with 4" plates was used. Three typical oscillograms from this set is shown in Fig. 24.

Set II -

10 Oscillograms	-	30 Amp	W/F	coil & 4" plate used
10	"	-	50 Amp	W/F "
10	"	-	76 Amp	W/F "

c) The performance at 100 Amp was investigated in some details.

Without the application of magnetic field, 15 oscillograms were taken and another 15 oscillograms were taken with the application of magnetic field. Two typical oscillograms from set III are shown in Fig. 25.

Set III -

15 Oscillograms	(25 cycle representation)	-	100 Amp	-	N/F
15	"	(10 cycle	"	)	- 10 Amp - W/F
					i.e. coil with 4" plate used.

To study the effect of variation of magnetic field on the duration of arcing of an 100A arc a further set of oscillograms was taken -

Set IV -

10 Oscillograms	(10 cycle representation)	-	100A -W/F,	coil
				with 2" plate used
10	"	(25 cycle representation)	-	100A -W/F, only
				coil used.

List of oscillograms of induced voltage traces in seach coil for flux measurement is given in Sec. 8.4.

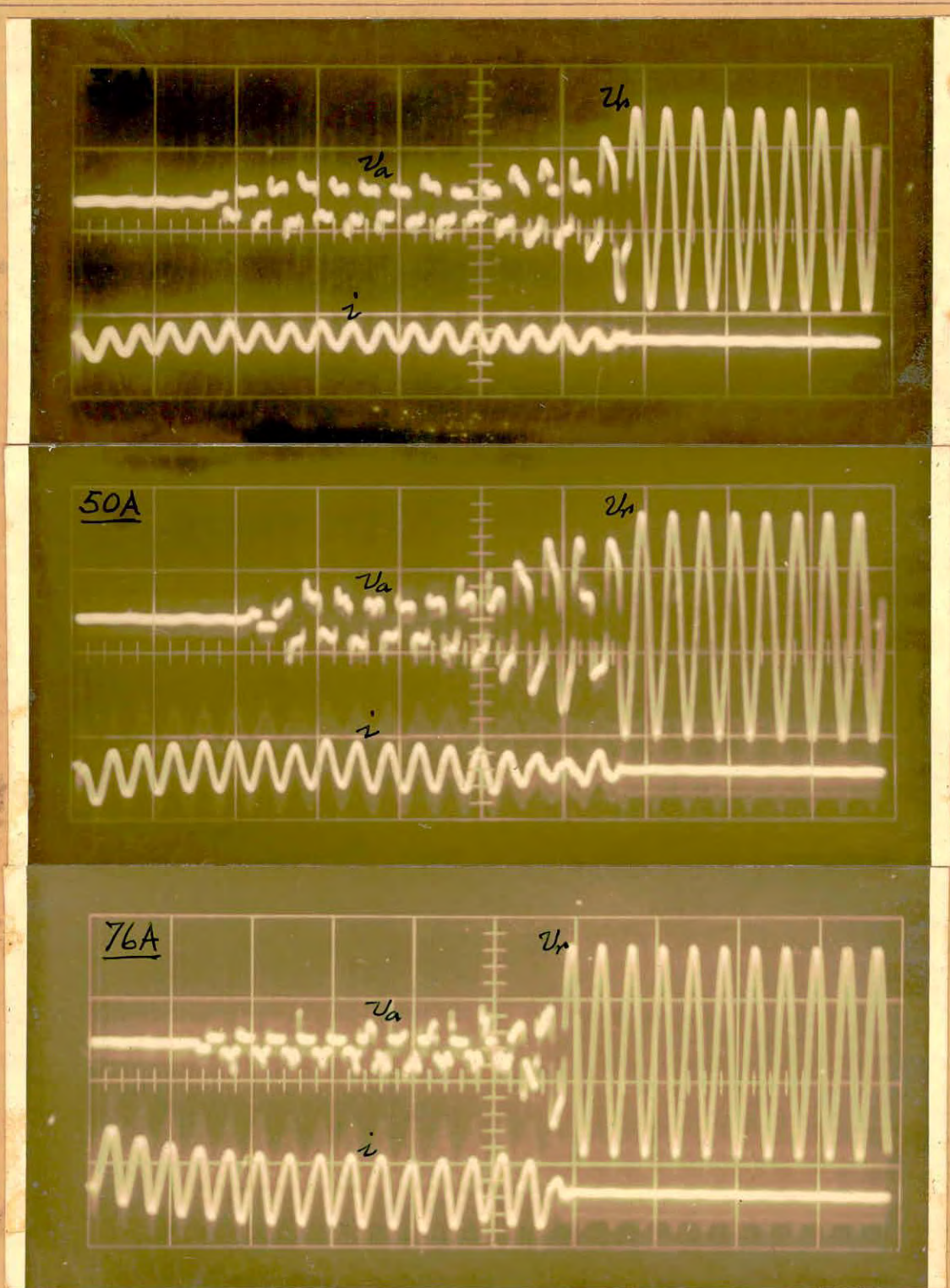


Fig 23. Typical oscillograms from Set I showing arc duration in absence of magnetic field- 25 cycle representations

v_a = arc voltage v_r = recovery voltage i = arc current

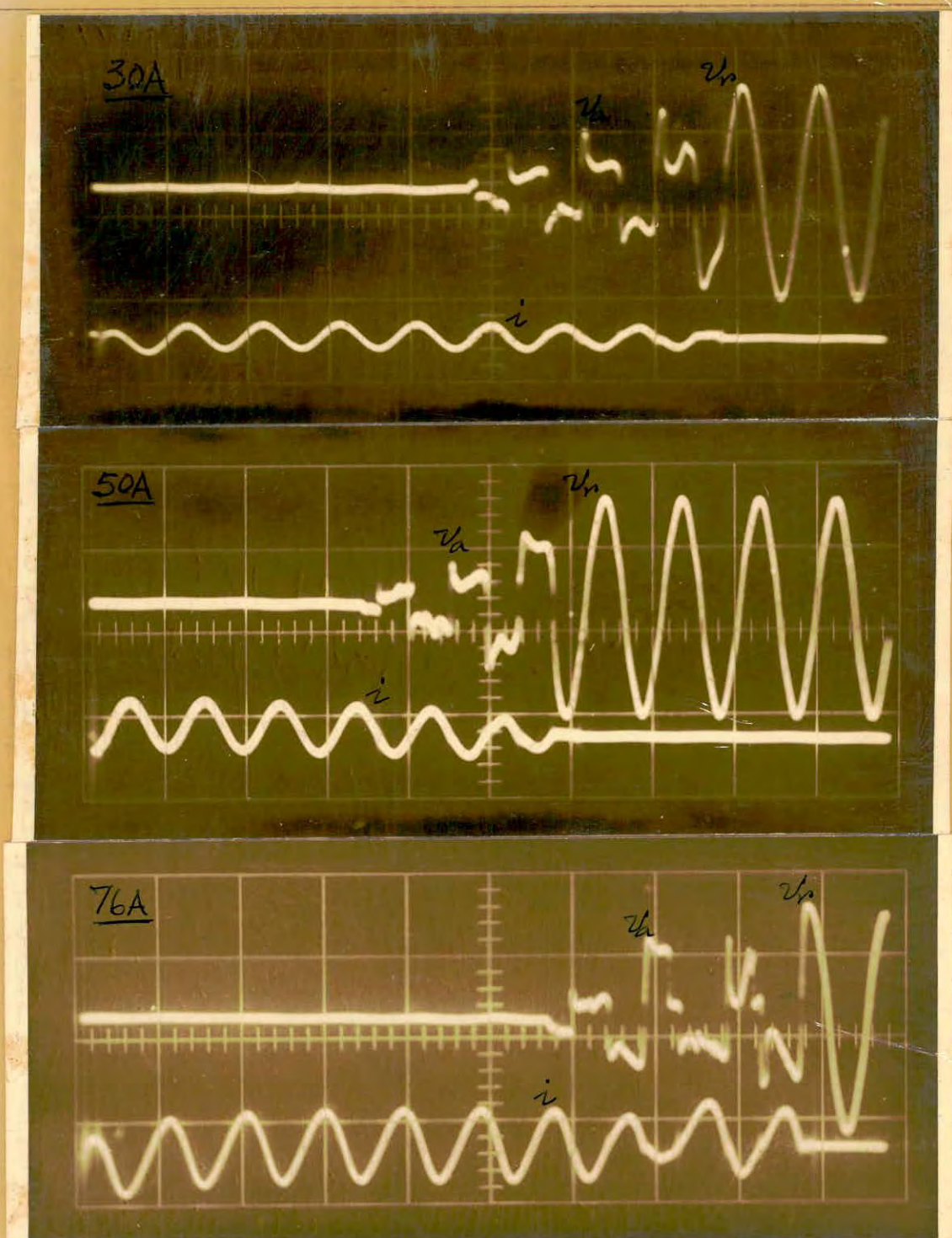
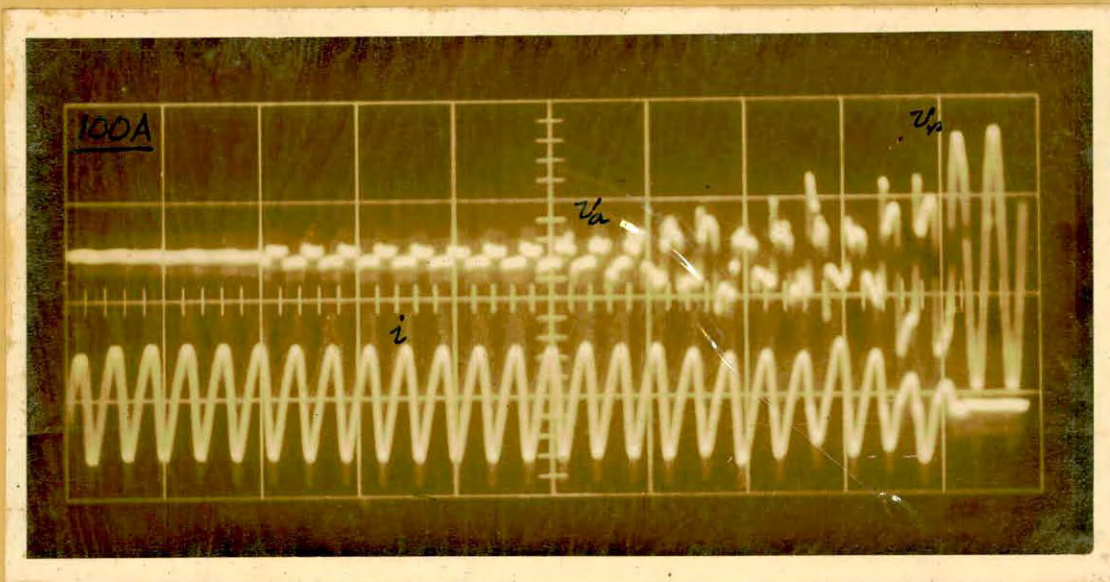
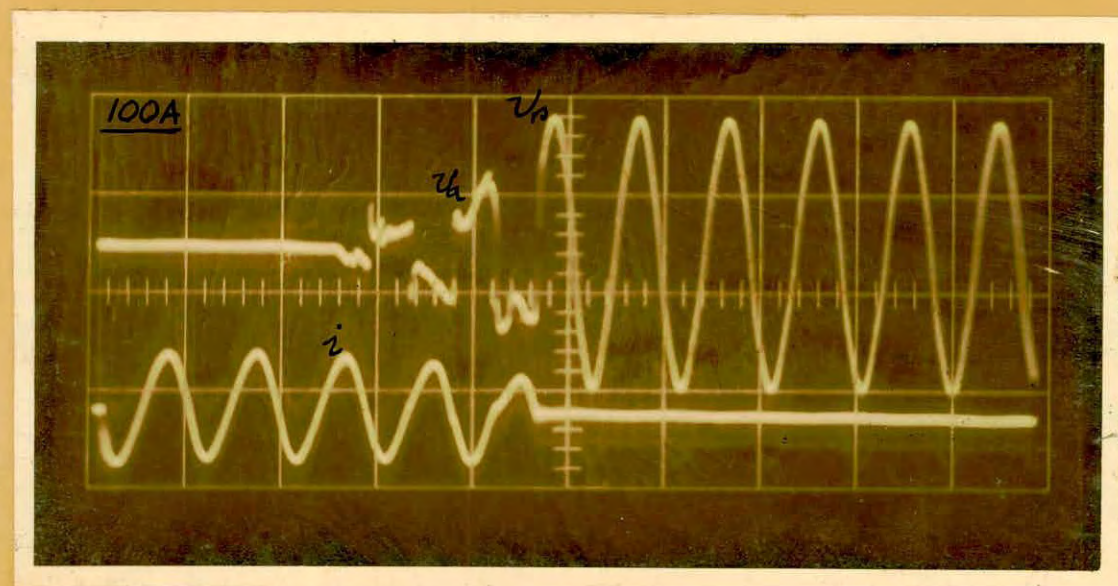


Fig 24. Typical oscillograms from Set II showing arc duration in presence of magnetic field - 10 cycle representations

v_a = arc voltage v_r = recovery voltage i = arc current



(a) In absence of magnetic field - 25 cycle representation



(b) In presence of applied magnetic field-10 cycle representation

Fig 25. Oscillograms from Set III showing arc durations

v_a = arc voltage v_r = recovery voltage i = arc current

8.3 EVALUATION OF OSCILLOGRAMS

The straight line portion of the voltage trace represent the time taken by fuse to blow out before arcing is initiated. The period of arcing till the appearance of normal circuit voltages i.e. arc duration were counted from each oscillogram and the values were tabulated. In many of the experiments without the application of magnetic field, arc was not interrupted within the recorded period of first 25 cycles. These values of the recorded periods of arcing are given in Tables and each of these data is marked with an asterisk.

Arc durations at 30A, 50A and 76A in the absence of magnetic field were obtained from oscillograms of set I. The results are given in Table - I, along with calculated values of mean arc durations and standard deviations from mean. These data are plotted in Histogram 1, (Fig. 26).

The changes in arc durations at 30A, 50A and 76A with the application of magnetic field are shown in Table 2 and Histogram 2 (Fig. 27), which were obtained from oscillograms of set II. The maximum flux densities in arc space given in Table 2, were taken from magnetisation curve (Fig. 30).

The change in arc duration with variation of magnetic field was studied in more detail at 100A. The results, which were obtained from oscillograms of sets III and IV are given in Tables 3 and 4. Histograms 3 & 4 (Fig. 28 and 29) correspond to these tables. The values of maximum flux densities are taken from Sec. 8.4.1 (b).

TABLE - 18.3.1 Arc Duration in Absence of Magnetic Field.Circuit Voltage: 400 - V ; Phase Angle = 87.5° ; Fixed Gap = $1/8"$

Arc current		30 A	50 A	76 A
		Arc Duration (cycles)		
Number of observa- tions.	1	14.00	* 22.5	12.0
	2	16.5	* 22.5	10.0
	3	* 17.0	12.5	10.0
	4	14.5	13.0	10.0
	5	16.0	10.0	10.0
	6	* 22.5	* 12.5	11.5
	7	13.5	12.5	20.5
	8	20.0	* 20.0	10.5
	9	14.5	11.0	11.5
	10	13.5	10.5	* 25.0
Mean Arc Duration		16.20 cycles = 324 milli sec.	13.70 cycles = 274 milli sec.	13.05 cycles = 263 milli sec.
¹ Standard Devia- tion from Mean .		3 cycles = 60 milli sec.	5.05 cycles = 105 milli sec.	5.38 cycles = 107 milli sec.

¹ See Appendix I for method of calculation.

* See paragraph one of Sec. 8.3

Histogram 1 : Frequency Distribution of Arc Duration
in absence of Magnetic Field

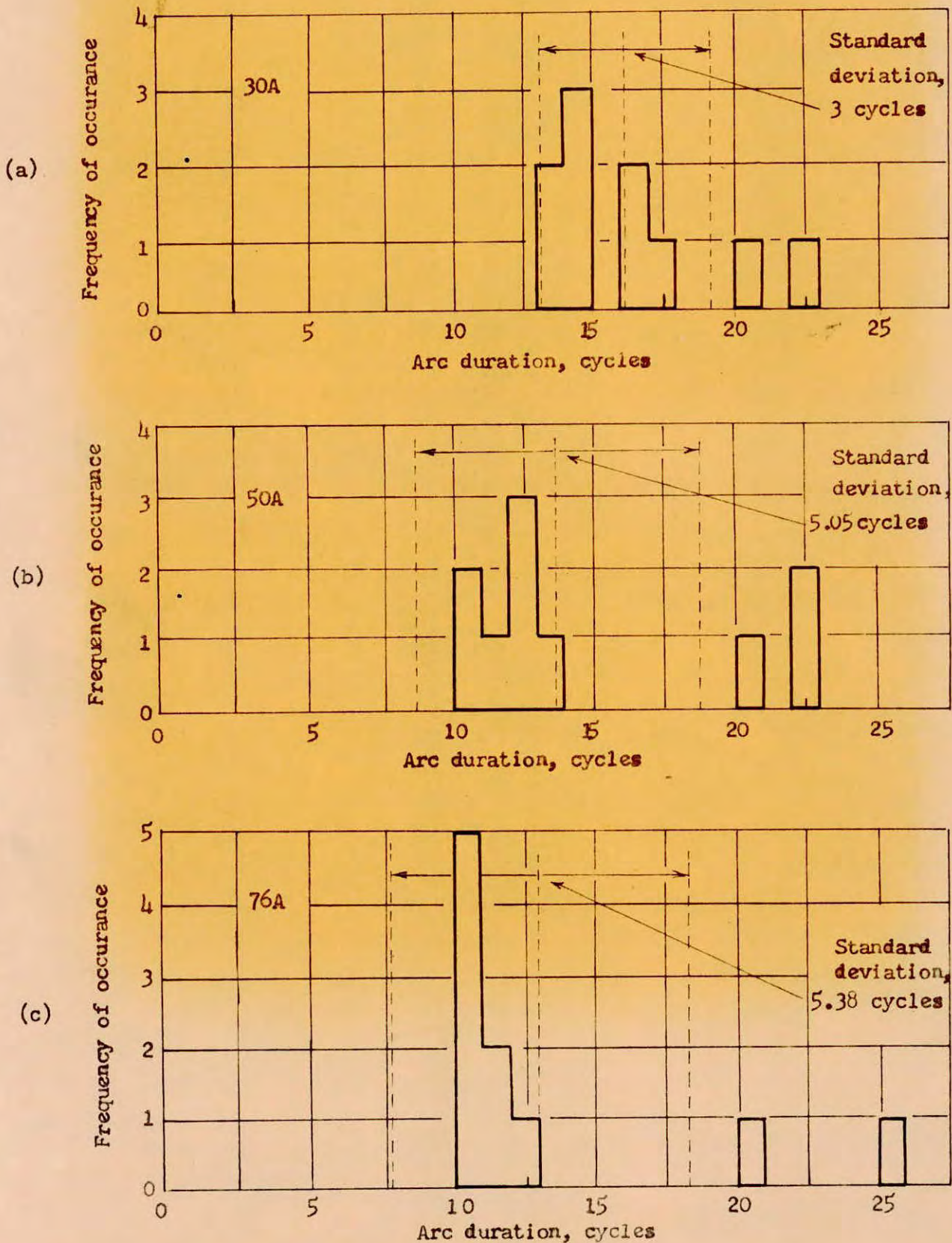


Fig.26 Histogram for data of Table 1

TABLE - 2

8.3.2 Arc Duration in Presence of Magnetic Field

(Blow-out coil with 4" plates is used)

Circuit Voltage = 400 V ; Phase Angle = 87.5° ; Fixed Gap = $1/8"$

Arc Current	30 A	50 A	76 A
Maxm. Flux Density in 1 Arc space	1.87×10^{-2} weber/m ²	2.35×10^{-2} weber/m ²	2.80×10^{-2} weber/m ²
Arc Duration (cycles)			
1	3.0	2.5	3.5
2	2.0	2.0	2.5
3	2.0	4.0	2.0
4	4.5	10.0	2.0
5	7.0	3.0	2.5
6	3.0	3.0	2.5
7	2.5	2.5	1.5
8	1.5	5.5	4.5
9	3.5	3.5	3.5
10	3.0	3.5	4.0
Mean Arc Duration	3.2 cycles = 64 milli sec.	2.95 cycles = 59 milli sec.	2.85 cycles = 57 milli sec.
Standard Deviation from Mean	1.58 cycles = 30.6 milli sec.	2.55 cycles = 51 milli sec.	0.975 cycles = 19.5 milli sec.

1 - Taken from Magnetisation Curve Fig. 30

Histogram 2 : Frequency Distribution of Arc Duration
in Presence of Magnetic Field

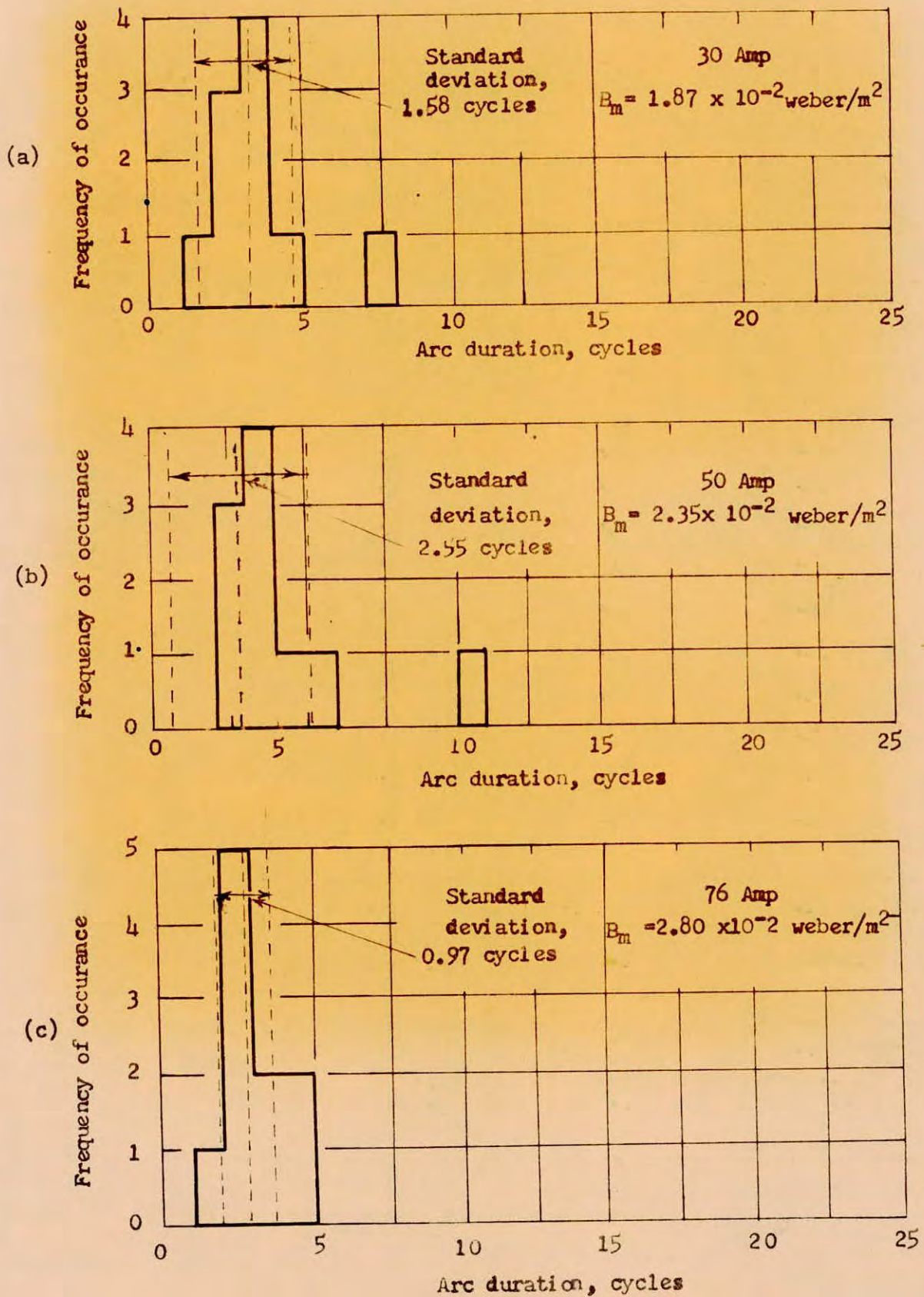


Fig. 27 Histogram for data of Table 2

TABLE - 3

8.3.3 Arc Duration with Variation of Magnetic Field(1)

Circuit Voltage= 400 V; Arc Current= 100A ;Phase Angle = 87.5° ; Fixed Gap=1/8"

Condition of the Magnetic circuit		Blow-out coil is disconnected.	Blow-out coil will 4" plates is used.
Maximum flux Density 1 in Arc Space.		nil	$B_m = 3.17 \times 10^{-2}$ weber/m ²
		Arc Duration (Cycles)	
Number of Observations	1	22.5	2.0
	2	* 22.5	2.0
	3	7.5	2.5
	4	* 23.5	3.5
	5	17.0	4.5
	6	8.5	2.5
	7	* 22.5	2.5
	8	* 22.5	2.0
	9	9.0	2.0
	10	10.0	3.0
	11	* 25.0	2.5
	12	* 15.0	3.0
	13	15.0	4.0
	14	22.5	2.0
	15	14.5	3.5
Mean Arc Duration		17.16 cycles = 343.2 milli sec.	2.7 cycles = 54 milli sec.
Standard Deviation from Mean		6.5 cycles = 130 milli sec.	0.82 cycles = 16.4 milli sec.

1 - From Magnetisation Curve, Fig. 30

* See paragraph one of Sec. 8.3

Histogram 3 : Frequency Distribution of Arc duration with Variation of Magnetic Field(1)

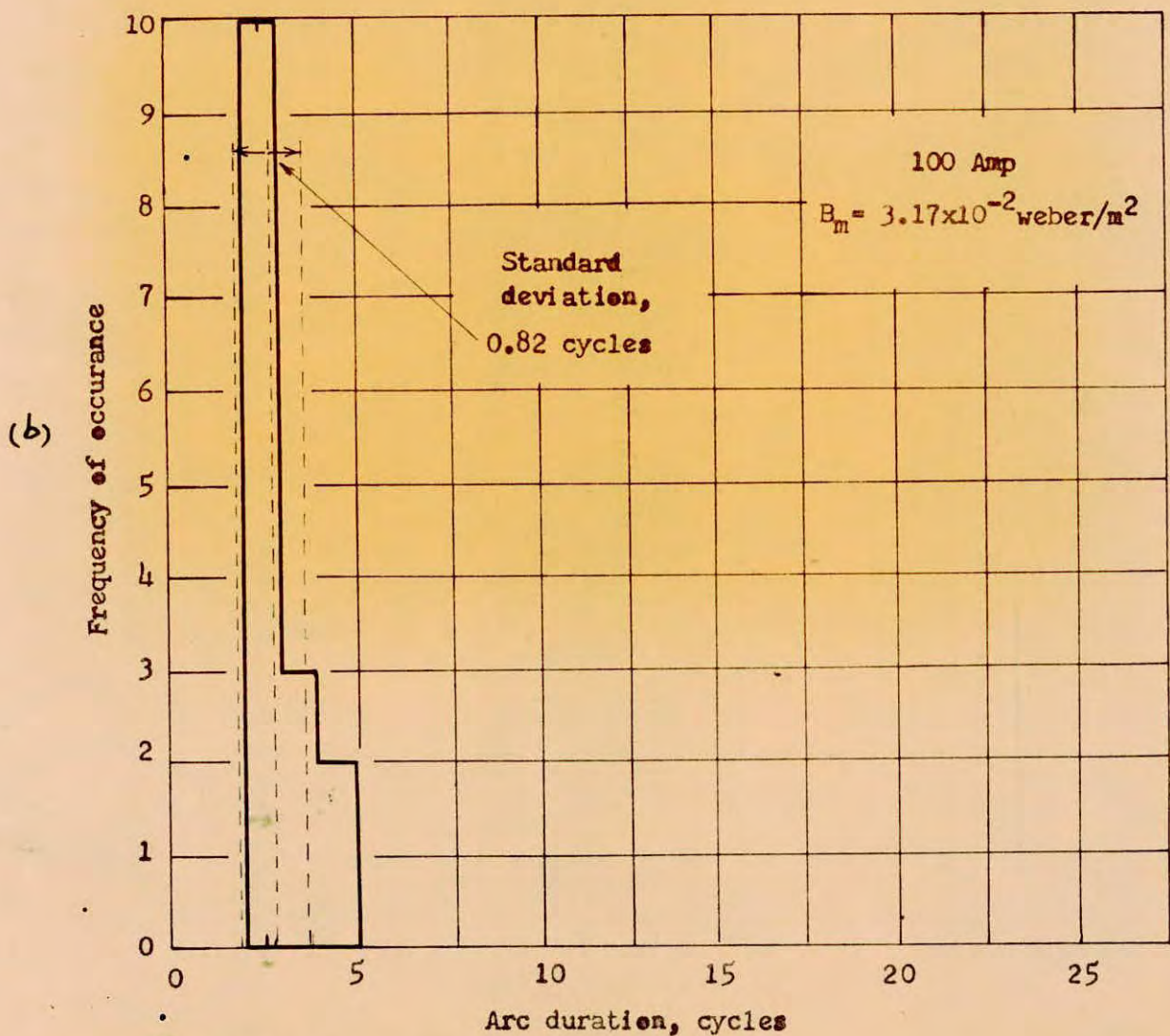
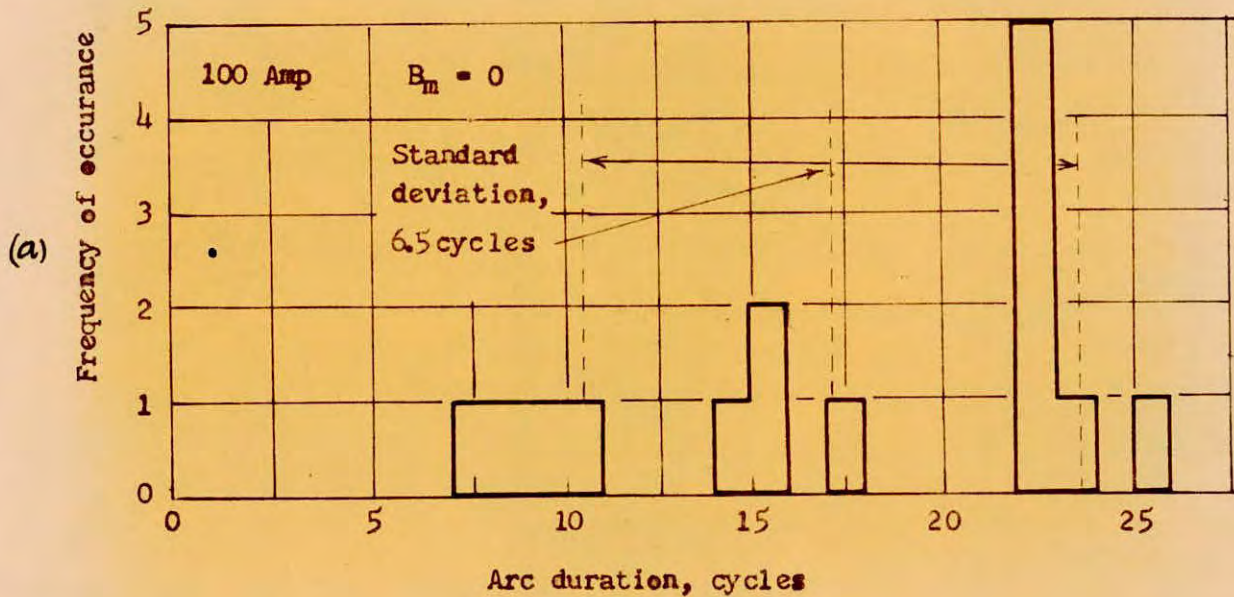


Fig.28 Histogram for data of Table 3

TABLE - 4

8.3.3 Arc Duration with Variation of Magnetic Field (2)

Circuit Voltage = 400 V; Arc Current = 160A; Phase Angle = 87.5°; Fixed Gap = 1/8"

Condition of the Magnetic circuit		Blow-out-coil with 2" plates is used.	Only Blow-out coil is used.
1	Maximum Flux Density in Arc space.	$B_m = 1.71 \times 10^{-2}$ weber/m ²	$B_m = 1.01 \times 10^{-2}$ weber/m ²
		Arc Duration (cycles)	
Number of Observations	1	3.5	14.5
	2	3.0	7.0
	3	6.0	7.0
	4	4.5	7.5
	5	2.0	14.5
	6	4.0	14.5
	7	7.5	3.0
	8	13.5	* 16.0
	9	1.0	6.5
	10	6.0	* 16.5
Mean Arc Duration		5.10 cycles or 102.0 milli sec.	10.65 cycles or 213.0 milli sec.
Standard Deviation from Mean		3.56 cycles or 71.2 milli sec.	4.87 cycles or 89.4 milli sec.

1 - From Sec. 8.4.1 (b)

* See paragraph one of Sec. 8.3

Histogram 4 : Frequency Distribution of Arc Duration with Variation of Magnetic Field (2)

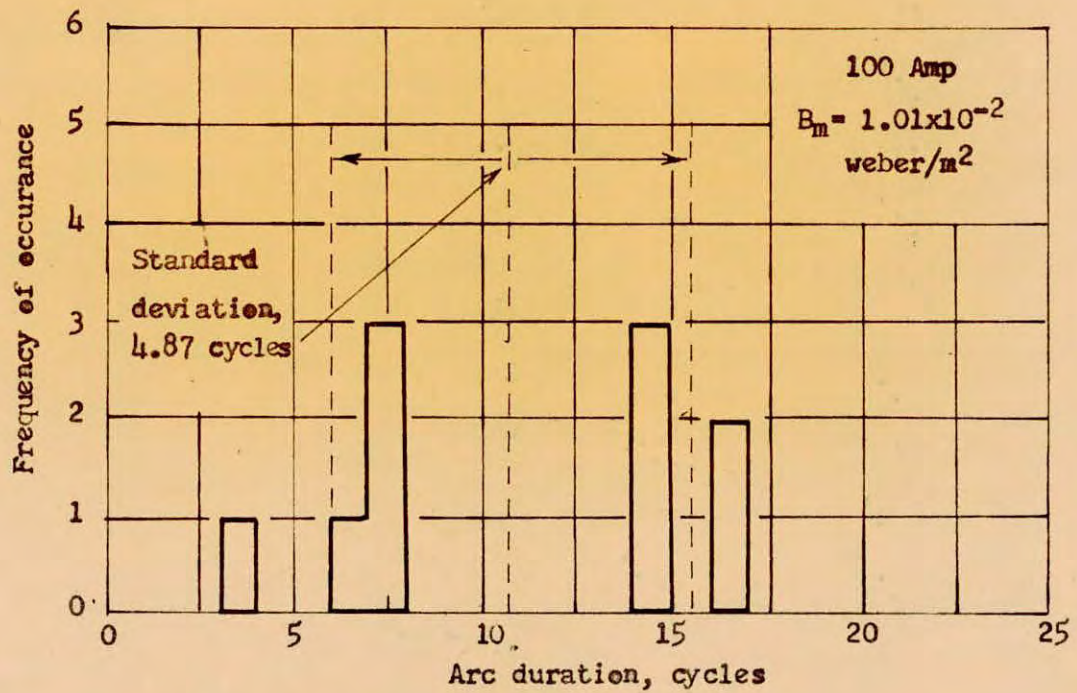
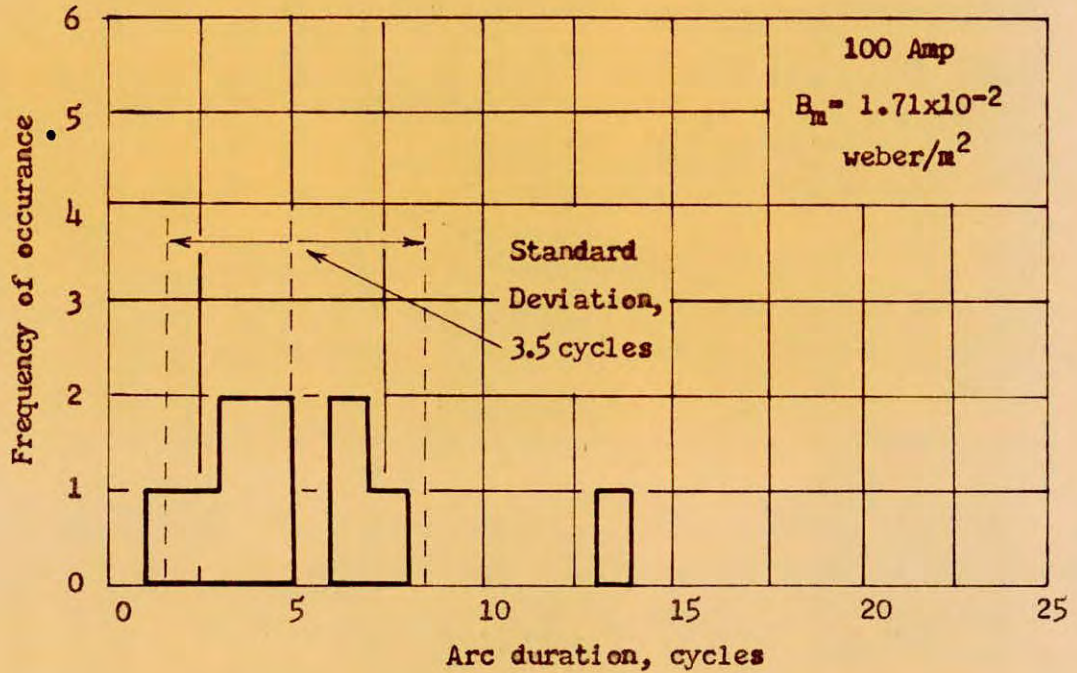


Fig.29 Histogram for data of Table 4

Y IN THE ARC SPACE

Flux density in the arc space was calculated from
induced voltage in the search coil. Oscillograms at the follow-
ing currents were taken using blow-out coil with 4" plates -
100A, 80A, 50A, 30A, 23A, and 17A.
Oscillograms were taken at 100A, of which one was taken using blow-out
coil with 4" plates and the other, using blow-out coil only. The enlarged
wave-forms of induced voltages are shown in Fig. 31 - 33 .

Because of non-sinusoidal wave-forms of induced voltages, due to
saturation in the magnetic circuit, the waves were analysed by step by step
calculation. (See Appendix II). Using finite interval of time of $t = 0.001$
Sec., maximum flux densities were calculated (in Tables 5 - 8), using the
following formulee -

$$\text{Change in Flux } \Delta\phi = \frac{e_a \Delta t}{N} \quad \text{weber}$$

Where e_a = Average value of the induced voltage
within the finite interval of time

N = Numbers of turns in the search coil

$$\text{Maximum Flux density } B = \frac{\sum_0^{T/2} \Delta\phi}{2 A} \quad \text{weber/m}^2$$

where A = Average of the outer and inner area
of the coil - (meter)²

T = Period of one cycle.

The search coil was drawn to scale on a graph paper the area of each small squares of which was 0.01 sq. in. The area was calculated by counting the number of small squares within the area. Parts of small squares, less than half of a full square within the area were neglected; while these greater than half were considered as full squares. The area of the search coil drawn to scale is shown in Fig. 33(b).

$$\text{Outer area} = 4.72 \text{ in.}^2$$

$$\text{Inner area} = 1.86 \text{ in.}^2$$

$$\text{Average area} = 3.29 \text{ in.}^2$$

$$= 21.4 \times 10^{-4} \text{ m}^2$$

The calculated values of the maximum flux densities in summarised form is given in Sec. 8.4.1(a) & (b). From values of Sec. 8.4.1(a) the magnetisation curve ($B_m - I$) was plotted. The magnetisation curve (Fig. 30) may be referred to for obtaining the flux densities at different currents when blow-out coil with 4" plates was used. Other necessary values of flux densities will be formed in the summary (Sec. 8.4.1) for the Tables 5 - 8.

It should be mentioned that the maximum flux densities correspond to symmetrical values of short-circuit currents. Induced voltage waves corresponding to high asymmetrical values or low values of arc currents were not used for evaluation of the flux densities.

8.4.1 Summary of Maximum Flux Densities.

a) The magnetisation curve was plotted from the following values of maximum flux densities obtained from Tables 5-7. Blow-out coil with 4" plates was used for each of the following measurements:

<u>From Table</u>	<u>Current</u>	<u>Maximum Flux Density</u>
5	100A	3.30×10^{-2} weber/m ²
5	80A	2.88×10^{-2} "
6	53A	2.41×10^{-2} "
6	30 A	1.80×10^{-2} "
7	23A	1.69×10^{-2} "
7	17 A	1.40×10^{-2} "

b) The following values of maximum flux densities obtained from Tables 5 & 8 correspond to investigation (Tables 3 & 4) on arc duration with variation of magnetic field.

<u>From Table</u>	<u>Change in Magnetic circuit</u>	<u>Current</u>	<u>Maxm. Flux Density</u>
5	Blow-out coil with 4" plates used	100A	3.17×10^{-2} weber/m ²
8	Blow-out coil with 2" plates used	100A	1.71×10^{-2} "
8	Blow-out coil with coil used	100A	1.01×10^{-2} "

c) The following values of maximum flux densities in arc space were taken from magnetisation curve (Fig.30) for investigation on arc duration in presence of magnetic field (Table 2).

$$\begin{aligned}
 30A - B &= 1.87 \times 10^{-2} \text{ weber/m}^2 \\
 50A - B &= 2.35 \times 10^{-2} \text{ " } \\
 76A - B &= 2.80 \times 10^{-2} \text{ " }
 \end{aligned}$$

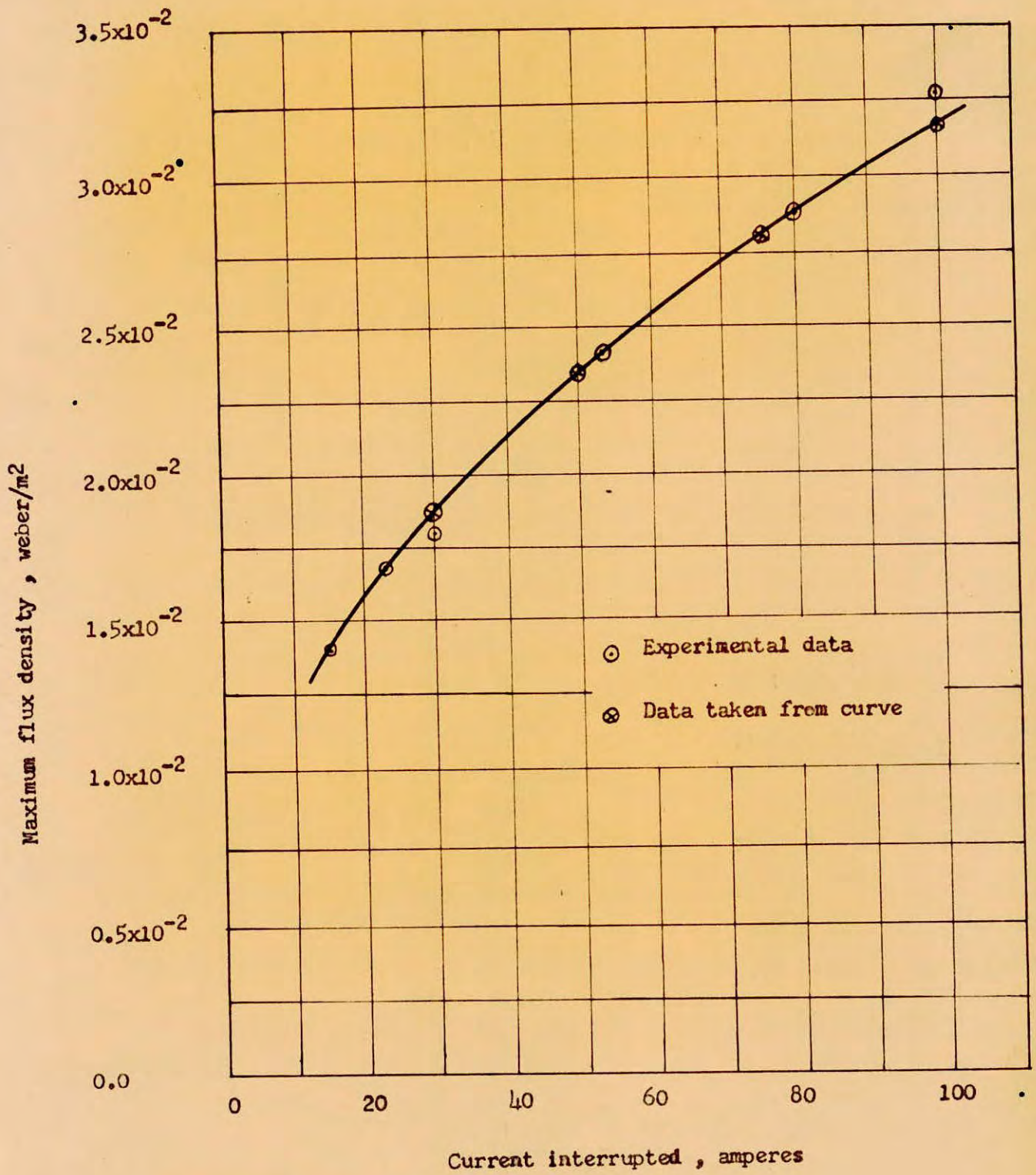


Fig. 30 Magnetisation curve : B_m - I curve

TABLE -5

I Cal. of Maximum flux Density : 100A - Arc : Fig.31 (a)

Period	t seconds	e volts	$e_a = \frac{e_o + e_t}{2}$ volts	$\Delta\phi = \frac{e_a \times \Delta t}{N}$ weber	$\sum \Delta\phi$ weber	$B_m = \frac{\sum \Delta\phi}{2A}$ weber/m ²
1	.0	0	0	0	0	N=500 turns A = 21.4x10 ⁻⁴ sq.m $B_m = \frac{140.66 \times 10^{-6}}{2 \times 21.4 \times 10^{-4}}$ = 3.28x10 ⁻² weber/m ²
2	.001	2	1.0	2x10 ⁻⁶	2x10 ⁻⁶	
3	.002	5.2	3.6	7.2x10 ⁻⁶	9.20x10 ⁻⁶	
4	.003	7.3	6.25	12.5x10 ⁻⁶	21.70x10 ⁻⁶	
5	.004	14.6	10.95	21.90x10 ⁻⁶	43.60x10 ⁻⁶	
6	.005	15.0	14.53	29.06x10 ⁻⁶	72.66x10 ⁻⁶	
7	.006	14.0	14.50	29.00x10 ⁻⁶	101.66x10 ⁻⁶	
8	.007	6.4	10.20	20.40x10 ⁻⁶	122.06x10 ⁻⁶	
9	.008	4.1	5.25	10.50x10 ⁻⁶	132.56x10 ⁻⁶	
10	.009	2.0	3.05	6.10x10 ⁻⁶	138.66x10 ⁻⁶	
11	.01	0.0	1.00	2.00x10 ⁻⁶	140.66x10 ⁻⁶	

II Cal. of Maximum Flux Density : 80A Arc : Fig. 31(b)

1	0	0	0	0	0	$B_m = \frac{123.54 \times 10^{-6}}{2 \times 21.4 \times 10^{-4}}$ = 2.88x10 ⁻² weber/m ²
2	.001	1.5	0.75	1.5x10 ⁻⁶	1.5x10 ⁻⁶	
3	.002	3.2	2.35	4.70x10 ⁻⁶	6.20x10 ⁻⁶	
4	.003	6.6	4.90	9.80x10 ⁻⁶	16.00x10 ⁻⁶	
5	.004	9.9	8.25	16.50x10 ⁻⁶	32.50x10 ⁻⁶	
6	.005	12.4	10.56	21.12x10 ⁻⁶	53.62x10 ⁻⁶	
7	.006	12.2	12.30	24.60x10 ⁻⁶	78.22x10 ⁻⁶	
8	.007	9.4	10.80	21.60x10 ⁻⁶	99.82x10 ⁻⁶	
9	.008	4.6	7.00	14.00x10 ⁻⁶	113.82x10 ⁻⁶	
10	.009	2.6	5.57	7.12x10 ⁻⁶	120.94x10 ⁻⁶	
11	.01	0.0	1.30	2.60x10 ⁻⁶	123.54x10 ⁻⁶	

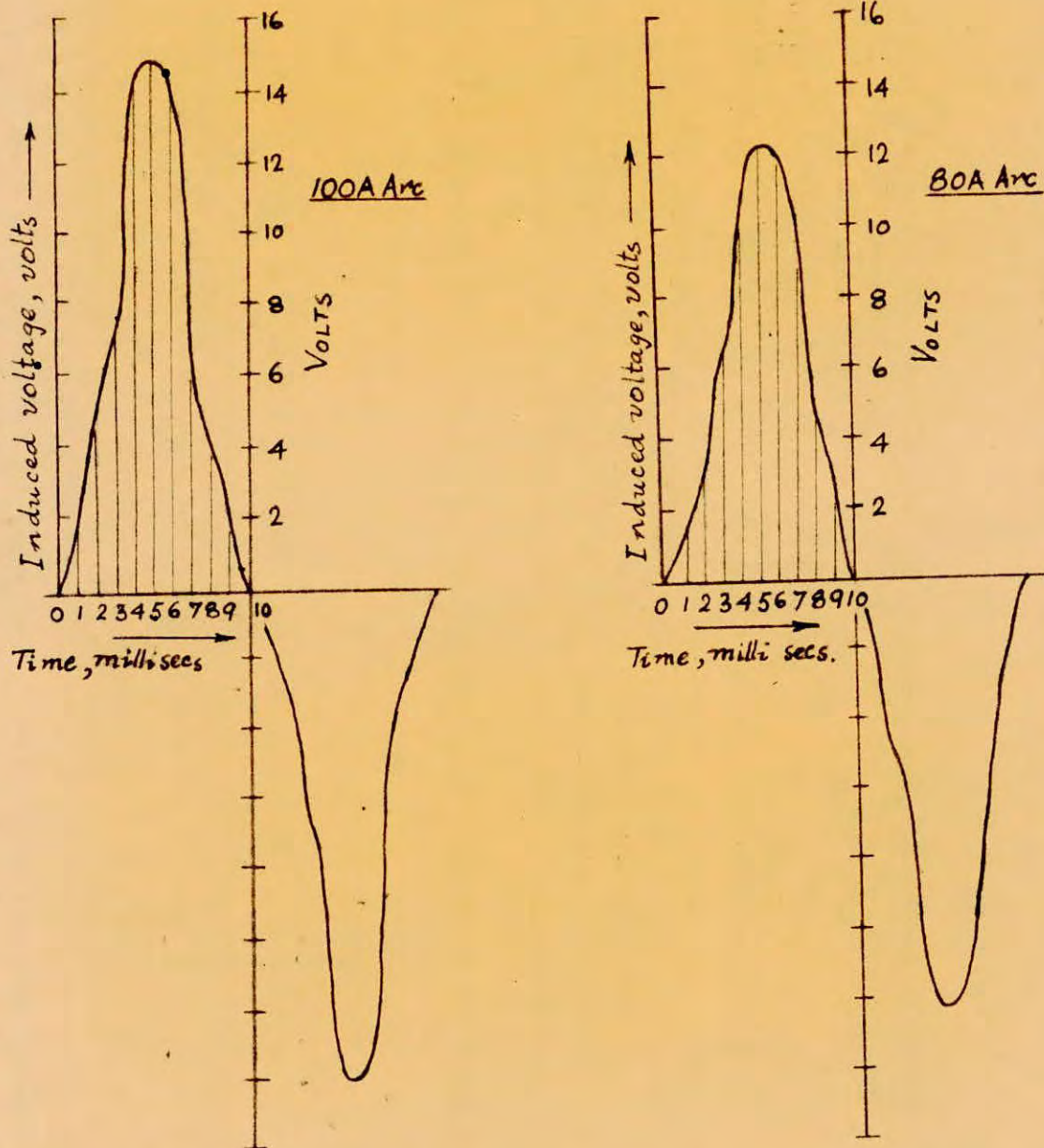


FIG. 31 Waveforms of induced voltage in search coil
when blow-out coil with 4" plates is used
— 100A & 80A arc.

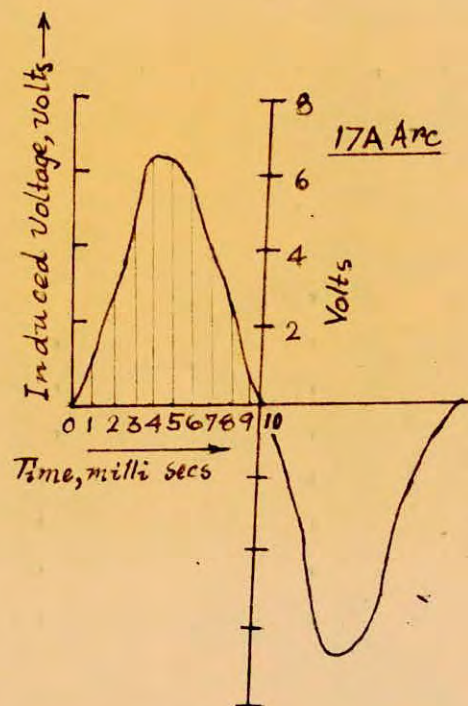
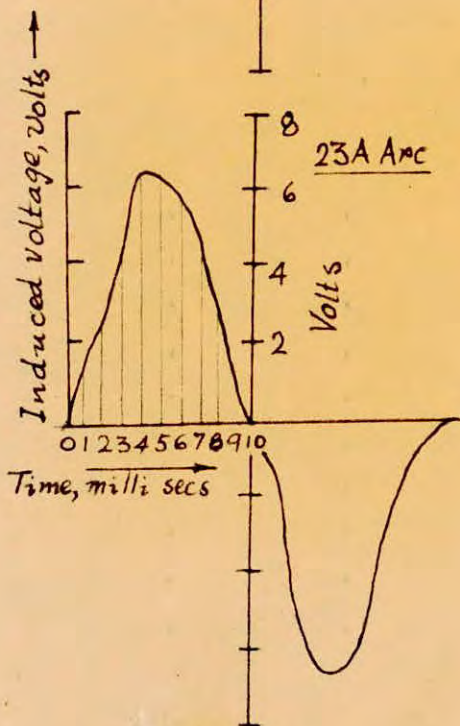
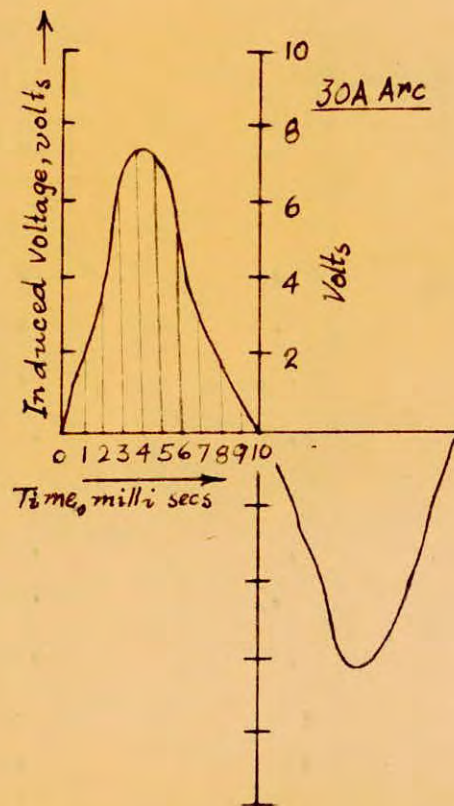
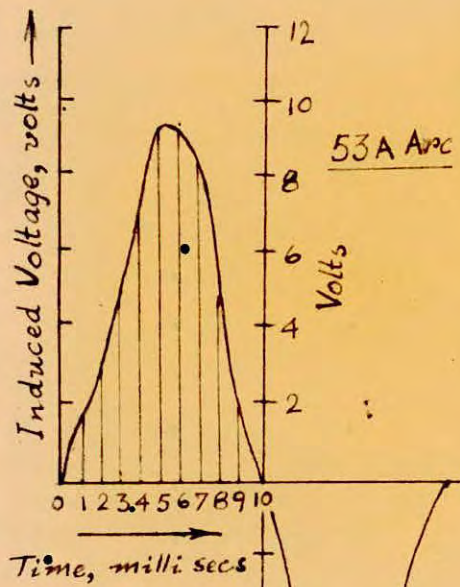
TABLE - 6

III Cal. of Maximum Flux Density : 53A Arc : Fig. 32(a)

Period	t seconds	e volts	$e_a = \frac{e_0 + e t}{2}$ volts	$\Delta \phi \frac{e_a \times \Delta t}{N}$ weber	$\sum \Delta \phi$ weber	$B_m = \frac{\sum \Delta \phi}{2A}$ weber/m ²
1	.0	0	0	0	0	
2	.001	1.7	0.85	1.70×10^{-6}	1.70×10^{-6}	N=500 turns A=21.4x10 ⁻⁴ sq.m
3	.002	3.0	2.35	4.70×10^{-6}	6.40×10^{-6}	
4	.003	4.8	3.90	7.80×10^{-6}	14.20×10^{-6}	$B_m = \frac{102.80 \times 10^{-6}}{2 \times 21.4 \times 10^{-4}}$ $= 2.41 \times 10^{-2}$ weber/m ²
5	.004	7.1	5.95	11.90×10^{-6}	26.10×10^{-6}	
6	.005	9.5	8.30	16.60×10^{-6}	42.70×10^{-6}	
7	.006	9.2	9.35	18.70×10^{-6}	63.40×10^{-6}	
8	.007	8.3	8.75	17.50×10^{-6}	8.90×10^{-6}	
9	.008	4.8	6.55	13.10×10^{-6}	94.00×10^{-6}	
10	.009	2.0	3.40	6.80×10^{-6}	100.80×10^{-6}	
11	.010	0.0	2.00	2.00×10^{-6}	102.80×10^{-6}	

IV Cal. of Maximum Flux Density : 30A Arc: Fig. 32(b)

1	0	0	0	0	0	
2	.001	2.1	1.05	2.10×10^{-6}	2.10×10^{-6}	
3	.002	3.5	2.80	4.90×10^{-6}	7.00×10^{-6}	
4	.003	6.3	4.90	9.80×10^{-6}	16.80×10^{-6}	
5	.004	7.5	6.95	13.90×10^{-6}	30.70×10^{-6}	$B_m = \frac{76.80 \times 10^{-6}}{2 \times 21.4 \times 10^{-4}}$ $= 1.80 \times 10^{-2}$ weber/m ²
6	.005	7.4	7.50	15.10×10^{-6}	45.80×10^{-6}	
7	0.006	5.8	6.60	13.20×10^{-6}	59.00×10^{-6}	
8	0.007	3.2	4.50	9.00×10^{-6}	68.00×10^{-6}	
9	.008	2.0	2.60	5.20×10^{-6}	73.20×10^{-6}	
10	.009	0.8	1.40	2.80×10^{-6}	76.00×10^{-6}	
11	.010	0.0	0.40	0.80×10^{-6}	76.80×10^{-6}	



• Fig 32 Wave-forms of induced voltage in search coil when blow-out coil with 4" plates is used
- 53A, 30A, 23A & 17A Arcs.

TABLE - 7

V Cal. of Maximum Flux Density : 23A Arc : Fig. 32 (c)

Period	t seconds	e volts	$e_a = \frac{e_0 + e_t}{2}$ volts	$\Delta\phi = \frac{e_a \Delta t}{N}$ weber	$\sum \Delta\phi$ weber	$B_m = \frac{\sum \Delta\phi}{2A}$ weber/m ²
1	0	0	0	0	0	
2	.001	1.5	0.75	1.50×10^{-6}	1.50×10^{-6}	N = 500 turns A = 21.4×10^{-4} sq.m
3	.002	2.8	2.15	4.30×10^{-6}	5.80×10^{-6}	
4	.003	4.7	3.75	7.50×10^{-6}	13.30×10^{-6}	
5	.004	6.8	5.75	11.50×10^{-6}	24.80×10^{-6}	
6	.005	6.7	6.75	13.50×10^{-6}	38.30×10^{-6}	$B_m = \frac{72.80 \times 10^{-6}}{2 \times 21.8 \times 10^{-4}}$ $= 1.69 \times 10^{-2}$ weber/m ²
7	.006	6.0	6.35	12.70×10^{-6}	50.00×10^{-6}	
8	.007	4.7	5.35	10.70×10^{-6}	60.70×10^{-6}	
9	.008	3.0	3.85	7.70×10^{-6}	68.40×10^{-6}	
10	.009	0.7	1.85	3.70×10^{-6}	72.10×10^{-6}	
11	.010	0.0	0.35	0.70×10^{-6}	72.80×10^{-6}	

VI Cal. of Maximum Flux Density: 17A Arc : Fig. 32(d)

1	0	0	0	0	0	
2	.001	1.1	0.55	1.10×10^{-6}	1.10×10^{-6}	
3	.002	2.8	1.95	3.90×10^{-6}	5.00×10^{-6}	
4	.003	5.0	3.80	7.60×10^{-6}	12.60×10^{-6}	$B_m = \frac{59.80 \times 10^{-6}}{2 \times 21.4 \times 10^{-4}}$ $= 1.4 \times 10^{-2}$ weber/m ²
5	.004	6.6	5.80	11.60×10^{-6}	24.20×10^{-6}	
6	.005	6.5	6.55	13.10×10^{-6}	36.30×10^{-6}	
7	.006	5.8	6.15	12.30×10^{-6}	39.60×10^{-6}	
8	.007	4.0	4.90	9.80×10^{-6}	49.40×10^{-6}	
9	.008	2.5	3.25	6.50×10^{-6}	55.90×10^{-6}	
10	.009	0.7	1.60	3.20×10^{-6}	59.10×10^{-6}	
11	.010	0.0	0.35	0.70×10^{-6}	59.80×10^{-6}	

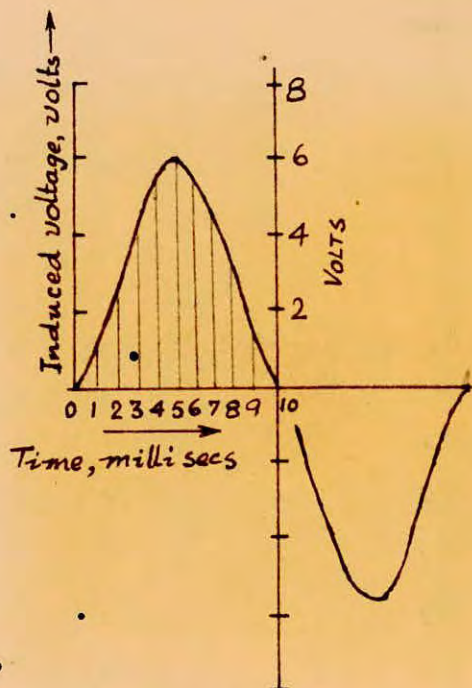
TABLE - 8

VII Cal. of Maximum Flux Density : 100A Arc : Fig. 33(a)

Period	t seconds	e volts	$e_a = \frac{e_0 + e_t}{2}$ volts	$\Delta\phi = \frac{e_a \times \Delta t}{N}$ weber	$\sum \Delta\phi$ weber	$B_m = \frac{\sum \Delta\phi}{2 A}$ weber/m ²
1	.0	0	0	0	0	
2	.001	1.2	0.60	1.20×10^{-6}	1.20×10^{-6}	N = 500 turns
3	.002	1.7	1.45	2.90×10^{-6}	4.10×10^{-6}	
4	.003	4.5	3.10	6.20×10^{-6}	10.30×10^{-6}	A = 21.4×10^{-4} sq.m
5	.004	6.1	5.30	10.60×10^{-6}	20.90×10^{-6}	
6	.005	6.6	6.35	12.70×10^{-6}	33.60×10^{-6}	$B_m = \frac{73.20 \times 10^{-6}}{2 \times 21.4 \times 10^{-4}}$
7	.006	5.9	6.25	12.50×10^{-6}	46.10×10^{-6}	
8	.007	5.1	5.50	11.00×10^{-6}	57.10×10^{-6}	= 1.71×10^{-2} weber/m ²
9	.008	3.6	4.35	8.70×10^{-6}	65.80×10^{-6}	
10	.009	1.9	2.75	5.50×10^{-6}	71.30×10^{-6}	
11	.010	0.0	0.95	1.90×10^{-6}	73.20×10^{-6}	

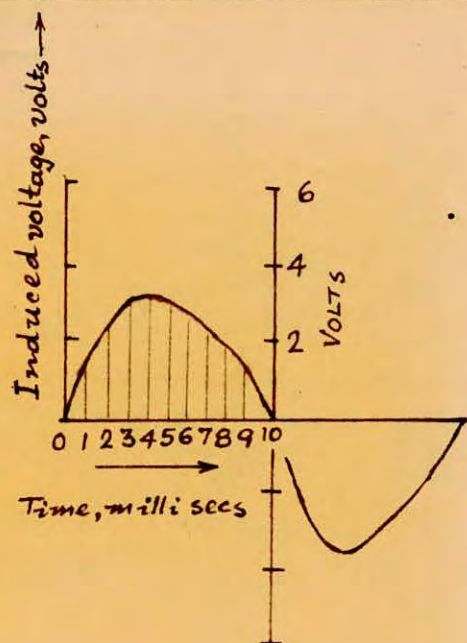
VIII Cal. of Maximum Flux Density : 100A Arc. Fig. 33(b)

1	0	0	0	0	0	
2	.001	1.40	0.70	1.40×10^{-6}	1.40×10^{-6}	
3	.002	2.40	1.90	3.80×10^{-6}	5.20×10^{-6}	
4	.003	3.10	2.75	5.50×10^{-6}	10.70×10^{-6}	$B_m = \frac{43.60 \times 10^{-6}}{2 \times 21.4 \times 10^{-4}}$
5	.004	3.4	3.25	6.50×10^{-6}	17.20×10^{-6}	
6	.005	3.2	3.30	6.60×10^{-6}	23.80×10^{-6}	= 1.01×10^{-2} weber/m ²
7	0.006	2.7	2.95	5.90×10^{-6}	29.70×10^{-6}	
8	.007	2.2	2.45	4.90×10^{-6}	34.60×10^{-6}	
9	.008	1.9	2.05	4.10×10^{-6}	38.70×10^{-6}	
10	.009	1.50	1.7	3.40×10^{-6}	42.10×10^{-6}	
11	.010	0.0	0.75	1.50×10^{-6}	43.60×10^{-6}	



100A Arc:

Blow-out coil with
2" plates used.



100 A Arc:

Only blow-out coil used.

Fig 33(a) Wave-forms of induced voltage in search coil

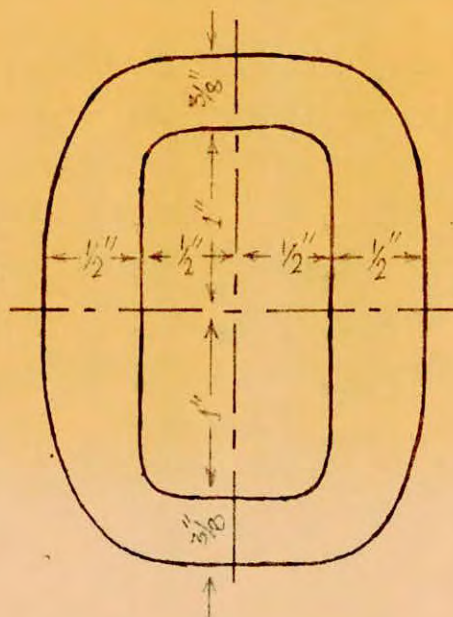


Fig 33(b) Area of search coil drawn to scale

8.5 INTEGRATED PHOTOGRAPHS OF ARC MOVEMENTS

The photographs obtained on a still camera gives only the integrated movement of the arc-column. But the use of a ' soot filter ' (glass plate very faintly gassed from the top of a candle flame) brought out many details viz. sites of high electron emission, gas cloud etc, which will not be apparent to an/undaid observer.

The photographs relate to 100A arcs initiated at the bottom of arc runners by fusing a wire. Fig. 34(a) show are movement in absence of any applied magnetic drive while Fig. 34(b) show the movements aided by applied magnetic drive. The photographs indicate that movement occurs by a stepping process of individual sites of electron emission, old sites dying out while current transfer take place to new site or sites. In the first case, are movement being only due to convection current in air the arc-column never rises to the top of arc runner. The arc velocity is considerably low, allowing the arc to burn at each site for a considerable period thus raising the arc temperature to several thousand degree centegrade. In the second case, arc column aided by magnetic drive rises quickly to the top of arc-runner. The arc velocity is high with the arc burning at a larger number of sites up the runners, resulting in faster deionisation of arc-core. Hot gases bearing the arc space form the gaseous cloud, which dissipate their heat into atmosphere.

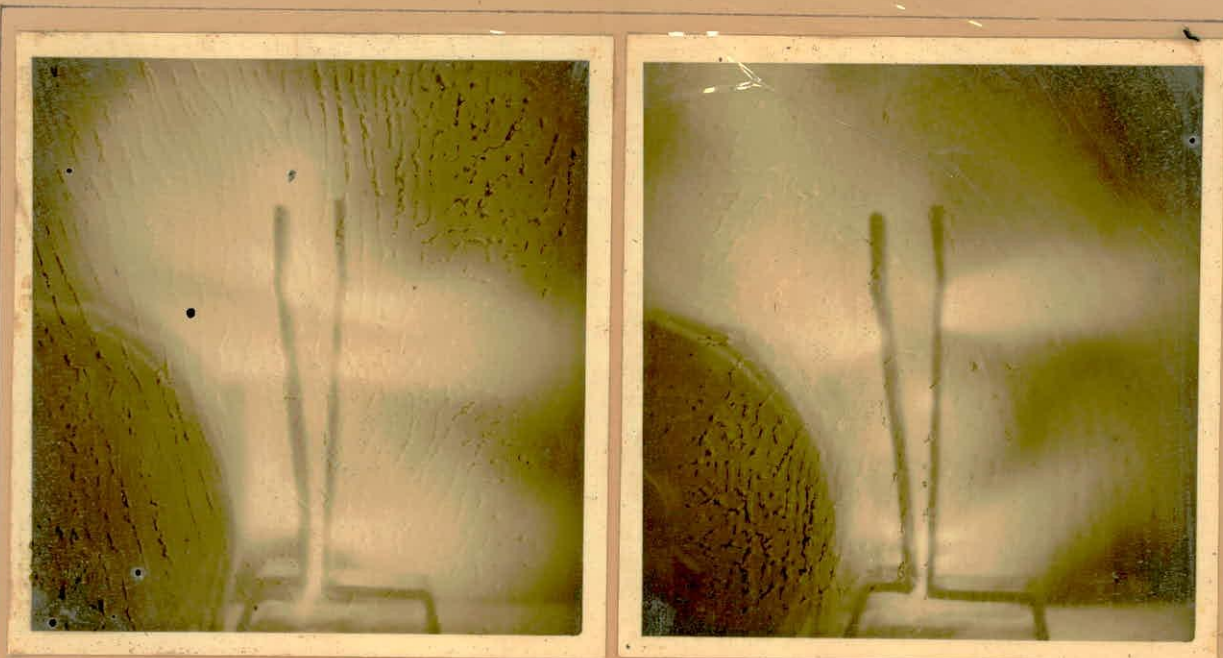


Fig 34(a) ' Integrated ' photographs of arc movements of 100A arcs in absence of applied magnetic field showing column never rises to the top

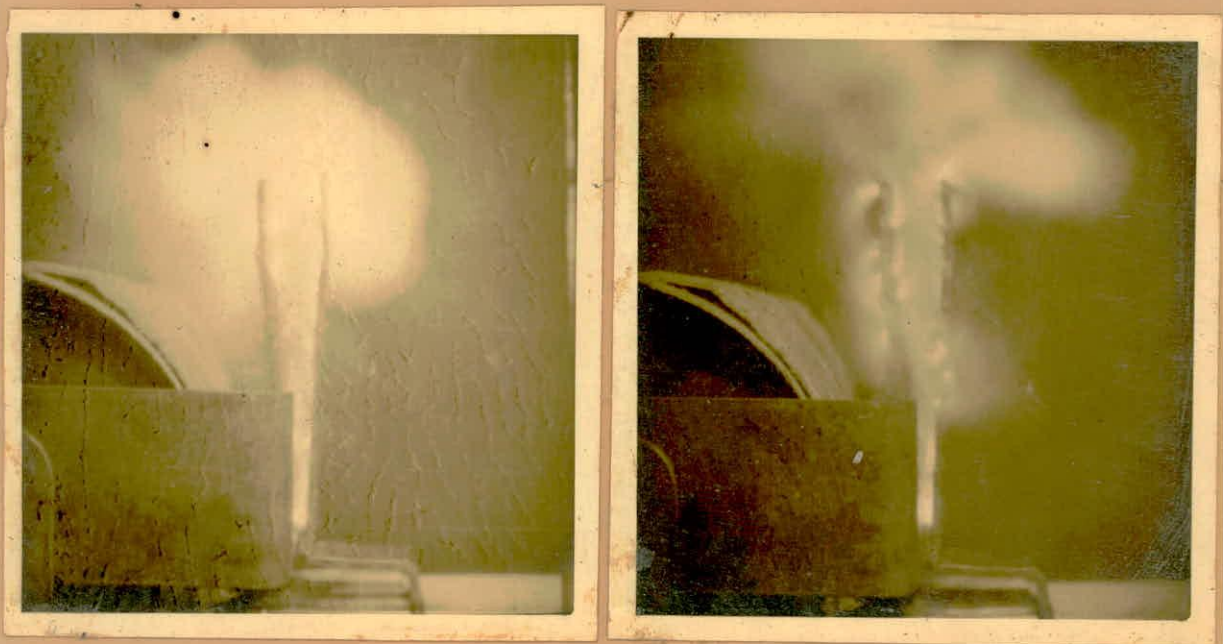


Fig 34 (b) ' Integrated ' photographs of arc movements of 100A arcs in presence of applied magnetic field

Chapter - 9

DISCUSSIONS OF RESULTS

9.1 REPEATABILITY OF RESULTS.

The circuit conditions viz. the voltage current, power factor and interelectrode spacing were kept constant for each series of experiments but it was observed that arc durations are only reproducible within a certain range of variation. Circuit impedance only fixes the symmetrical value of short circuit current while the asymmetrical value depends on the point of the wave at which the circuit is closed as will be seen from oscillograms under sec. 8.2. The varying asymmetrical values contributed in some degree to the variations.

Two other factors which are not easily controllable but which influence the arc velocity considerably are (1) the surface roughness of electrodes and (2) the thickness of oxide layer on them²⁰. The electrodes were made of polished copper plates but in the process of experiments surface roughness increases as the electrodes were cleaned. A uniform increase in surface roughness gives an initial increase in arc velocity, which settles down to an uniform value afterwards. Local asperity on surface tend to form site of high field emission due to local enhancement of electric field. In air copper oxidises, the bulk of layer is made up of cuprous oxide (Cu_2O) with a surface film of cupric oxide (CuO). An equilibrium thickness of cupric oxide is considered to give a constant arc velocity. But in air the thickness of CuO film continuously changes ($2 \text{ Cu}_2\text{O} + \text{O}_2 \rightleftharpoons 4 \text{ CuO}$) resulting in variation of arc velocity and conse-

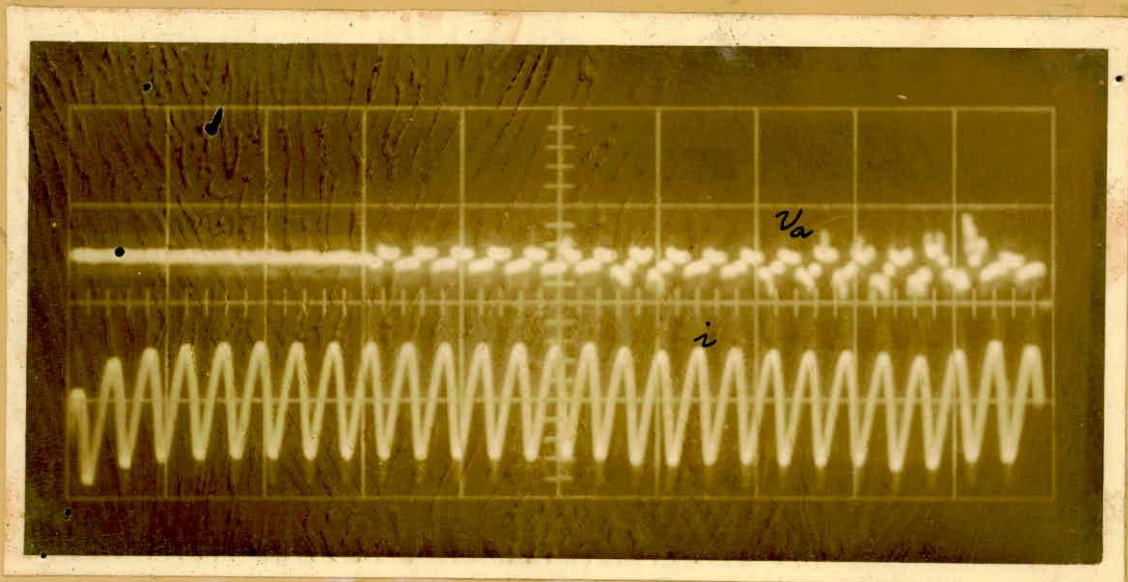


Fig 35(a) Oscillogram showing the effect of localised emission on arc voltage

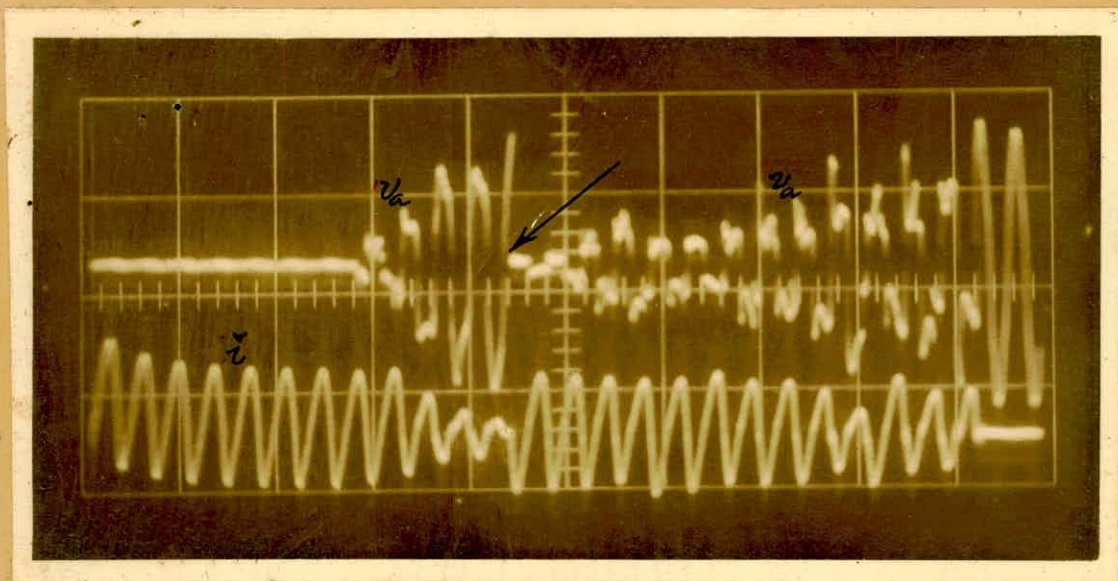


Fig 35(b) Oscillogram of a ' restriking'

quently variation in arc duration .

The formation of 'hot spot' on cathode - site of high discharges ~~af~~ from which current transfer to less conditioned site or sites does not easily take place was the reason for many sustained breakdown of gas gap. Surface asperities and thickness of oxide layer are considered to influence the formation of such localised emission. Oscillogram of one such case in which a 100 A arc was burning with a very low voltage drop across it is shown in Fig. 35(a). Another oscillogram (Fig. 35(b) shows that arc voltage is building up fast initially, after which a ' restrike ' from another spot gives rise to long period of arcing. These factors influence the repeatability of results.

9.2 ARC DURATION UNDER THE INFLUENCE OF CONVECTION CURRENT IN AIR.

The experimental results of Table - 1 (p 76) along with Histogram -1 (Fig. 26) and Table -3. Col.1 (p 80) along with Histogram 3(a) (Fig.28) show the influence of convection current in the neighbourhood of arc column on duration of arcing. In the absence of an applied magnetic field, the convection current is induced by gravity. The mean arc durations ($\bar{m}$) at 30 A, 50 A, 76 A and 100 A were 16.2, 13.70 , 13.05 and 17.16 cycles respectively with standard deviations (s) of 3, 5.05, 5.38 and 6.5 cycles respectively. Considering the deviations on either sides of the means, the intervals ($\bar{m} \pm S$), which accomodates about two-third of data at each current (see Appendix I(b)) overlap over a wide range as can be seen on the Histograms. The arc duration

for this horn gap is therefore nearly same in this current range. This is in agreement with the fact that buoyancy force being equal to $g(\rho_{air} - \rho_{core})$ per unit volume varies with the diameter of the arc core. With increase in current the diameter of arc core increases and buoyancy force on arc column proportionally increases giving rise to a constant convection velocity.

The results were plotted to give time - current curve (Fig.36).

The gap dip in the curve was not considered significant and was assigned to factors outlined in Sec. 9.2. An arithmetic average of the arc durations was 15.2 cycles. This is a fair estimate of the arc duration for this horn-gap in this current range.

9.3 ARC DURATION IN PRESENCE OF APPLIED MAGNETIC FIELD.

The immediate effect of magnetic field on arc column appears in a change in arc velocity. An increase in arc velocity causes the arc column to rise quickly through cool surrounding air giving rise to increased rate of heat loss by conduction - convection and consequently a shorter arc duration. A reference to data in Table 2 (p 78) and Table 3 col.2 (p 80) will bear this out. The mean arc durations at 30A, 50A, 76A and 100A in presence of magnetic field were 3.2, 2.95, 2.85 and 2.7 cycles with standard deviations of 1.58, 2.55, 0.975 and 0.82 cycles respectively. The large values of standard deviations of 1.58 and 2.55 cycles at 30A and 50A respectively were due to two extreme data of arc durations of 7 and 10 cycles in the two cases. Making allowance for these extreme cases, in view of the complexities of arc phenomena,

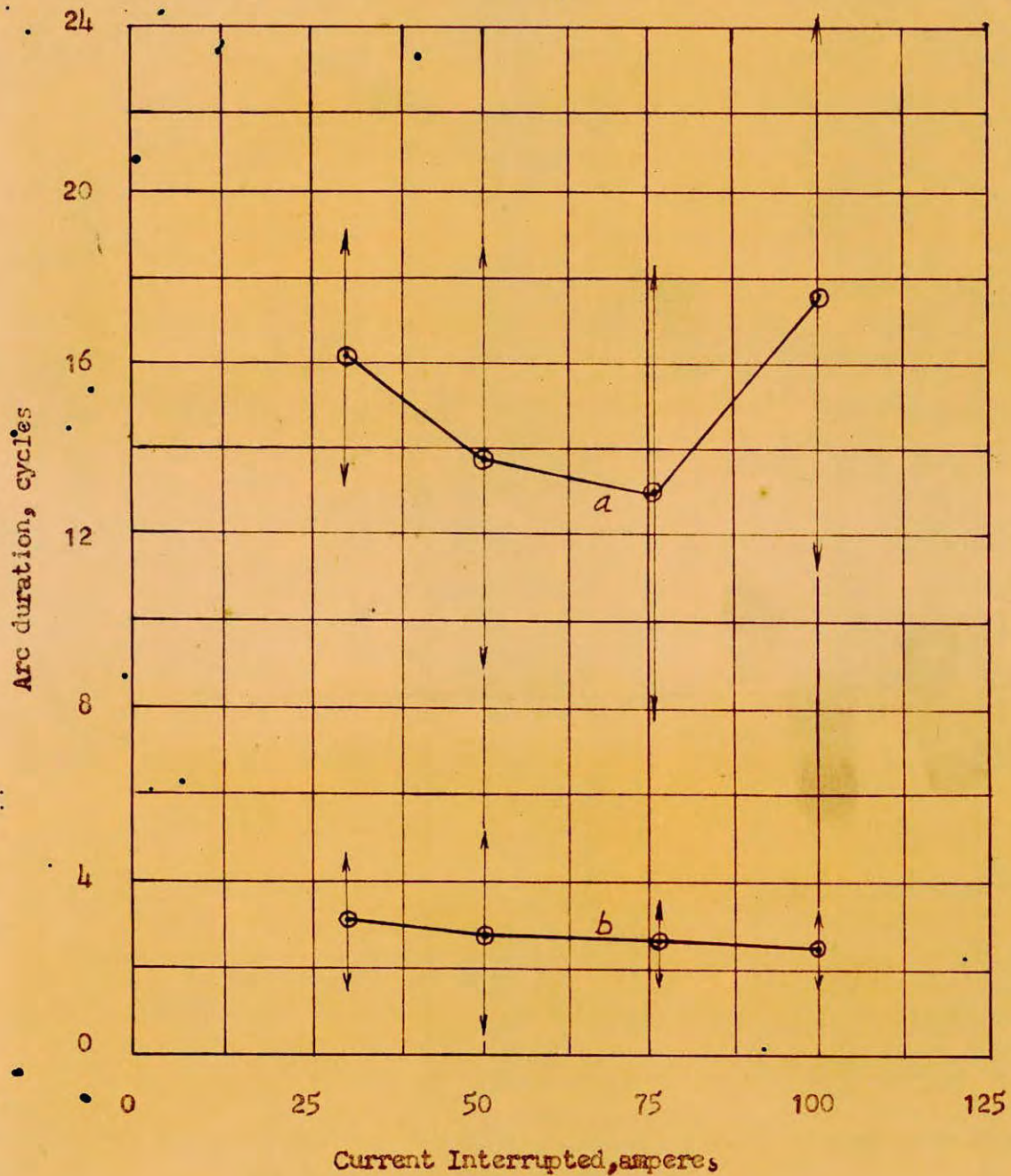


Fig.36(a) Arc duration/Current interrupted curve showing the effect of buoyancy force on arc column.

(b) Arc duration/Current interrupted curve showing the decrease in arc duration due to application of magnetic field.

the results were very consistent and there was no unsuccessful interruption.

A comparison between the Histograms 1 and 2 (Fig. 26 & 27) will show that there is a large shift to left in the latter while a similar shift can be seen in Histogram 3(b) (Fig.28) when compared with Histogram 3(a). The shift indicates a significant decrease in arc durations as will be seen on the time-current curve (Fig. 36), which shows a minimum decreased of 10 cycles. This is the contribution of the applied magnetic field.

The large scatter of data in the Histograms of arc durations in the absence of applied magnetic field brings out that convection loss induced exclusively by buoyancy force on arc column is not very effective in extinguishing an arc. Nevertheless this shows the effectiveness of providing magnetic drive, which rapidly displaces the arc column from its initial position thus preventing a localised emission or a restriction, which can cause unsuccessful interruption. The degree of the effectiveness of magnetic field in bringing about faster gap recovery depends, obviously, on the strength of the magnetic field. The values of flux densities in the arc space at which consistent results were obtained are given in Tables 2 & 3, and in the theoretical curve.

9.4 ARC DURATION WITH VARIATION OF MAGNETIC FIELD

The buoyancy force on arc column, when augmented by an electromagnetic force of $'Bi'$ per unit length (see sec. 6.4), a decrease in arc duration results because of increased arc velocity. If the current is kept fixed and

flux density in arc space is varied, variation in arc velocity and in duration of arcing will be exclusively due to magnetic field. Arc velocity being directly proportional the flux density, arc duration should vary inversely with the flux density.

On the basis of above consideration, experiment was performed on a 100 A arc with variation of magnetic field in horn gap. The mean arc durations ($\bar{m}$) were 2.7 (0.82), 5.10(3.56), 10.65 (4.87) for values of maximum flux density in arc space of 3.17×10^{-2} , 1.71×10^{-2} and 1.01×10^{-2} weber/m² respectively. The data in parenthesis are the values of standard deviations (s). The ($\bar{m} \pm s$) intervals are shown by vertical lines on arc duration/maximum flux density plot (Fig. 37). The arc duration/maximum flux density curve approaches the dashed straight line at higher values of maximum flux densities. A reference to Tables 3 & 4 (sec. 8.3) and Histograms 3 & 4 (Fig. 28 & 29) will show that scatter of data increases as the maximum flux density is decreased. The arc duration of 2.7 cycles at 3.17×10^{-2} weber/m² is the most consistent; while that of 5.10 cycle at 1.71×10^{-2} weber/m² is reasonably consistent except for two extreme data of observation 8 & 9 in Table 3. If the dashed line, which nearly coincides with arc duration/maximum flux density curve between 2.7 and 5.10 cycles' points, is extended it gives an arc duration of 6.10 cycles at 1.01×10^{-2} weber/m² instead of the mean value of 10.65 cycles. It is seen from Table 4.col.2 that half^{of} the data give a mean of 6.2 cycles at 1.01×10^{-2} weber/m². These considerations leads to the conclusion that at higher values of maximum flux density in the arc space dependent on the magnetude of current

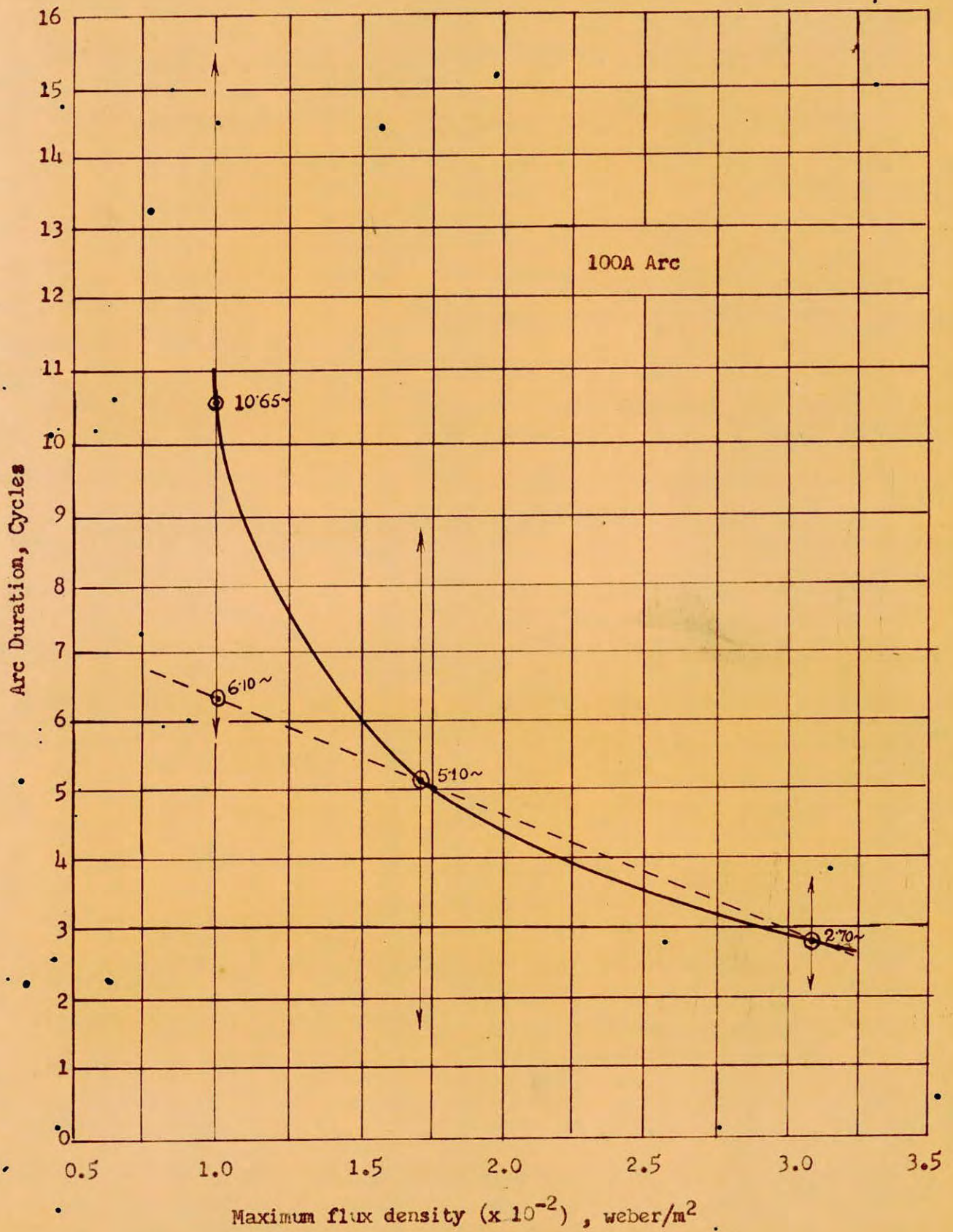


Fig. 37 Arc duration/ Maximum flux density curve

to be interrupted, arc durations vary inversely with the maximum flux densities; while at lower flux densities, when the effect of magnetic field is less pronounced, a departure from this inverse relationship is likely to occur.

9.5 AN EMPIRICAL FORMULA OF ARC DURATION

Arc duration i.e. the time from initiation of arc to its extinction depends on the period of interaction between the ' reignition forces ' and ' recovery forces '. Reignition of arc depends on the watts input to the arc after a current-zero. Since a fall in arc voltage is always accompanied with a rise in current or vice-versa, the magnitude of either voltage or current may be indicative of reignition possibilities. The gap recovery is due to watts lost as heat from arc column. Losses are caused by the action of buoyancy forces and magnetic field on arc column. As has been shown buoyancy force gives a constant arc duration. Arc duration has been shown to be inversely proportional to maximum flux density in presence of strong magnetic field ; while at lower values of flux-density arc duration tend to rise exponentially to the value given by buoyancy force exclusively.

On the basis of this analysis and the experimental results obtained an empirical formula of arc duration is proposed. The formula holds for a horizontal A.C. arc between copper electrodes in air in presence of transverse magnetic field. The electrodes i.e. the arc-runners form a horn gap. Although voltage does not appear in the empirical equation but the gap between the electrodes will be determined by the voltage as also by the current.

The formula which is non-dimensional has the form -

$$t = K e^{c \frac{B_m}{I} \cdot 35} \quad (I)$$

where

t = arc duration - cycles

K = constant arc duration given by buoyancy force

B_m = maximum flux density - weber/m²

I = symmetrical R.M.S. value of current to be interrupted Amp.

c = constant depending on the size of arc runners and the angle given to them.

The constant c must be negative for successful arc control. A positive c will have opposite effect. With negative c , an increase in flux density (B_m) will give shorter arc duration while an increase in current (I) will give longer arc duration.

The constants K and c can be determined from at least two sets of data of t , B_m and I but a larger number of sets of widely placed data will give more accurate values of K and c . The formula helps to calculate the necessary value of B_m at a certain value of I to give a desired value of t i.e. from a few known sets of data, other sets of data may be calculated.

The values of t , B_m and I from Tables 2,3 co. 2 and 4 (experiment performed in presence of magnetic field) gives -

$$* K = 15.7 \text{ cycles}$$

$$c = -.28 \times 10^3$$

This value of K agrees well with the arithmetic average of the experimental value

of arc durations at different currents in the absence of magnetic field which is 15.2 cycles (see sec. 9.2). When K and c were calculated from half of available set of data of t , B_m and I , a slight variation in both K and c occurred. Since either a decrease or increase occurred in both, values of t , B_m and I of the remaining sets were obtained with fair degree of accuracy, when calculated with the changed values of K and c .

The * values $K = 15.7$ and $c = -.28 \times 10^3$ are more accurate determination of the constants for the horn-gap used. With these values of the constant, arc durations at another current and flux density from the tables were calculated with a variation of only $\pm 10\%$. It can be calculated that at a current of 150A, with a maximum flux density of 2.35×10^{-2} weber/m² the arc duration will be 5.1 i.e. 5 cycles; while at the same flux density a 50A arc 'clears' in 2.85 i.e. 3 cycles (Table - 2). The fractional values of arc duration in cycles should be corrected to include the period upto the nearest current-zero i.e. 3.2 cycles should be taken as 3 cycles and 3.4 cycles, as 3.5 cycles.

* See Appendix III for calculation.

Chapter - 10

CONCLUSIONS

The extinction of an A.C. arc in air in presence of transverse magnetic field is caused by the action of buoyancy force and magnetic field on arc column. Arc duration i.e. the time from initiation of arc to its final extinction has a constant value within a certain range of current, when the arc column is acted on by buoyancy force alone. This range of current depends on the size of horn-gap and the angle given to arc-runners. Magnetic field has a marked influence in causing faster gap recovery by subjecting the arc column to rapid motion through air. Arc duration is inversely proportional to maximum transverse magnetic flux density in presence of strong magnetic field dependent on the magnitude of the current to be interrupted ; while at lower values of the flux density, when the action of magnetic field becomes less pronounced, a departure from inverse relationship is likely to occur with the arc duration tending to rise exponentially to the value given by buoyancy force exclusively.

An empirical formula relating arc duration(t) to applied maximum flux density (B_m) and current(I) to be interrupted in terms of two constants (K & c) is obtained on the basis of experimental results. The formula holds for A.C. arc between copper electrodes in air, the transverse magnetic field being produced by a coil, energised by the current to be interrupted. The formula is non-dimensional and has the form -

$$t = K e^{\frac{c B_m}{(I)^{.35}}}$$

The contributing factors to the constants K and c need investigation.

While the constant K has been separated as reflecting mainly the effect of buoyancy force on arc column, the constant c is expected to be mainly dependent on electromagnetic force on arc column. The surface roughness of electrodes, the electrode material and the angle given to arc-runners are expected to influence both the constants. With a change in the shape of flux wave the value of constant c will change.

APPENDIX

APPENDIX - I(a) CALCULATION OF STANDARD DEVIATION *

If a sample is small (number of variates equal to 30 or less) ,
 its standard deviation s , can not/used as a fair estimate of the standard deviation of the population σ . Since in general a population will contain more extreme data than a sample, it is to be expected that σ will be somewhat larger than $\hat{s}$. In most cases, however, for a small sample of n variates $x_1, x_2, \dots, x_n$, the best estimate of the standard deviation of the population" is given by -

$$S = \sqrt{\frac{n}{n-1}} \hat{s} = \sqrt{\frac{\sum (x - \bar{x})^2}{n-1}}$$

A sample calculation of standard deviation for data given in

Cal. 1 of Table 1 (See 8.3) is shown below -

	x	$x - \bar{x}$	$(x - \bar{x})^2$
1	14.0	2.2	4.82
2	16.5	0.3	0.09
3	17.0	0.8	0.64
4	14.5	1.7	2.89
5	16.0	0.2	0.04
6	22.5	6.3	39.69
7	13.5	2.7	7.30
8	20.0	3.8	14.40
9	14.5	1.7	2.89
10	13.5	2.7	7.30

* $\sum x = 162.0$

$(\sum (x - \bar{x})^2) = 80.06$

$$\bar{x} = \frac{\sum x}{n} = \frac{162.0}{10} = 16.2 \text{ cycles} = m \text{ (mean)}$$

$$\sum (x - \bar{x})^2 = 80.06$$

$$s = \sqrt{\frac{(x - \bar{x})^2}{n - 1}} = \sqrt{\frac{80.06}{10 - 1}} = 3 \text{ cycles.}$$

b)

A t - distribution is applicable when the number of variates is small. With increase in number of degrees of freedom a t-distribution approach a normal distribution. The number of degrees of freedom for data in Tables 1 - 4 (Sec. 8.3) being equal to 9 or more, the statement (sec. 9.2) that $(m \pm s)$ intervals at each current will accomodate about 2/3 of data of mean arc durations is based on a fair approximation.

* From chap. 10 of " Introduction to Probability and Statistics",

Alder H.L., Roeseber E.B.,
Foreman, Sanfransisco & Lon., 1960.

APPENDIX - IIFORMULAE FOR STEP-BY-STEP CALCULATION OF MAXIMUM FLUX DENSITY

The maximum flux density is calculated from oscillograms of induced voltage in a search coil placed close to arc space.

$$\text{The induced voltage } e = N \frac{d\phi}{dt} \quad \dots \quad (1)$$

or

$$\text{Change in flux } d\phi = \frac{1}{N} e dt \quad \dots \quad (2)$$

from which

$$\text{flux density } B = \frac{\phi}{A} = \frac{1}{NA} \int e dt \quad \dots \quad (3)$$

where N = number of turns in search coil

A = mean of the inner and outer area of search coil sq. m.

$\int e dt$ = area under the voltage trace volt-sec.

Because of saturation in the magnetic circuit, the induced voltage has a non-sinusoidal waveform and the integral term $\int e dt$ does not lend itself to convenient analytical evaluation.

The method of finite differences is, therefore, applied to overcome the difficulty with variable permeability. The step-by-step calculation is based upon the assumption that permeability remains sensibly constant over a small finite interval of time. If finite differences in ϕ and t are employed, equation (2) takes the form -

$$\text{Change in Flux } \Delta\phi = \frac{e_a t}{N} \quad (4)$$

where e_a = average value of the induced voltage within the finite interval of time.

If step-by-step integration is employed to calculate the positive loop area of the induced voltage i.e. from $t = 0$ to $t = T/2$, the corresponding flux variation is from $+\phi_m$ to $-\phi_m$, ϕ_m being the maximum value of flux.

Therefore equation (3) should be modified to

$$\text{Maximum flux density } B_m = \frac{\sum_0^{T/2} e_a \frac{\Delta t}{N}}{2 A} \text{ weber/m}^2$$

$$\text{or } B = \frac{\sum_0^{T/2} \Delta \phi}{2 A} \quad \dots (5)$$

APPENDIX - III(a) Determination of Constants - K and c.

Taking logarithm on both side of the empirical equation

$$t = K e^{\frac{c B_m}{(I)^{.35}}} \quad \dots (1)$$

$$\text{We have } \log t = \log K + \frac{c B_m}{(I)^{.35}} \log e$$

$$= a + 0.432 \frac{B_m}{(I)^{.35}} c \quad \dots (2)$$

which is the equation of a straight line with constants $\log K = a$ and c .

The necessary terms of this equation are evaluated in Table - I from data of t ,

B_m and I obtained from Tables 2 - 4 (Sec. 8.3).

TABLE - I

No. of set	From table (sec.8.3)	I (Amp)	B_m weber/m ²	t cycles	log t	$.432 \frac{B_m}{(I)^{.35}}$
1	4	100	1.01×10^{-2}	10.65	1.025	0.86×10^{-3}
2	4	100	1.71×10^{-2}	5.10	0.707	1.47×10^{-3}
3	2	30	1.87×10^{-2}	3.20	0.505	2.48×10^{-3}
					2.237	4.81×10^{-3}
4	2	50	2.35×10^{-2}	2.95	0.469	2.57×10^{-3}
5	2	76	2.80×10^{-2}	2.85	0.454	2.66×10^{-3}
6	3	100	3.17×10^{-2}	2.70	0.431	2.74×10^{-3}
					1.354	7.97×10^{-3}

To determine the constants, the first three points are taken in one group and the last three in the other. The sums of each group are substituted in the transformed equation (2) giving -

$$2.237 = 3a + 4.81 \times 10^{-3} c \quad \dots \quad (3)$$

$$1.354 = 3a + 7.97 \times 10^{-3} c \quad \dots \quad (4)$$

$$0.883 = 0 - 3.16 \times 10^{-3} c$$

$$c = - \frac{0.883}{3.16} \times 10^3 = -0.28 \times 10^3$$

From equation (3)

$$a = \frac{2.237 + 4.81 \times 0.28}{3} = 1.195$$

Now . K = Antilog a
 = Antilog 1.195
 = 15.70

Thus the empirical equation (1) for arc duration becomes

$$t = 15.70 e^{\frac{-0.28 B_m}{(I)^{.35}}} \quad \dots \quad (5)$$

(b) Testing the Validity of the Empirical Equation

To test the validity of the empirical equation, let K and c be calculated from fewer sets of data of Table I, so that the experimental values of arc durations, in the remaining Sets may be treated as ' unknowns '. This if data of Sets 1 & 2 are taken in one group while that of Sets 3 & 5 in the

other, then proceeding as before the following value of constants are obtained -

$$K = 15.38$$

$$c = -.275 \times 10^3$$

With these values of K and c, let us calculate the arc durations for currents and maximum flux densities in the remaining Sets. Thus for Set 4, where in $I = 50$ Amp and $B_m = 2.35 \times 10^{-2}$ weber/m², the calculated arc duration is -

$$\begin{aligned} t &= 15.38 e^{\frac{-.275 \times 10^3 B_m}{(I)^{.35}}} \\ &= 15.38 e^{\frac{(-.275 \times 10^3) (2.35 \times 10^{-2})}{(50)^{.35}}} \\ &= \frac{15.38}{5.22} \\ &= 2.94 \text{ cycles.} \end{aligned}$$

Similarly for Set 6, where in $I = 100$ Amp and $B_m = 3.17 \times 10^{-2}$ weber/m² the calculated arc duration is 2.67 cycles. A reference to Table I will show that these calculated values of arc durations agree with the experimental values.

The values of K and c should be evaluated from as many widely placed data as are available and so the values of $K = 15.70$ and $c = -.28 \times 10^3$ obtained in the last sections are more accurate values for the constants. Since the values of $K = 15.38$ and $c = -.275 \times 10^{-2}$ obtained in this section show small variations, the calculated values of arc durations are obtained fairly accurately.

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