THE UNIVERSITY OF MANITOBA

Investigation of the D-C Arc Characteristics in Fluorinated Cyclic Ether (FC 75)

by

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ABSTRACT

The d-c arc characteristics in FC 75 have been investigated and compared with those in Transformer Oil and SF_6 gas.

The arc voltage was compared in the three media and found to have a lower value in the case of SF_6 than in either of the two liquids.

It has also been shown that the arc instability increased with an increase in the current and that the arc time duration was scattered, probably due to the deterioration of the medium tested.

The effect of the gap length on the arc voltage was also observed.

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1. INTRODUCTION

GENERAL

The object of this research was to study the d-c arc characteristics in Fluorinated Cyclic Ether which is industrially known as FC 75 and whose chemical formula is $C_8F_{16}O$. The d-c arc properties in this liquid were also compared with those in Transformer Oil and Sulphur Hexafluoride (SF_6) for the same circuit conditions and contact opening.

1.1 TRANSFORMER OIL AS AN ARC QUENCHING MEDIUM

The a-c arc characteristics in Transformer Oil have been investigated by many authors who studied its effectiveness when used as an arch quenching medium, by examining the rate of recovery of its dielectric strength after current zero. Also, the construction of different circuit breakers and studying the effectiveness of the deion grids as means of making more efficient use of oil in arc rupture were investigated (1). In the same field of study, the superiority of oil blast circuit breaker to plain oil as an arc quenching medium was shown (2). The validity of both the displacement and diffusion theories in fluid-flow arc extinction were studied (3), showing that the diffusion theory is more valid. The effect of the length of the arc in Transformer Oil was studied by Slepian (4) who investigated the influence of holes and slots in oil circuit breakers on the quenching capability.

1.2 SF_6 AS AN ARC QUENCHING MEDIUM

Sulphur Hexafluoride was first discovered by Moisson and Lebeau (5) in 1900. The gas did not attract much attention until the 1940's when Charlton et al (5) suggested that the halogenated gases possess better insulating properties than many liquid and solid dielectrics. In recent work, Fukuda et al (6) confirmed that SF_6 has excellent and unique electrical properties as an arc quenching medium. The existence of fine arc core, its tendency to loop out and the profile of negative ion formation around current zero have been revealed.

Browne (7) studied the behaviour of the a-c arc in SF_6 near current zero by means of mathematical models. He used Mayr's differential equation in the case of high arc resistance and circuit controlled voltage e(t) which is of the form

$$\frac{dR}{dt} - \frac{N_o}{Q_o} R = - \frac{1}{Q_o} e^2(t)$$

where R is the instantaneous arc resistance per unit length, N_o is the power loss from the arc per unit length at time t = 0 and Q_o is characteristic energy quantity that governs the dynamic behavious of the arc.

The general solution of the above equation is of the form

$$R = e^{t/\theta} \left[R_o - \frac{1}{N_o \theta} \int_o^t e^2(t) \cdot e^{-t/\theta} dt\right]$$

where $\theta = \frac{Q_o}{N_o}$ and R_o = R at time t = 0.

He applied this form of solution to study the arc behaviour after current zero with various forms of applied voltage such as constant voltage, square wave,sine wave, as well as constant rate of rise.

In further studies of the electrical properties of SF_6, it was shown that its arc quenching ability is of greater importance than its insulation properties (8). The rate of recovery of dielectric strength is high and it was thought that the electro-negativity of the gas or its decomposition products are basically responsible for this effect, but the reasons for the rapid dielectric strength recovery are not yet fully understood. Different papers dealing with the study of SF_6 filled circuit breakers (9,10) as well as the gas characteristics showed the effectiveness of SF_6 as an arc quenching medium. It should be noted that SF_6 compared with Nitrogen can attain successful interruption even under 100 $\sim$ 200 times more severe circuit conditions and it was shown to have an arc time constant which is largely affected by the current levels in the range of several amperes (11). Therefore, voltage or current transients cannot be fully simulated by using a single time constant.

The experimental work done on arc characteristics in SF_6 (11) showed that the value of time constant obtained at the extreme neighbourhood of current zero is smaller than 0.3 μsec. If the current level is increased to several amperes the value of the time constant is of the order 3 μsec. Occasionally the reciprocal of the time constant can give a good indication of the a-c interrupting ability.

In a recent study using boundary layer techniques (14), the arc equation has been integrated and transformed into a partial differential equation for dynamic arc radius.

Starting from a quasi-steady solution for the arc radius at peak current, the dynamic arc equation was solved for a linear current ramp to obtain the arc radius at current zero. During the pre-zero arcing period, energy may be removed from arc column by axial convection or by radiation and diffusion. For both convection and radiation-diffusion controlled arcs, the current zero arc radius at peak is attenuated by certain heat transfer parameters.

The main disadvantages of the gas are the harmful decomposition products and the need for a sealed gas system. Studies of decomposition (16) of SF_6 due to arcing indicate that such a large amount of arc energy is required to decompose a cubic foot of the gas at atmospheric pressure that a hundred or more high-power interruptions can be made in the gas before even this relatively small volume would be decomposed. The gaseous decomposition products are believed to be chiefly lower fluorides of sulfur, and are readily removed by absorption in activated alumina. The used up gas may then be replaced, but the reduction in pressure is so negligible that this need seldom be done. For a 1,000 MVA 115-KV SF_6 breaker filled to 45 psig, it is estimated that the absorption of the decomposition products from 50 interruptions at full rated short circuit current of 5000 amperes would reduce the chamber pressure by only 1 psig.

Although the unarced SF_6 is extremely stable and nontoxic, some decomposition products formed by arcing are toxic. Fortunately, these products have a strong odor, giving ample warning of their presence. In addition to the active gases, there are also some metallic fluorides formed from reaction with the contacts during arcing.

1.3 PROPERTIES OF FLUORINATED LIQUIDS(12)

This group of compounds has a completely fluorinated structure and for this reason they are nonflammable and chemically non-reactive.

1.3.1 STABILITY

The fully fluorinated Inert liquids are among the most stable fluids known. Because of the strong bonding between the atoms in their molecules, these fluids show a high degree of chemical, thermal and radiation stability.

1.3.2 CHEMICAL INERTNESS

The Inert liquids are nonflammable and exceedingly resistant to chemical attack. They are untouched by a variety of strong acids, such as Hydrochloric acid, strong bases, oxidizing agents and reducing agents.

1.3.3 THERMAL STABILITY

All the Inert liquids possess high temperature stability. Test results for FC 75 after 240 hours at 750^0F with copper, nickel or 304 stainless steel indicated only a trace amount of acid formation, and only minor changes in composition via gas liquid chromatography. At 797^0F, the rate of degradation was more rapid, but even then only one to two percent of the starting material per day.

1.3.4 RADIATION STABILITY

The Inert liquids are moderately stable to gamma radiation. The amount of gaseous products formed is much less for these fluoro-carbons than for hydrocarbons. G (gas) value for FC 75 was less than 0.1 after a dosage of 5×10^8 rads. The Inert liquids seem as stable toward ionizing radiation as some hydrocarbons.

1.3.5 ELECTRICAL PROPERTIES

The dielectric strength of the fluids is high, typically ranging from 430 volts/mil for FC 78 to 560 volts/mil for FC 43. Contamination with trace amounts of water or oil will reduce these values slightly. The breakdown strength in the vapour phase is about 350 volts/mil for FC 75. Therefore, electrical insulation can be maintained by the vapors. Thus, the vapor bubbles formed during boiling do not have a detrimental effect upon the electrical insulating properties of the liquid. With decreasing temperature, the vapor pressure decreases and so does the dielectric strength of the vapors.

The dielectric constants of the Inert liquids are less than 2.0

1.3.6 HEAT TRANSFER PROPERTIES

The Inert liquids exhibit good heat transfer capabilities. Their high density, low viscosity and high thermal expansion result in high convective heat transfer coefficients, as shown in Figure 1H. The higher heat transfer coefficients produces component temperatures lower than those obtained with other conventional coolants. The most effective usage of the Inert liquids as coolants is found when their low boiling characteristics can be utilized. The heat transfer coefficient obtained is normally 1 to 2 watts/in^2/o_c.

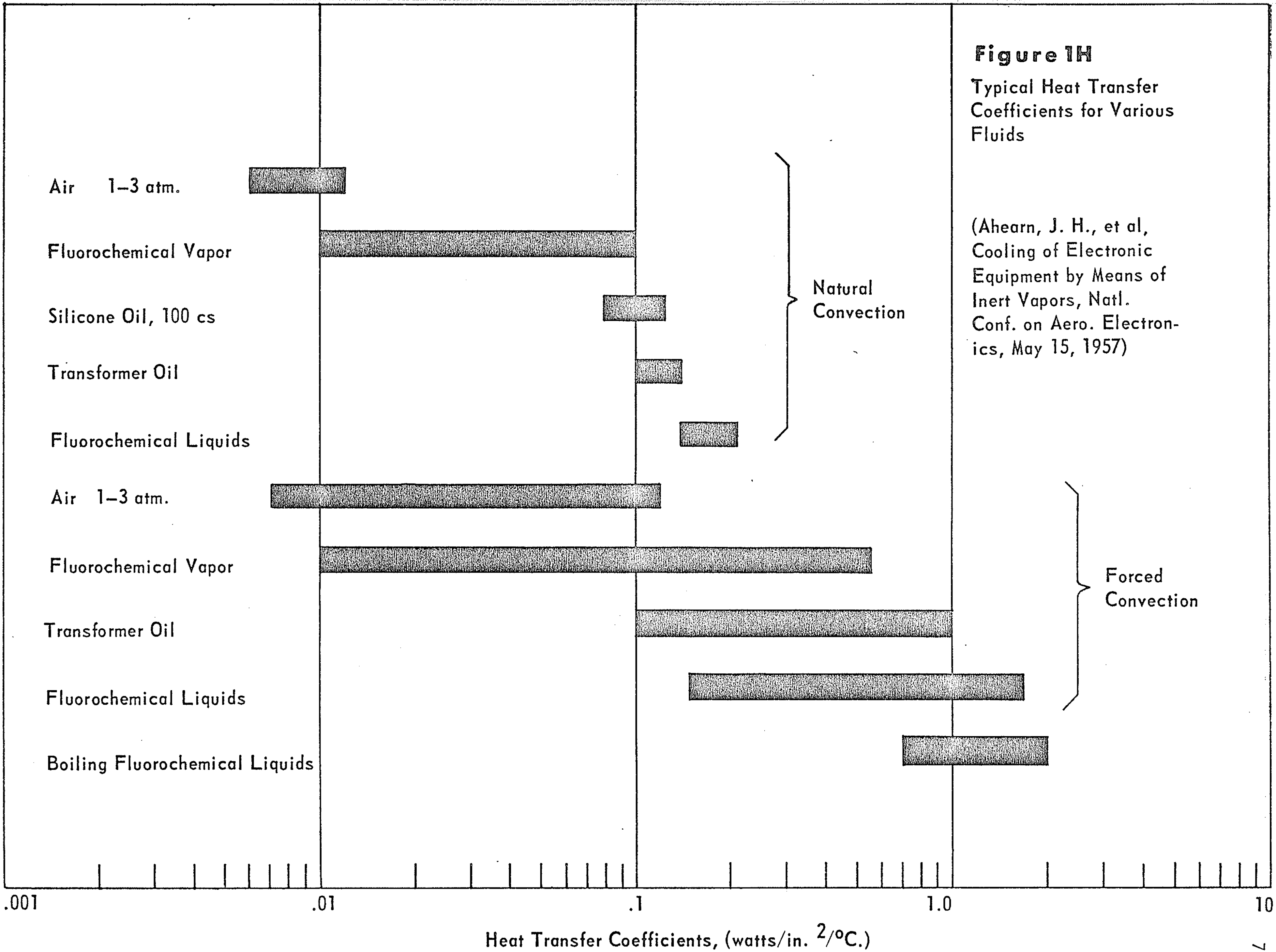


Figure 1H

Typical Heat Transfer Coefficients for Various Fluids

(Ahearn, J. H., et al, Cooling of Electronic Equipment by Means of Inert Vapors, Natl. Conf. on Aero. Electronics, May 15, 1957)

1.4 APPLICATIONS OF FLUORINATED LIQUIDS

The Inert liquids have been successfully incorporated in a variety of applications. A large percentage of these are based upon their high efficiency as dielectric coolants, where electrical insulation and high heat transfer properties are desirable. For example, the Inert liquids are being used to cool and stabilize the temperature of Klystron tubes, even though a wide range of ambient conditions may exist. This operation at a reduced and constant temperature permits transmission at a constant frequency. The miniaturization of many systems, such as power supplies, transformers and amplifiers has been made possible by use of the Inert liquids. This is because of their ability to remove heat more efficiently and to serve as electrical insulation, thus permitting construction of a more compact unit.

Various types of transformers have been insulated and cooled by these fluids. In the case of transformers, maintenance has been drastically reduced because the sampling and filtering required with conventional oil is no longer necessary. The fluids are used as pressure transferring fluids in transducers and furnish the protection from vibration and shock for components in missile applications. The high coefficient of thermal expansion characteristic of these fluids has led to usage as working fluids in thermally actuated valves. Because of their high optical transmittance, many investigations are now underway with regard to their being utilized as coolants in laser systems.

These are but a few of their uses. Many others are found in the areas of instrumentation, low temperature fluids and test baths.

1.5 FLUORINATED CYCLIC ETHER

A completely fluorinated cyclic ether of chemical formula $C_8F_{16}O$ has been given the commercial designation FC 75. Its molecular structure is not yet clearly established but it is believed to contain a five or six membered ring with a fluorinated side chain. The oxygen atom is contained in the cyclic ring structure.

FC 75 fluorinated liquid is chemically stable under the requirements usually established for the application of insulating liquids in electrical equipment. It is claimed to be stable when heated to temperatures even as high as 500 - 600^{0}C. Although easily miscible with other fluorinated liquids, FC 75 compound has but little solvent action on the insulating materials normally used in electrical equipment. Within the temperatures of normal use (up to 230^{0}F), FC 75 will not attack the usual insulating resins and is not corrosive to metals. Although volatile, this fluorinated liquid and its vapour are nonexplosive, nonflammable, and physiologically nontoxic. If the liquid is to be applied at temperatures well above 90 - 100^{0}C, purity must be maintained in order to avoid excessive corrosion of the resin insulations and metals with which it may be in contact.

2. DESCRIPTION OF THE TEST CELL AND THE TEST PROCEDURE

2.1 DESCRIPTION OF THE TEST CELL

The cell consisted of a brass cylinder of four inches internal diameter, six inches in height, and 3/4 of an inch wall thickness, fitted with two quartz windows, each one an inch in diameter. The two contacts were made of Tungsten, each one inch in diameter and 1/4 of an inch thick. The upper contact was movable while the bottom contact was fixed. The gap separation could be adjusted by moving the bottom contact up or down. The range of gap separation can be adjusted between zero and 1/2 inch. The positive terminal of the supply was connected to the upper contact through a flexible braid to allow the electrode to move freely. The bottom contact was kept at Earth's potential. In order to prevent the braid from touching the cylinder during its movement, a piece of Teflon was used between the cylinder and the braid. All entrances such as windows and bottom electrode opening were sealed by means of "O" rings. The upper contact was fixed to a plunger of a solenoid which, by applying 110 volts a-c to it, was energized and the gap was opened. A diagram of the test cell is shown in Figure (1).

When the cell was used to test transformer oil, it was totally filled in order to suppress any fire hazard due to production of gases during arcing, such as hydrogen, methane, acetylene, carbon monoxide, ethane and ethylene. When testing SF_6, one of the cell inlets was connected to SF_6 cylinder while the other opening was left free and the gas was allowed to circulate for a while in the cell, and since SF_6 is heavier than air, it was expected to have a certain amount of SF_6 inside. On the other hand,

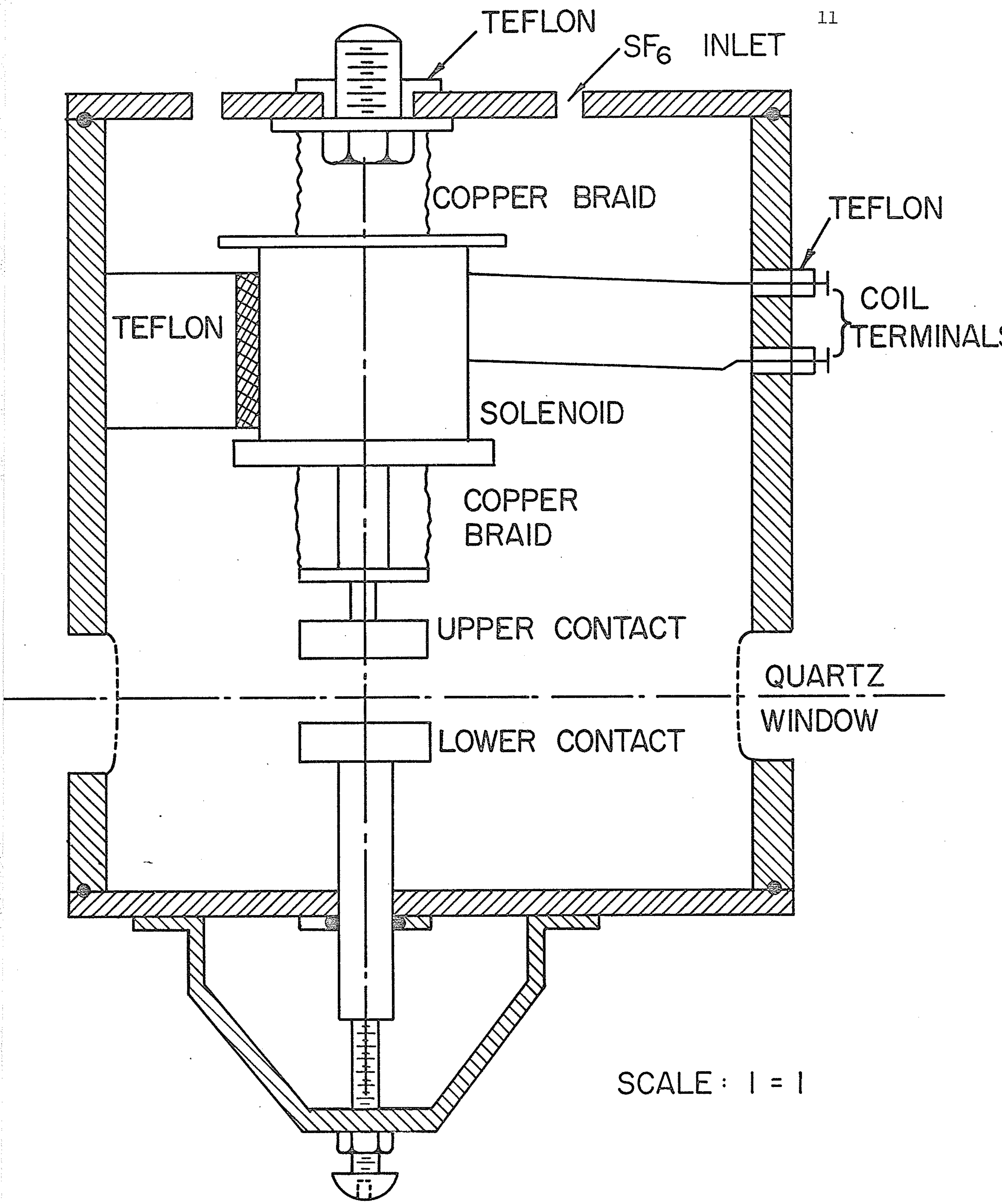


FIGURE 1 DIAGRAM OF THE TEST CELL.

when testing FC 75, the cell was partially filled enough to cover the top contact when it is fully open, because there was no fire hazard due to the products of the arc. This difference in the volume of the two liquids has minor effect on the results because the net volume of the cell is 270 $inch^3$ and to cover the top contact when it is fully open the volume involved is 180 $inch^3$; hence the effect is small.

2.2 THE TEST CIRCUIT

The positive terminal of a d-c generator (100 KW, 550 volts, 182 amperes and 900 R.P.M.) was connected through one pole of a two-pole switch to the upper contact, and the remaining pole of the switch was used to connect the a-c signal to the terminals of the solenoid. When the switch was closed, the d-c voltage was applied to the contacts and at the same time the a-c was applied to the solenoid, but the contacts did not open immediately due to the mechanical time delay between the voltage application to the solenoid winding and its mechanical reaction. The negative terminal of the d-c generator was connected directly to the resistance in the circuit and the midpoint between the bottom contact and the resistance was connected to ground.

The test circuit is shown in Figure (2). The arc voltage was measured by taking the voltage signal across the arc to one channel of a Tektronix type 549 storage oscilloscope (points 1 and 3) while the arc current was measured by taking the voltage signal during the arc across the resistance in the circuit to the second channel of the oscilloscope (points 1 and 2).

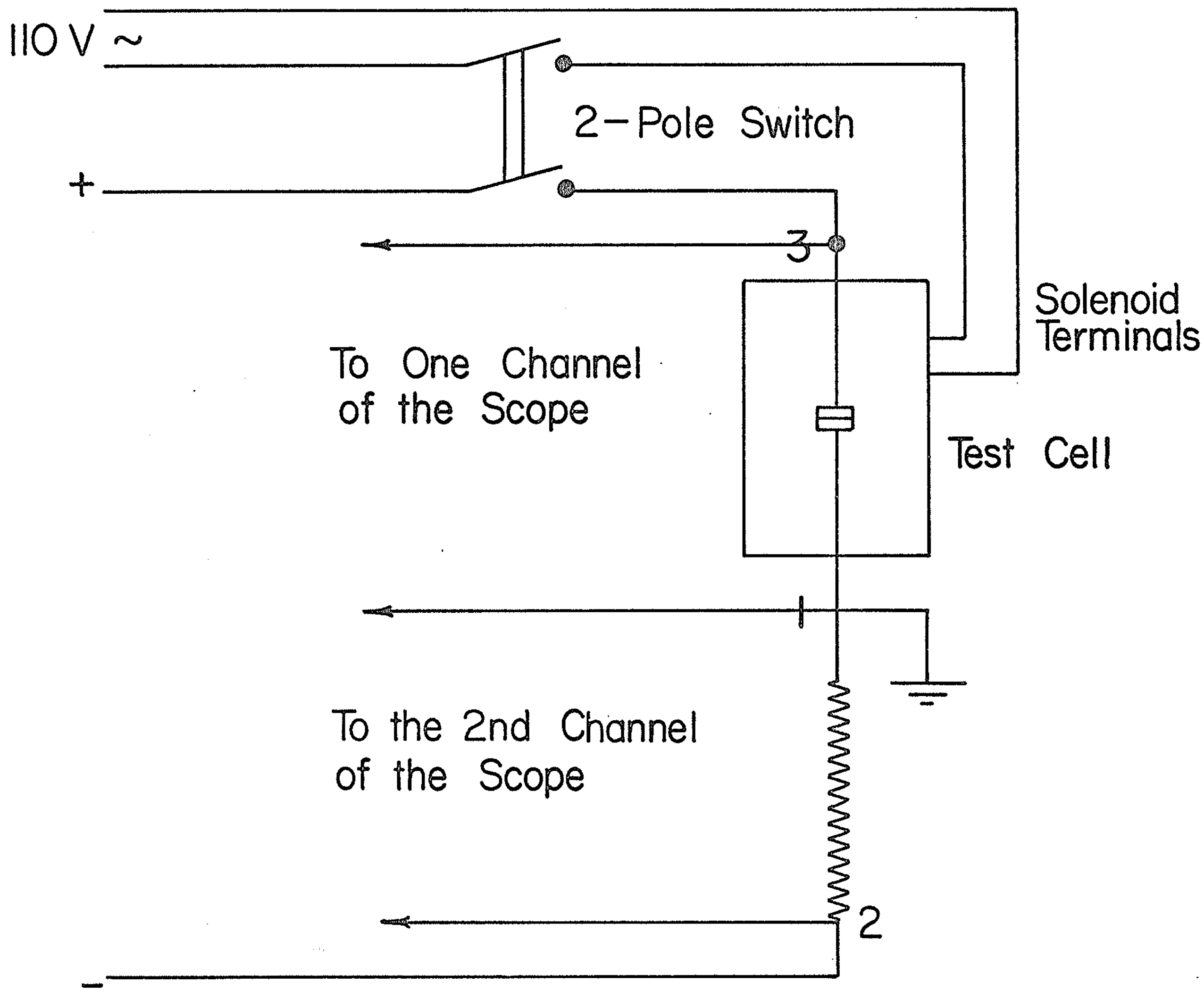

110 V ~
2-Pole Switch
+
3
Solenoid Terminals
To One Channel of the Scope
Test Cell
To the 2nd Channel of the Scope
2
–

FIGURE 2

2.3 TEST PROCEDURE

The load resistance used in the circuit had the value of 18 ohms and the applied d-c voltage started with the value of 250 volts. The arc voltage and arc current values were taken at increments of applied voltage of 25 volts. Since the maximum voltage available from the d-c generator was 550 volts, the load resistance was replaced by 10 ohm resistance for studying the arc characteristics at higher currents. For each value of the applied voltage, three tests were made and the arc voltage and arc current were calculated by taking the average of the three test results.

The average values of the arc voltage and current were measured as well as their values at the arc initiation point and at the arc extinction point when the contacts were fully opened.

The opening between the two contacts was set to 1/4 as well as 1/2 of an inch. To adjust the contact opening three steel gauges of 1/8, 1/4 and 1/2 of an inch were prepared and using an ohm-meter, it was possible to set the gap at any of these three settings. To ensure that the gap setting would not change due to the hammering of the top contact on the bottom one, a set screw was placed under the bottom contact to prevent its downwards movement during the experiment.

2.4 MEASUREMENT OF THE OPENING TIME OF THE CONTACTS

To measure the time required for the contacts to be fully opened from the instant the a-c voltage was applied, a slight modification was made to the test cell. Another contact was fixed to the movable part so that as soon as the gap was fully opened, it would contact a small lead at the same potential as the cell (Earth's potential) as shown in Figure (3).

The power was supplied by a 9-volt battery and as soon as the d-c voltage was applied, the contacts were opened but the current flowed for a short time due to the time delay between applying the a-c voltage and the upwards movement of the contact. The flow of current was interrupted during the movement of the contact and was re-established when the new contact was made as shown in Figure (4). This test was carried out for both air and transformer oil for 1/4 of an inch gap. It was found that there was no significant difference between the times of contact movement in oil or air. Although the viscosities are different, this probably was because the time delay was very short in both cases. Several tests were made at a contact opening of 1/4 of an inch and the photographs taken showed that the time delay was 12.5 m.sec. (Figure (4)). It was also found that this time delay was reproducable.

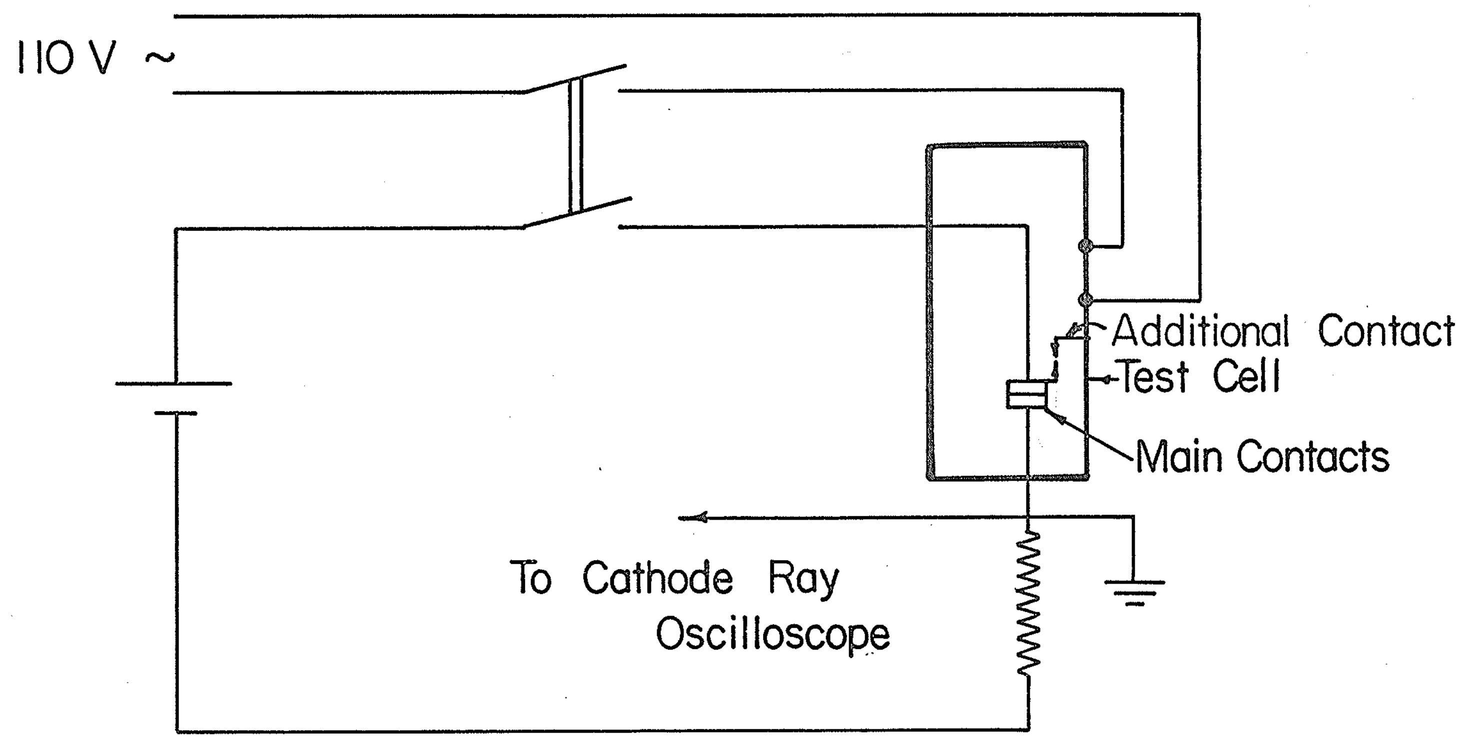

110 V ~
Additional Contact
Test Cell
Main Contacts
To Cathode Ray
Oscilloscope

FIGURE 3

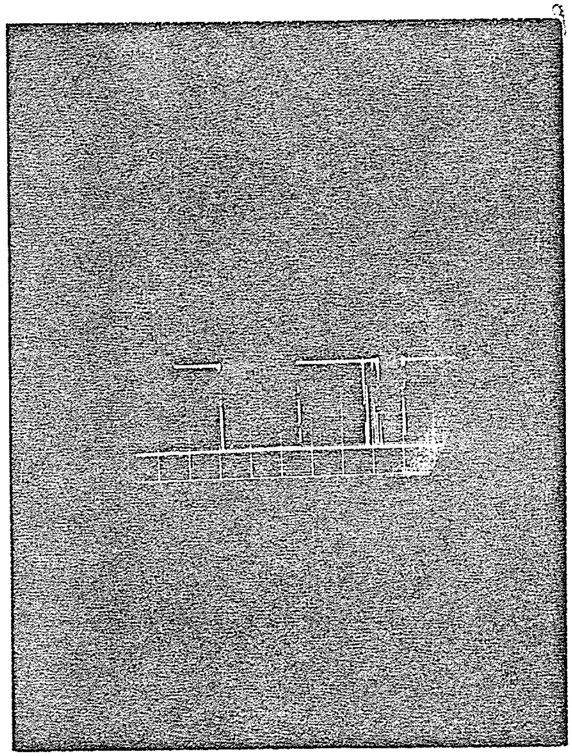


FIGURE (4)

The Opening Time of the Contacts for 1/4" Gap

time scales = 5 m.sec./div.

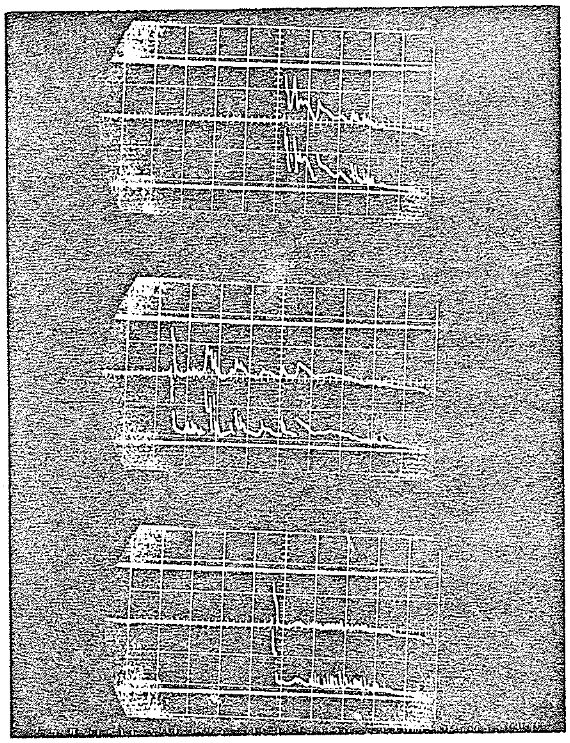
3. ANALYSIS OF THE RESULTS

This section deals with the analysis of the experimental results obtained. The parameters analysed include arc voltage, arc current and arc duration. The instantaneous arc resistance is obtained by dividing the corresponding arc voltage by the current. The experimental data for FC 75, transformer oil and SF_6 were obtained for the same circuit conditions and with the same contact openings in order to have a common basis for comparison of the results. Table (1) shows the measured values of the average arc voltage, average arc current and the corresponding values of arc resistance for FC 75 for a range of applied voltage ranging from 250 volts to 575 volts. For each step of the applied voltage three readings for the arc voltage and arc current were taken and the values in Table (1) were calculated by taking the average of the three readings.

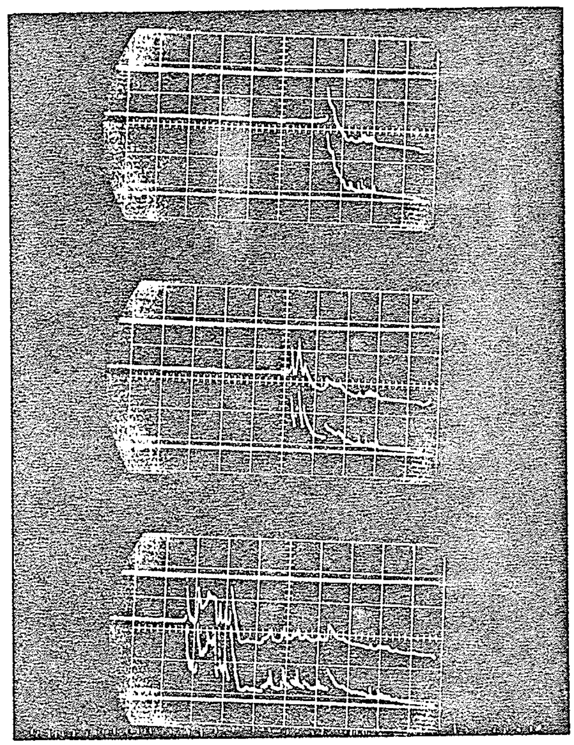
The relation between the average arc resistance and current is plotted in Figure (8). From Table (1) it is seen that the arc voltage remained constant at 60 volts and was not affected by the increase in the applied voltage, but the arc current increased and hence the arc resistance decreased. Table (2) shows the values of the arc voltage, arc current and resistance for FC 75 corresponding to the instant of the arc initiation for a gap of 1/4 of an inch.

The results of Table (2) are plotted in Figure (9). From the above results, it can be seen that the arc voltage at the starting point is fixed at 10 volts and the parameter that increased with the increase of the applied voltage was the value of the arc current at the instant of arc initiation.

Applied Voltage = 375 volts



Applied Voltage = 425 volts



Top oscillograms show arc current.

Bottom oscillograms show arc voltage.

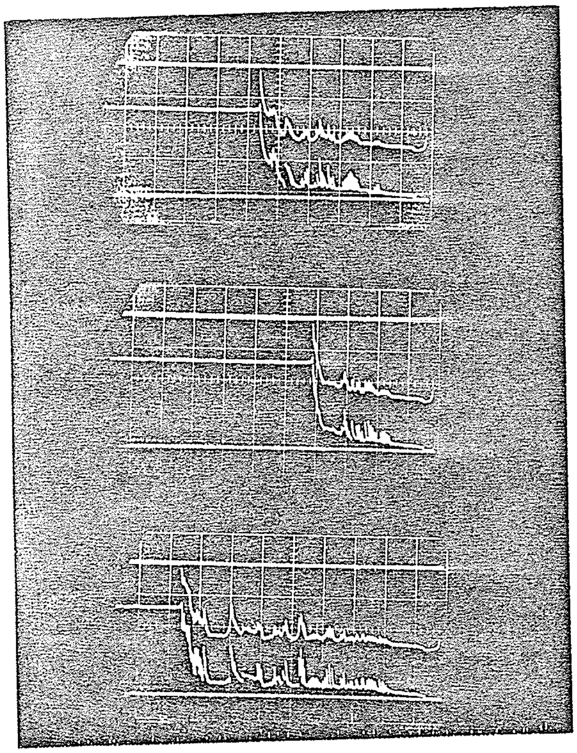
FIGURE (5)

Arc Characteristics in FC 75 for 1/4" Contact Opening

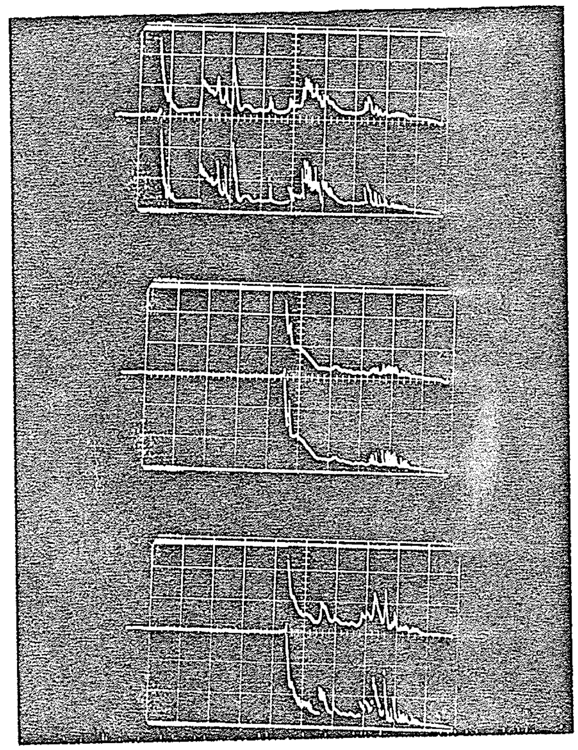
Scale per Division

time = 20 m.sec.
current = 2 amperes
voltage = 20 volts

Applied Voltage = 475 volts



Applied Voltage = 525 volts



Top oscillograms show arc current.

Bottom oscillograms show arc voltage.

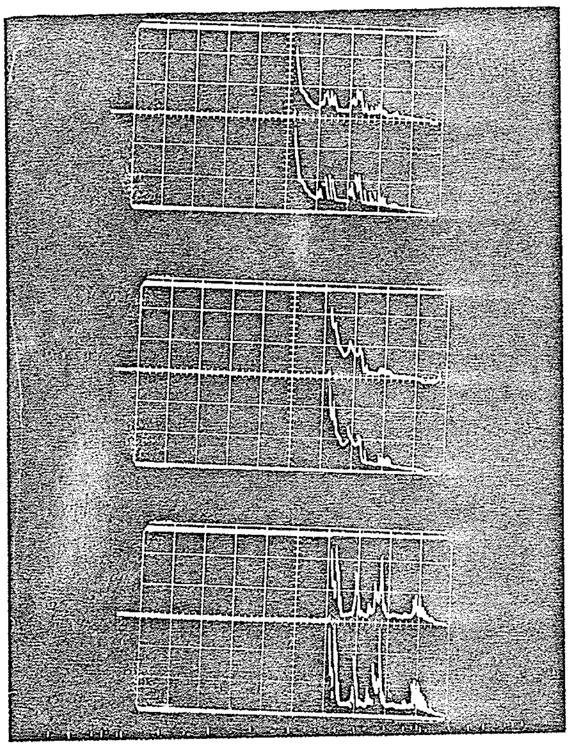
FIGURE (6)

Arc Characteristics in FC 75 for 1/4" Contact Opening

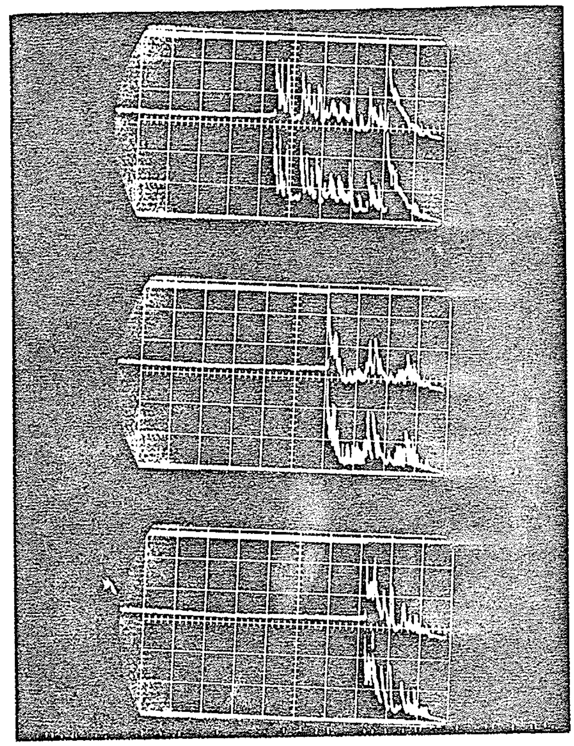
Scale per Division

time = 20 m.sec.
current = 2 amperes
voltage = 20 volts

Applied Voltage = 550 volts



Applied Voltage = 575 volts



Top oscillograms show arc current.

Bottom oscillograms show arc voltage.

FIGURE (7)

Arc Characteristics in FC 75 for 1/4" Contact Opening

Scale per Division

time = 50 m.sec.
current = 2 amperes
voltage = 20 volts

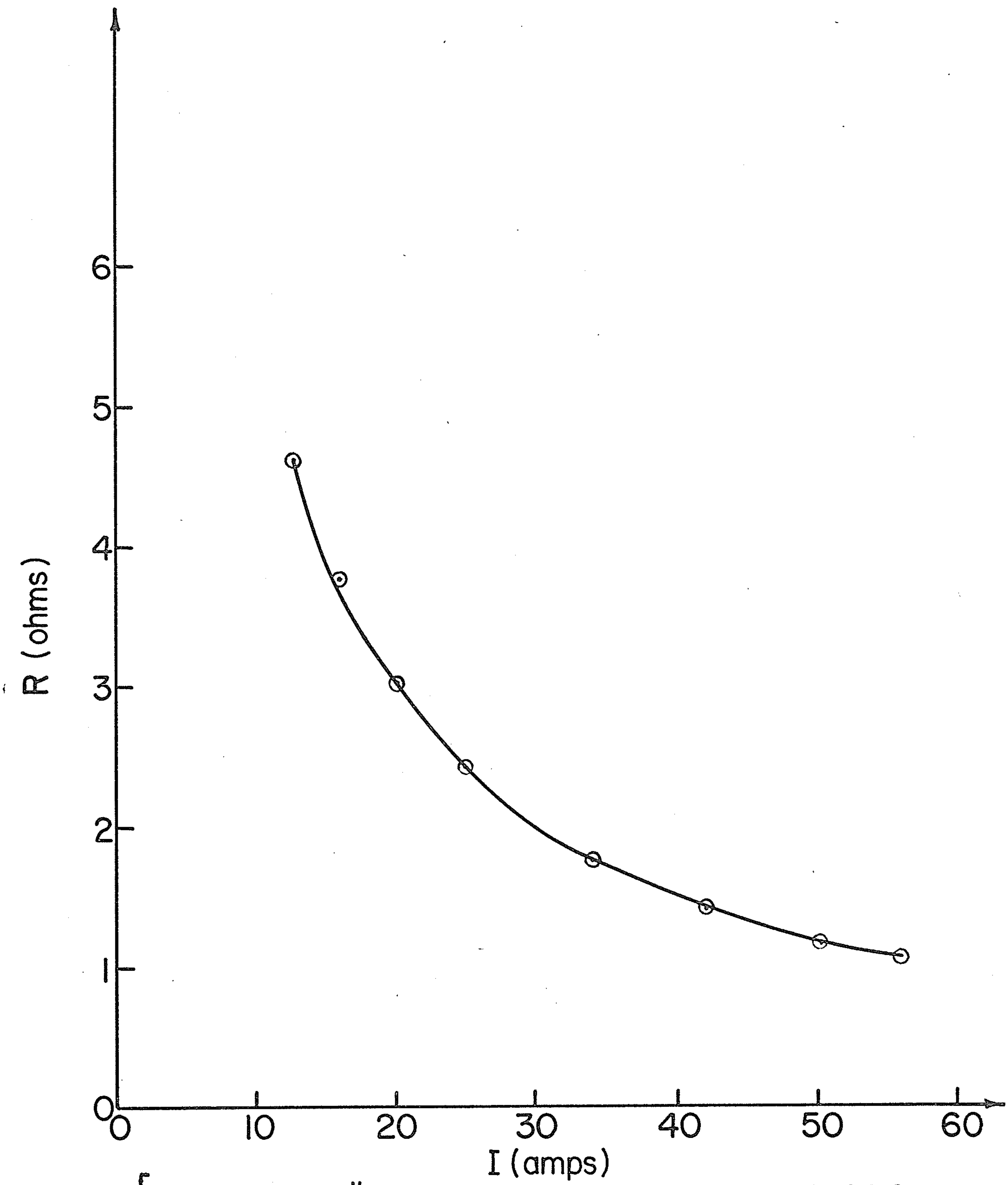


FIGURE 8 [FC 75 1/4" GAP RELATION BETWEEN ARC RESISTANCE AND ARC CURRENT]

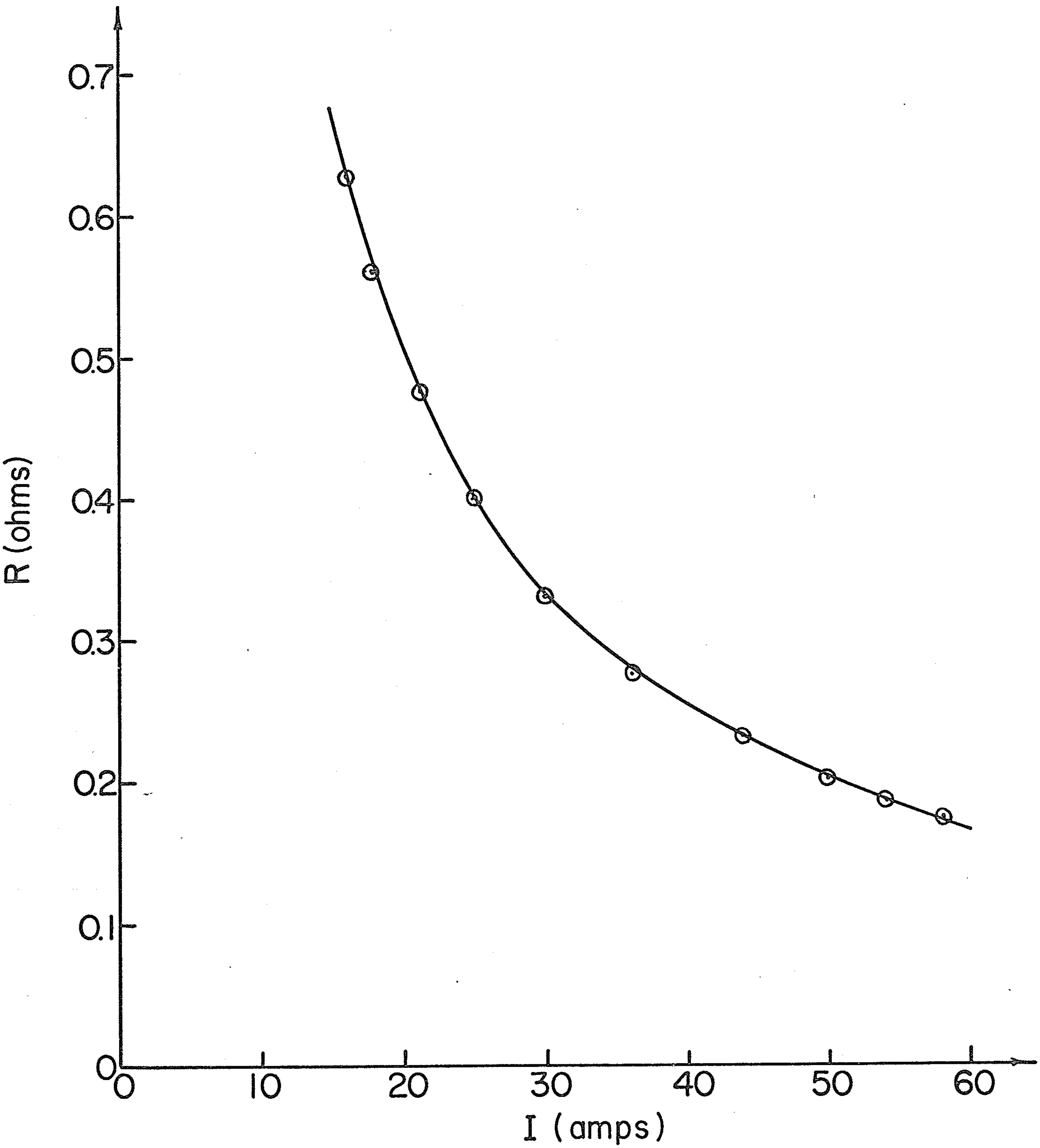


FIGURE 9 [Fc 75 1/4" GAP RELATION BETWEEN ARC RESISTANCE AND CURRENT AT STARTING POINT]

TABLE (1)

The relation between the applied voltage, arc voltage, arc current and arc resistance for a contact opening of 1/4 of an inch in FC 75.

Applied Voltage (volts)		Arc Voltage (volts)	Arc Current (amperes)	Arc Resistance (ohms)
250	18 ohm resistance	60	13	4.60
275		60	14	4.30
300		60	16	3.75
325		60	18	3.35
350		60	20	3.00
375		60	21	2.85
400		60	22	2.72
425		60	24	2.50
450		60	25	2.40
475		60	26	2.30
500		60	30	2.00
525		60	32	1.88
550		60	34	1.77
350	10 ohm resistance	60	32	1.88
375		60	34	1.77
400		60	36	1.66
425		60	42	1.42
450		60	46	1.30
475		60	48	1.25
500		60	50	1.20
525		60	52	1.16
550		60	54	1.12
575		60	56	1.08

TABLE (2)

The relation between the applied voltage, arc voltage, arc current and arc resistance in FC 75 at the instant of arc initiation for contact opening of 1/4 of an inch.

Applied Voltage (volts)		Arc Voltage (volts)	Arc Current (amperes)	Arc Resistance (ohms)
250	18 ohm resistance	10	15	0.675
275		10	16	0.625
300		10	18	0.560
325		10	20	0.500
350		10	21	0.476
375		10	23	0.435
400		10	25	0.400
425		10	27	0.370
450		10	28	0.360
475		10	30	0.333
500		10	32	0.310
525		10	34	0.295
550		10	35	0.285
350	10 ohm resistance	10	36	0.277
375		10	40	0.250
400		10	44	0.230
425		10	48	0.210
450		10	50	0.200
475		10	52	0.192
500		10	54	0.185
525		10	56	0.179
550		10	58	0.173
575		10	60	0.167

TABLE (3)

The relation between the applied voltage, arc voltage, arc current and arc resistance in FC 75 at the instant of arc extinction for an opening of 1/4 of an inch.

Applied Voltage (volts)		Arc Voltage (volts)	Arc Current (amperes)	Arc Resistance (ohms)
250	18 ohm resistance	86	12.0	7.20
275	18 ohm resistance	96	11.6	8.30
300	18 ohm resistance	72	14.8	4.86
325	18 ohm resistance	116	14.2	8.20
350	18 ohm resistance	100	16.0	6.25
375	18 ohm resistance	92	18.0	5.10
400	18 ohm resistance	120	18.8	6.40
425	18 ohm resistance	80	21.8	3.66
450	18 ohm resistance	176	18.6	9.50
475	18 ohm resistance	120	23.2	5.20
500	18 ohm resistance	176	22.8	7.70
525	18 ohm resistance	112	27.2	4.10
550	18 ohm resistance	96	28.8	3.34
350	10 ohm resistance	80.6	29.3	2.95
375	10 ohm resistance	93.3	33.3	2.80
400	10 ohm resistance	113.3	36.3	3.10
425	10 ohm resistance	126.6	36.0	3.52
450	10 ohm resistance	126.6	36.6	3.45
475	10 ohm resistance	153.3	36.0	4.25
500	10 ohm resistance	134	41.3	3.25
525	10 ohm resistance	126.6	44.0	2.86
550	10 ohm resistance	100	47.3	2.13
575	10 ohm resistance	153.3	42.6	3.6

TABLE (4)

The relation between the applied voltage, arc current and arc time duration in FC 75 for a contact opening of 1/4 of an inch.

Applied Voltage (volts)		Arc Current (amperes)	Arc Time Duration (m.sec.)
250	18 ohm resistance	13	46.8
275		14	68.4
300		16	91.2
325		18	76.4
350		20	110.8
375		21	83.6
400		22	67.6
425		24	68
450		25	86.4
475		26	79.6
500		30	68
525		32	103.2
550		34	108.8
350	10 ohm resistance	32	82
375		34	126.6
400		36	90.6
425		42	110
450		46	126.6
475		48	122
500		50	88
525		52	136.6
550		54	89.3

The arc voltage, arc current and the corresponding resistance measured at the end of contact opening for a 1/4 inch gap are included in Table (3).

The average value of the arc voltage at the instant of arc extinction was 115.5 volts, while that at the instant of arc initiation (Table (2)) was 10 volts. This gives an average value of 62.7 volts for the arc voltage, which agrees with the measured values introduced in Table (1) within an error of ±3%. Table (4) shows the relation between the arc current and the arc time duration for FC 75, for a contact opening of 1/4 of an inch.

From the above it was noticed that the arc time duration shows considerable scatter. This is due to the deterioration of the liquid and the existence of the by-products of the arc. It was observed that when the liquid was allowed to rest and then tested again the arc time duration was short and then increased with the increase of the number of arc interruptions, which appears to indicate that the time duration depends on the existence of the by-products of the arc and the degree of deterioration. The average time duration for the arc was calculated and found to be equal to 97 m.sec. From Tables (3) and (4) it was seen that the arc voltage at the instant of arc extinction and the arc time duration are not reproduceable. The oscillograms taken for the arc characteristics showed that before the arc was completely quenched, the liquid tended to quench the arc several times but before quenching was completed, it restriked and the value of the arc voltage at the instant of arc extinction was affected by these instabilities.

To compare the arc characteristics of FC 75 for different arc lengths, the liquid was tested at 200 volts applied from the d-c generator and 10 ohm load resistance connected in the circuit for three different contact openings.

The results are given in Table (5).

TABLE (5)

The relation between arc voltage, arc current, arc resistance and arc time duration in FC 75 for different contact openings.

Fig. No.	Gap Open.	Arc Voltage (volts)	Arc Current (amperes)	Arc Resistance (ohms)	Arc Duration (m.sec.)
12	1/2"	70	16	4.37	65.3
11	1/4"	60	18	3.35	65.3
10	1/8"	40	21	1.9	55

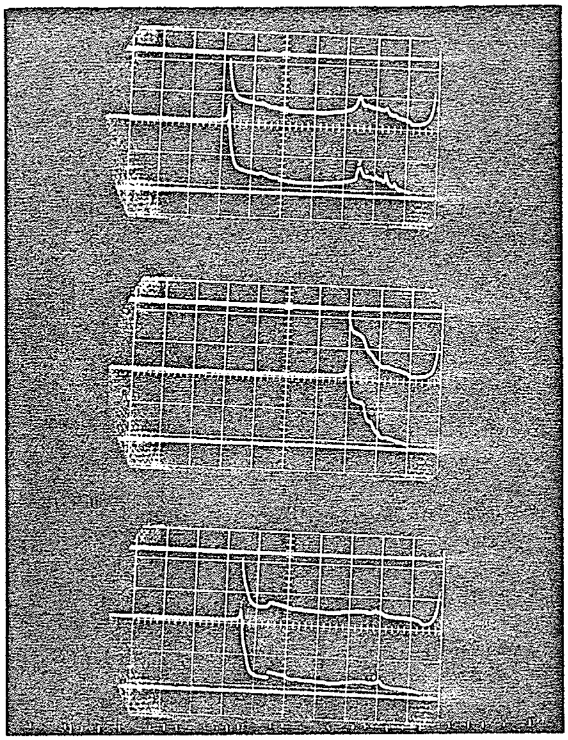
From the above results, it can be seen that when the gap length increased, the arc voltage increased and the arc current decreased, but the arc gradient did not remain constant. When the liquid in the test cell was examined, it was noticed that it consisted of two different compounds immisible in each other. When these two compounds were left overnight, they separated into two distinct layers with a very thin layer of carbon between them.

The chemical analysis of the two compounds showed that:

(1) compound resting on surface -

Carbon $\simeq$ 0.40%

Hydrogen $\simeq$ 11.25%



Top oscillograms show arc current.

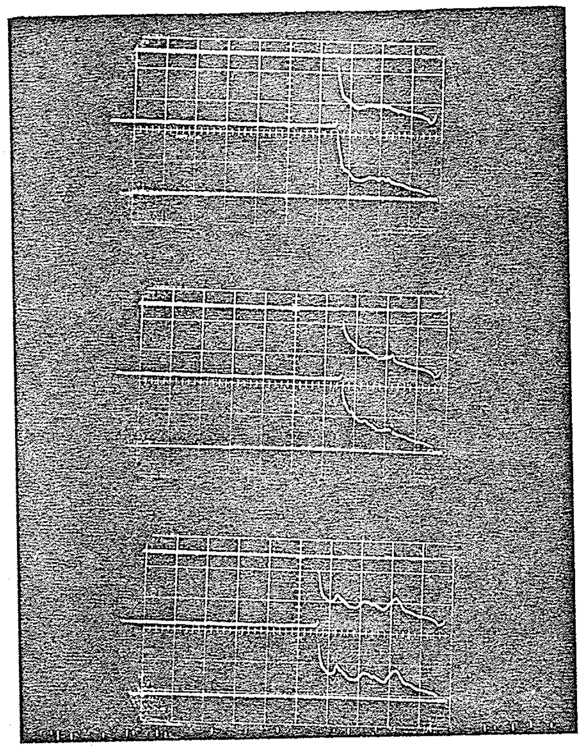
Bottom oscillograms show arc voltage.

FIGURE (10)

Arc Characteristics in FC 75 for 1/8" Contact Opening and 200 Volts Applied Voltage

Scale per Division

time = 10 m.sec., current = 1 ampere voltage = 10 volts



Top oscillograms show arc current.

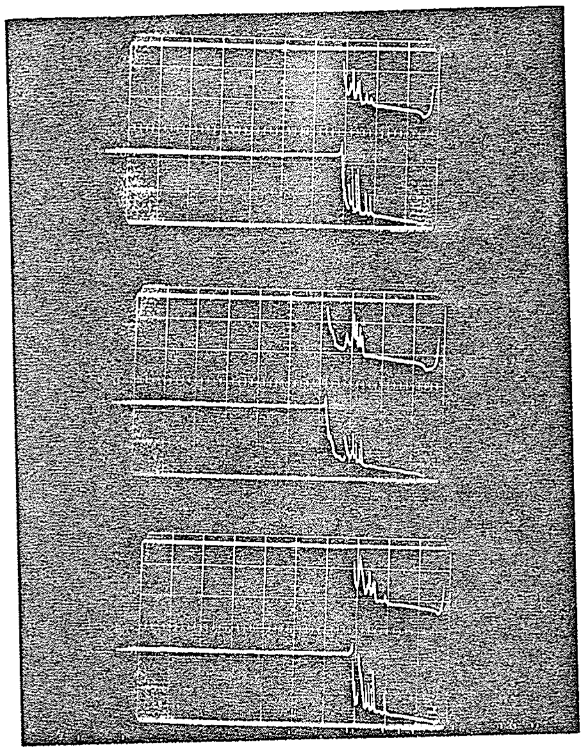
Bottom oscillograms show arc voltage.

FIGURE (11)

Arc Characteristics in FC 75 for 1/4" Contact Opening and 200 Volts Applied Voltage

Scale per Division

time = 20 m.sec., current = 1 ampere voltage = 10 volts



Top oscillograms show arc current.

Bottom oscillograms show arc voltage.

FIGURE (12)

Arc Characteristics in FC 75 for 1/2" Contact Opening and 200 Volts

Applied Voltage

Scale per Division

time = 20 m.sec., current = 1 ampere voltage = 10 volts

(2) compound at the bottom -

Carbon $\simeq$ 22.53%

Hydrogen $\simeq$ 0.1%

Nitrogen $\simeq$ 0.3%

In the chemical analysis, the compounds were not tested for oxygen or fluorine. The presence of hydrogen and nitrogen in the two compounds can be explained by considering the fact that the cell was not fully filled and this gives a chance for the by-products of the arc to combine with nitrogen and water vapour in the atmosphere.

It was noticed from Figures (10), (11), and (12) that as the contact opening increased, the arc characteristics became erratic. This is clear in the difference between Figure (12) and (10) corresponding to contact opening of 1/2 and 1/8 of an inch respectively. These instabilities occurring might be due to the increase in the arc resistance or as shown in Table (5) due to the increase in the energy stored in the arc column.

3.1 ANALYSIS OF THE EXPERIMENTAL RESULTS OBTAINED FOR TRANSFORMER OIL

Transformer oil was tested under exactly the same circuit conditions as were used for FC 75 and also for 1/4 of an inch contact opening.

Table (6) shows measured average arc voltage, arc current and the corresponding arc resistance for different applied voltages.

Figure (13) shows the relation between the average arc resistance and the average arc current. The above table shows that the arc voltage was constant at 80 volts and was not affected by the increase in the applied voltage. On the other hand, the arc current increased with the increase in the applied voltage and hence the arc resistance decreased.

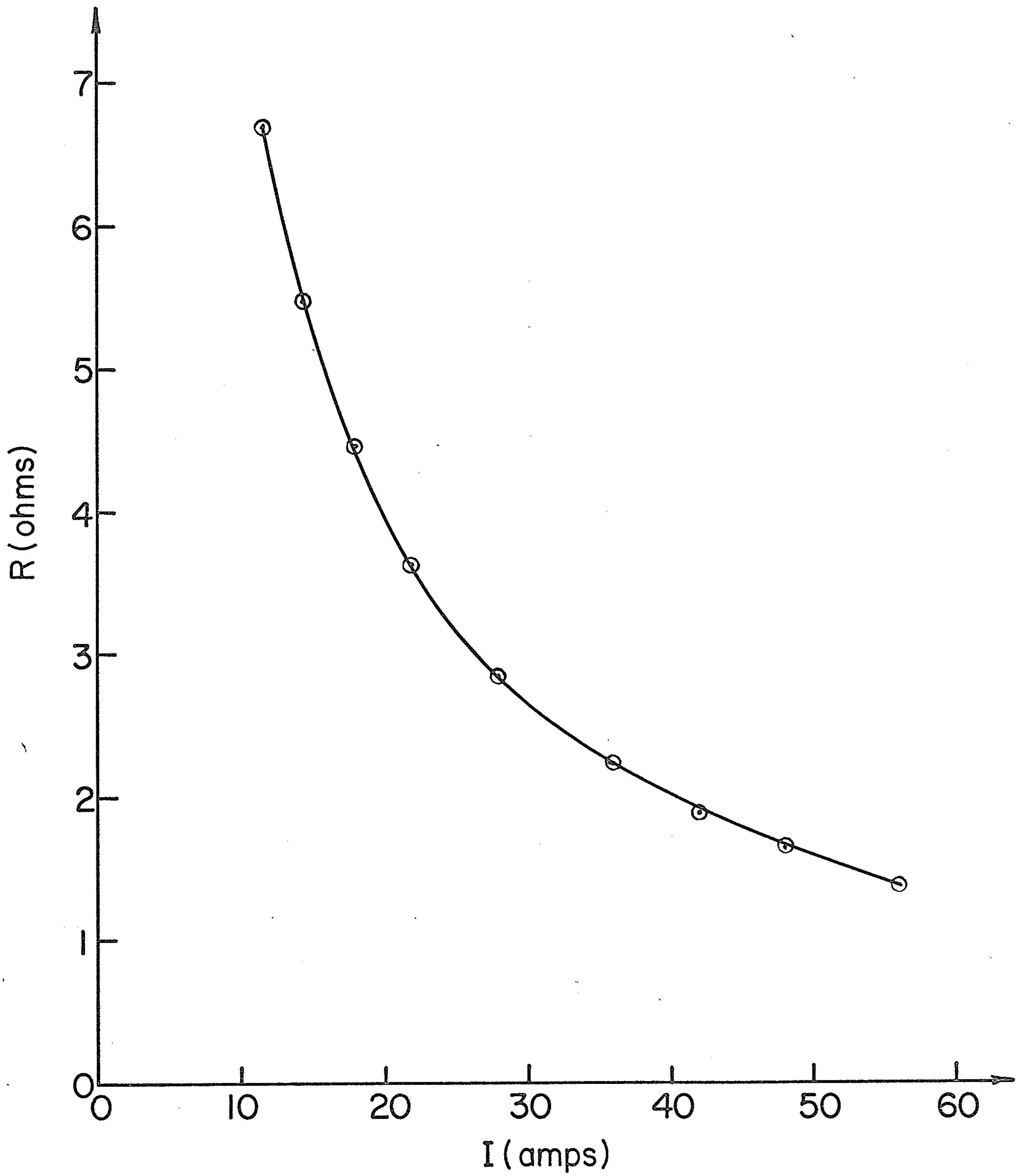
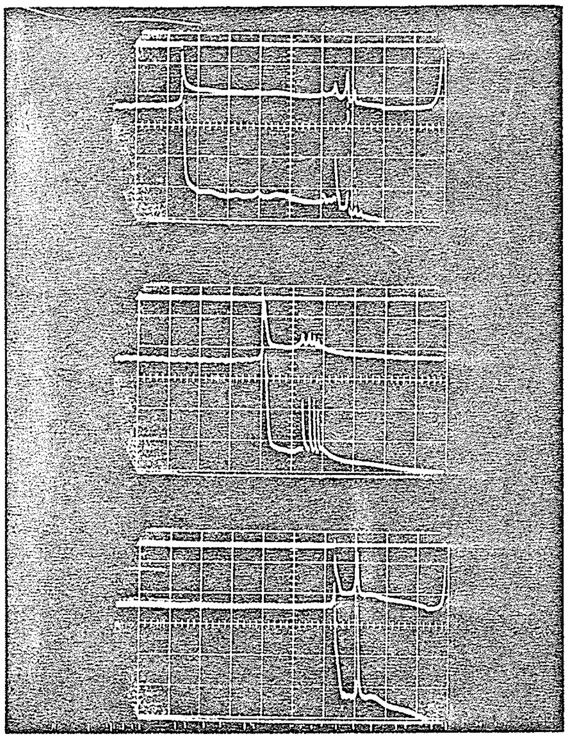
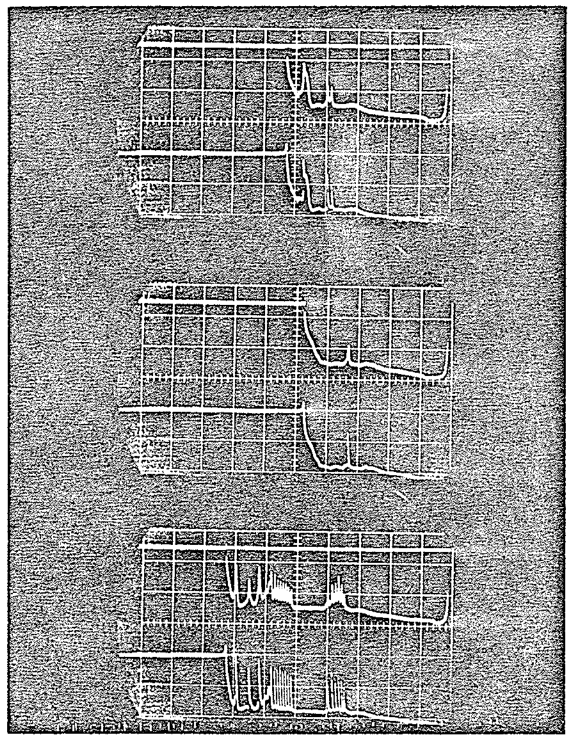


FIGURE 13 [TRANSFORMER OIL ARC RESISTANCE AGAINST CURRENT FOR 1/4" GAP]

Applied Voltage = 325 volts



Applied Voltage = 375 volts



Top oscillograms show arc current.

Bottom oscillograms show arc voltage.

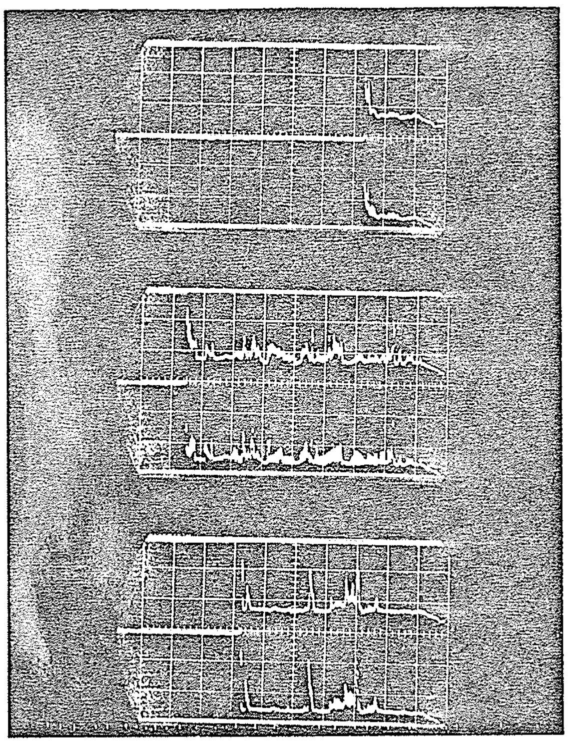
FIGURE (14)

Arc Characteristics in Transformer Oil for 1/4" Contact Opening

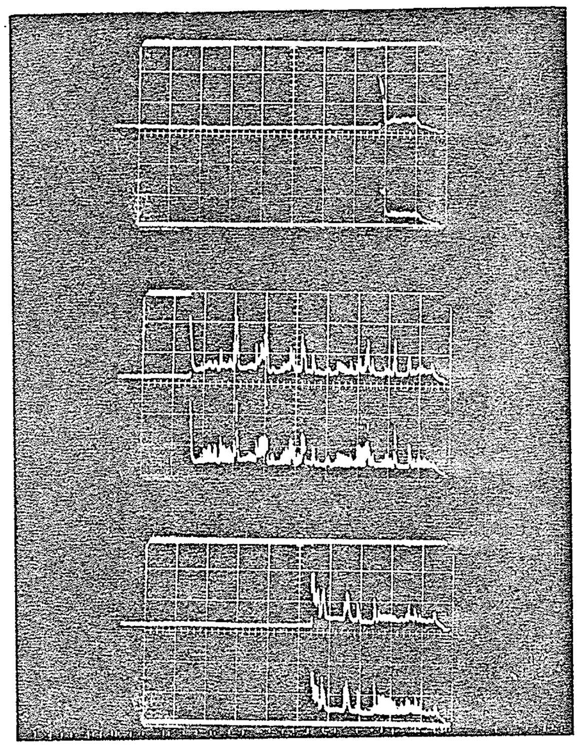
Scale per Division

time = 5 m.sec.
current = 0.5 amperes
voltage = 10 volts

Applied Voltage = 525 volts



Applied Voltage = 575 volts



Top oscillograms show arc current.

Bottom oscillograms show arc voltage.

<u>FIGURE (15)</u>

Arc Characteristics in Transformer Oil for 1/4" Contact Opening

Scale per Division

time = 50 m.sec.
current = 2 amperes
voltage = 20 volts

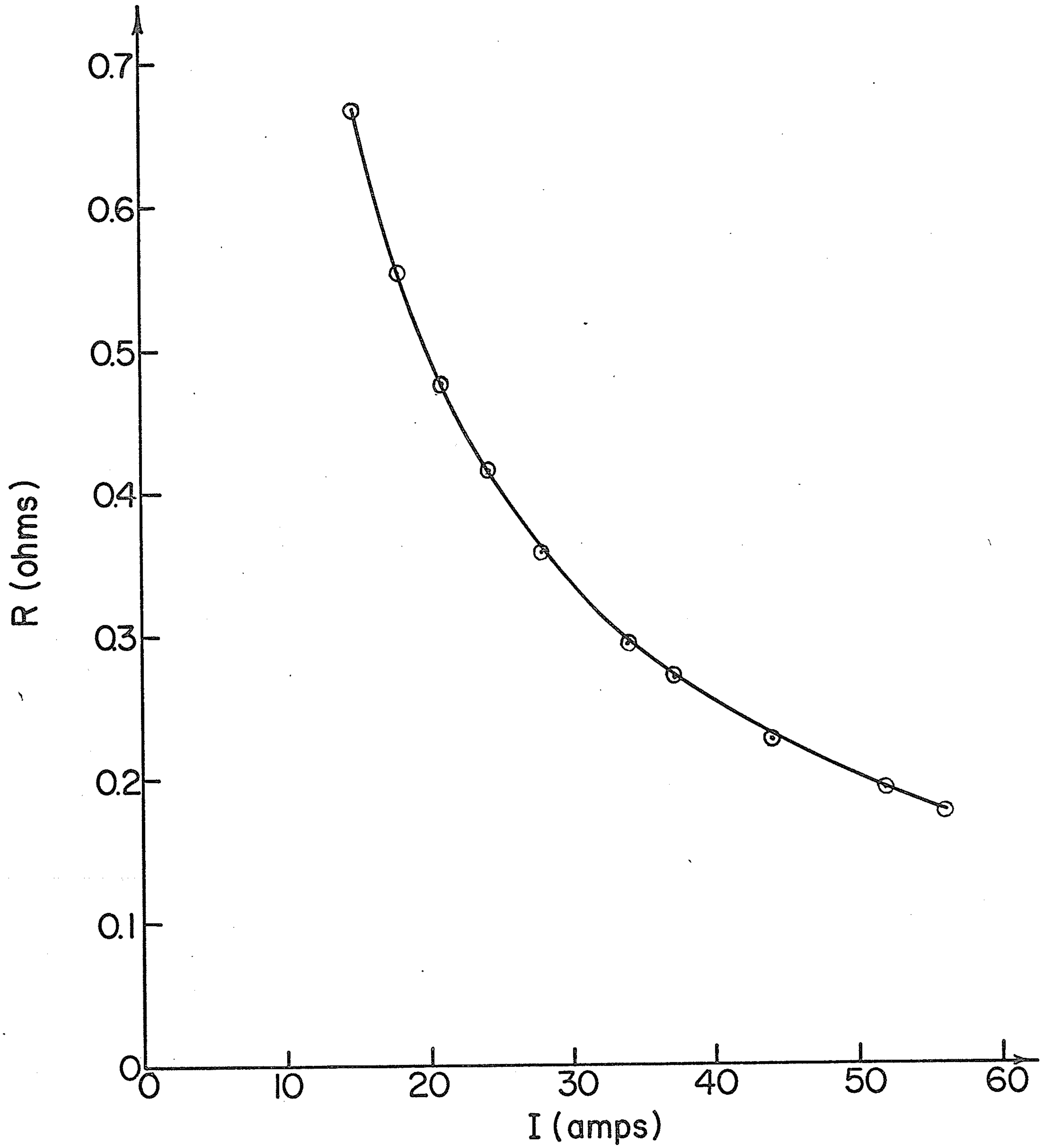


FIGURE 16 [TRANSFORMER OIL ARC RESISTANCE AGAINST CURRENT AT STARTING POINT]

TABLE (6)

The relation between the applied voltage, arc voltage, arc current and arc resistance in transformer oil for a contact opening of 1/4 of an inch.

Applied Voltage (volts)		Arc Voltage (volts)	Arc Current (amperes)	Arc Resistance (ohms)
250	18 ohm resistance	80	12	6.7
275		80	14	5.7
300		80	17	4.7
325		80	18	4.45
350		80	20	4.0
375		80	21	3.8
400		80	22	3.64
425		80	24	3.34
450		80	26	3.07
475		80	27	2.96
500		80	28	2.86
525		80	32	2.5
550		80	34	2.35
575		80	36	2.22
350	10 ohm resistance	80	37	2.16
375		80	40	2.0
400		80	42	1.9
425		80	44	1.82
450		80	48	1.67
475		80	50	1.6
500		80	52	1.54
525		80	52	1.54
550		80	54	1.48
575		80	55	1.46

The voltage and the current at the instant of arc initiation were also measured and the results are shown in Table (7).

Figure (16) shows the relation between the arc resistance and current at the instant of arc initiation. From the above results, it was noticed that the arc voltage at that instant was constant at 10 volts while the arc current increased. Table (8) shows the relation between the applied voltage, arc voltage, current and arc resistance when the contacts were fully open.

Table (9) shows the relation between the applied voltage, arc current and time duration. These results give an average time duration of 92 m.sec. It is clear from these results that the values of the time duration of the arc show considerable scatter. This large scatter may probably be attributed to the variation in the thermal conductivity of the liquid which changes due to the deterioration of the oil and due to the formation of the by-products of the arc.

From the oscillograms taken for the arc characteristics, it was noticed that before the arc was completely quenched, the liquid tended to quench the arc several times but it restriked before the quenching was completed and the value of the arc voltage before arc extinction was affected by these instabilities.

Transformer oil was also tested at three different gap settings and the applied voltage was 200 volts with a load resistance in the circuit of 10 ohms.

The results obtained are shown in Table (10).

TABLE (7)

The relation between applied voltage, arc voltage, arc current and arc resistance in transformer oil at the instant of arc initiation.

Applied Voltage (volts)		Arc Voltage (volts)	Arc Current (amperes)	Arc Resistance (ohms)
250	18 ohm resistance	10	15	0.67
275		10	17	0.588
300		10	18	0.555
325		10	20	0.50
350		10	21	0.476
375		10	22	0.455
400		10	24	0.416
425		10	27	0.37
450		10	28	0.36
475		10	28	0.36
500		10	30	0.333
525		10	34	0.295
550		10	34	0.295
350	10 ohm resistance	10	37	0.27
375		10	41	0.244
400		10	44	0.226
425		10	48	0.209
450		10	48.6	0.206
475		10	50	0.20
500		10	54	0.185
525		10	52	0.192
550		10	54	0.185
575		10	56	0.179

TABLE (8)

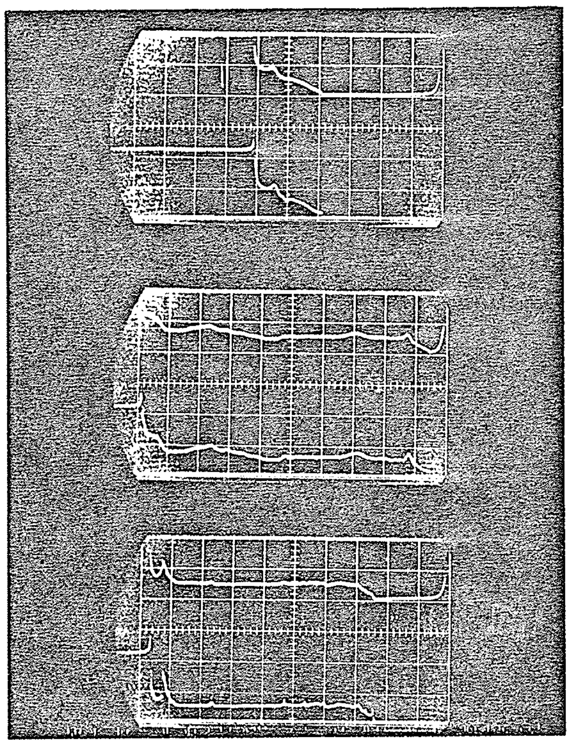
The relation between the applied voltage, arc voltage, arc current and arc resistance in transformer oil at the instant of arc extinction.

Applied Voltage (volts)	Arc Voltage (volts)	Arc Current (amperes)	Arc Resistance (ohms)
18 ohm resistance			
250	120	9.3	12.9
275	93.3	11.6	8.1
300	80	14.3	5.6
325	90	15.3	5.9
350	113.3	15.6	7.2
375	100	17	5.9
400	93.3	18.6	4.76
425	80	23	3.48
450	80	23.3	3.43
475	100	22	4.55
500	100	24.6	4.05
525	80	30	2.66
550	86.6	32.6	2.55
10 ohm resistance			
575	166.6	26	6.4
350	80	22	3.6
375	80	30.6	2.6
400	80	34	2.35
425	80	42.6	1.98
450	80	45.3	1.77
475	93.3	44.6	2.1
500	93.3	45.3	2.06
525	93.3	46	2.04
550	100	48.6	2.05
575	86.6	53.3	1.62

TABLE (9)

The relation between the applied voltage, arc current and arc time duration in transformer oil for a contact opening of 1/4 of an inch.

Applied Voltage (volts)		Arc Current (amperes)	Arc Duration (m.sec.)
250	18 ohm resistance	12	23.3
275		14	28.83
300		17	19.3
325		18	28.83
350		20	42.3
375		21	47.3
400		22	68.6
425		24	76.6
450		26	61.3
475		27	78.6
500		28	96
525		32	116
550		34	51.3
575		36	82
350	10 ohm resistance	37	56
375		40	66.6
400		42	78.6
450		48	42.6
475		50	63.3
500		52	281.6
550		54	196.6
575		55	433.3



Top oscillograms show arc current

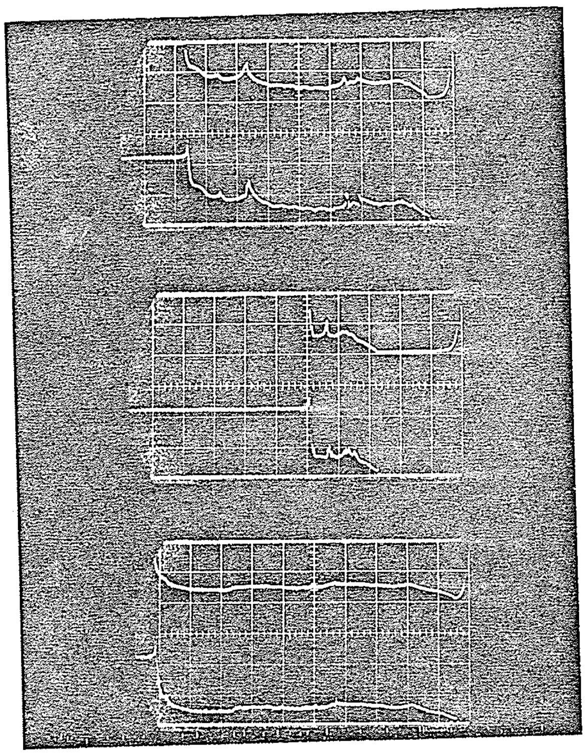
Bottom oscillograms show arc voltage.

FIGURE (17)

Arc Characteristics in Transformer Oil for 1/8" Contact Opening and 200 Volts Applied Voltage

Scale per Division

time = 10 m.sec., current = 1 ampere voltage = 10 volts



Top oscillograms show arc current.

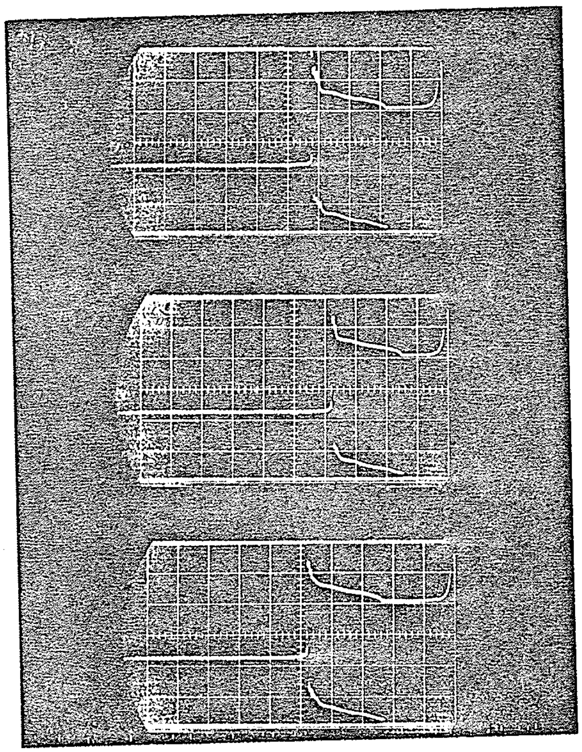
Bottom oscillograms show arc voltage.

FIGURE (18)

Arc Characteristics in Transformer Oil for 1/4" Contact Opening and 200 Volts Applied Voltage

Scale per Division

time = 10 m.sec., current = 10 amperes, voltage = 10 volts



Top oscillograms show arc current.

Bottom oscillograms show arc voltage.

FIGURE (19)

Arc Characteristics in Transformer Oil for 1/2" Contact Opening and 200 Volts Applied Voltage

Scale per Division

time = 10 m.sec., current = 1 ampere voltage = 10 volts

TABLE (10)

The relation between arc voltage, current, resistance and time duration in transformer oil for contact opening of 1/2, 1/4 and 1/8 of an inch.

Fig. No.	Gap Setting	Arc Voltage (volts)	Arc Current (amperes)	Arc Resistance (ohms)	Arc Duration (m.sec.)
19	1/2"	100	14	7.15	24.8
18	1/4"	80	14.3	5.6	25.3
17	1/8"	65	15	4.34	64.1

From the above results, it is clear that the arc voltage increased as the contact opening increased while the arc current decreased but the voltage gradient did not remain constant.

3.2 TESTING THE BREAKDOWN STRENGTH OF TRANSFORMER OIL AND FC 75

The a-c breakdown strength of both transformer oil and FC 75 was tested in the two conditions before and after arcing. The cell used for this purpose was Westinghouse oil test cup standard gap 0.1 inch.

The results obtained are shown in Table (11).

TABLE (11)

Breakdown values of transformer oil and FC 75 before and after arcing.

Transformer Oil		FC 75	
Before Arcing	After Arcing	Before Arcing	After Arcing
28 KV. (R.M.S.) 24.5 KV. (")	29 KV. (R.M.S.) 31.5 KV. (")	31 KV. (R.M.S.) 31 KV. (")	12 KV. (R.M.S.) 12 KV. (")

The above values are low due to the presence of moisture in the sample of oil tested.

3.3 ANALYSIS OF THE RESULTS OBTAINED FOR SF_6

The effect of opening contacts connected to a d-c supply in SF_6 was studied for three contact openings 1/2, 1/4 and 1/8 of an inch. The experimental results for a contact opening of 1/2 of an inch and 10 ohm load resistance are given in Table (12).

TABLE (12)

The relation between the applied voltage, arc voltage, arc current, and arc resistance in SF_6 for a contact opening of 1/2 of an inch.

Applied Voltage (volts)	Arc Voltage (volts)	Arc Current (amperes)	Arc Resistance (ohms)
200	60	16	3.75
250	60	20	3.0
300	60	25	2.4
350	60	30	2.0
400	60	36	1.76
450	60	40	1.5
500	60	44	1.36

From the above results, it is clear that the arc voltage is constant at 60 volts and the arc current increases with the increase in the applied voltage. Figure (20) shows the relation between the arc resistance and the arc current in SF_6.

When the contacts opening was reduced to 1/4 of an inch, it was noticed that the arc voltage dropped to 50 volts but the voltage gradient did not remain constant. Table (13) includes the values of the applied voltage, arc voltage, arc current and the corresponding resistance for a contact opening of 1/4 of an inch.

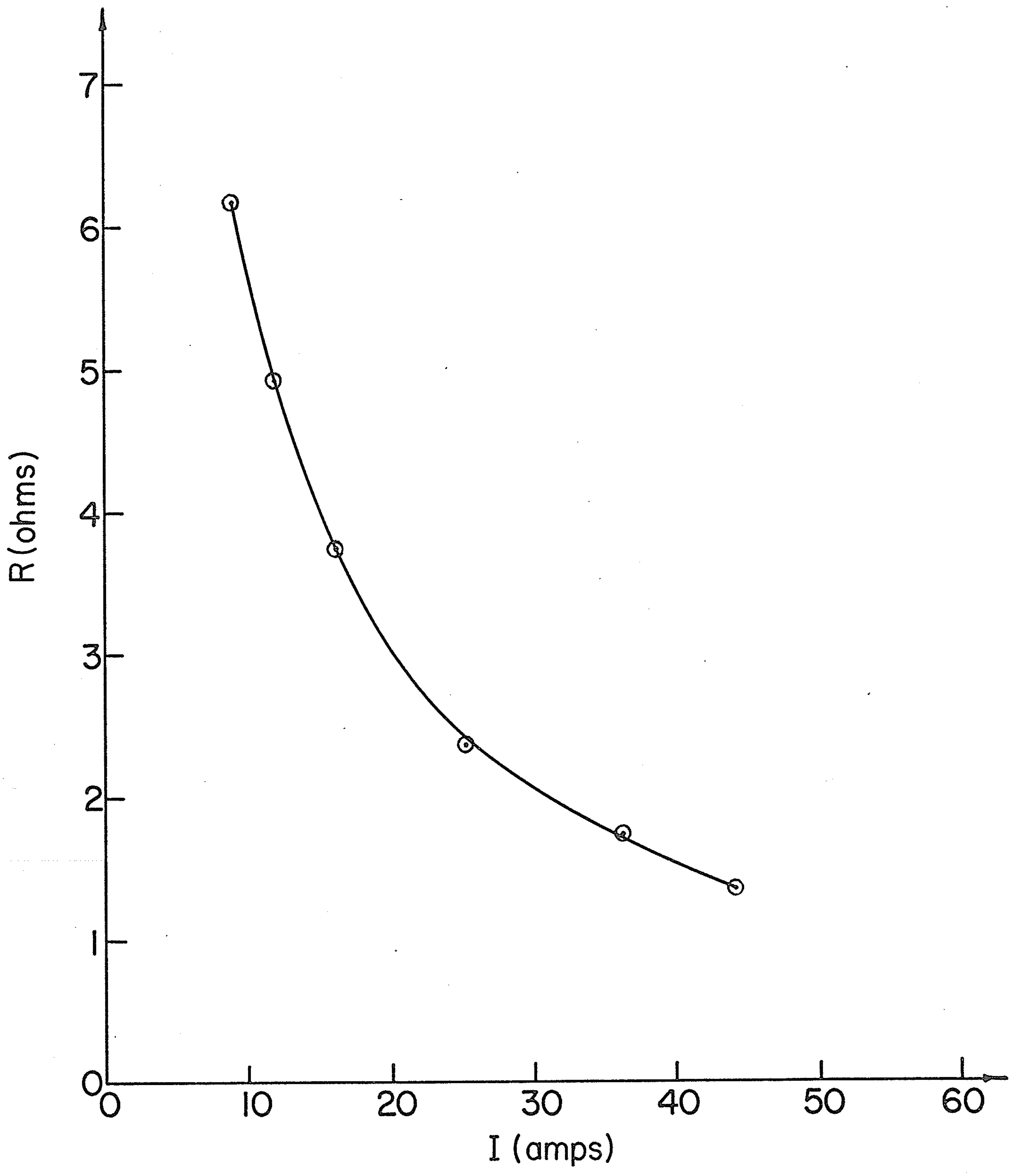
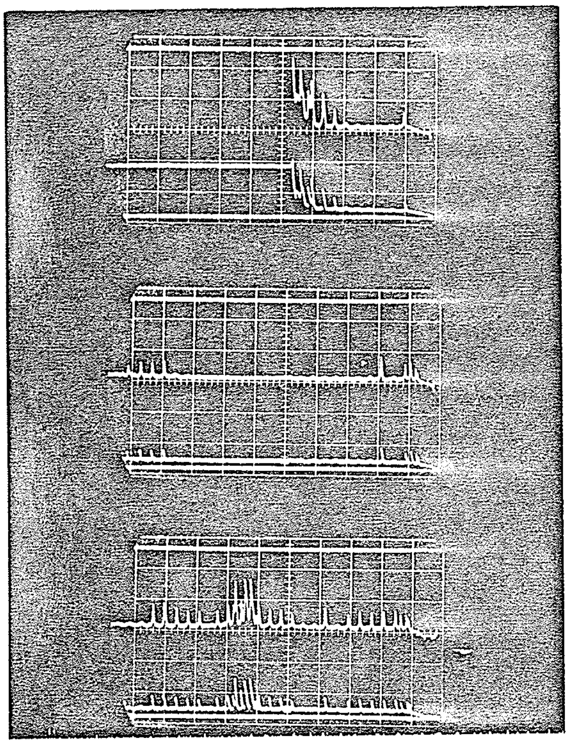
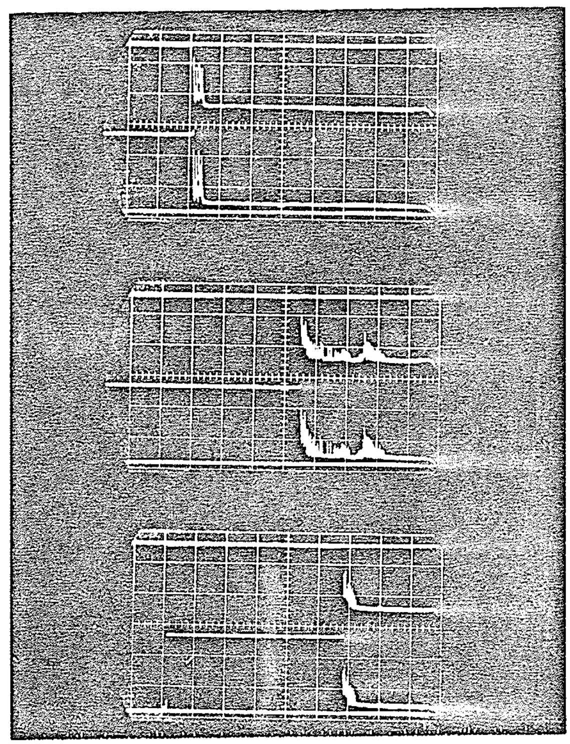


FIGURE 20 [SF_6 ARC RESISTANCE AGAINST CURRENT AT 1/2" GAP]

Applied Voltage = 300 volts



Applied Voltage = 450 volts



Top oscillograms show arc current.

Bottom oscillograms show arc voltage.

Scale per Division

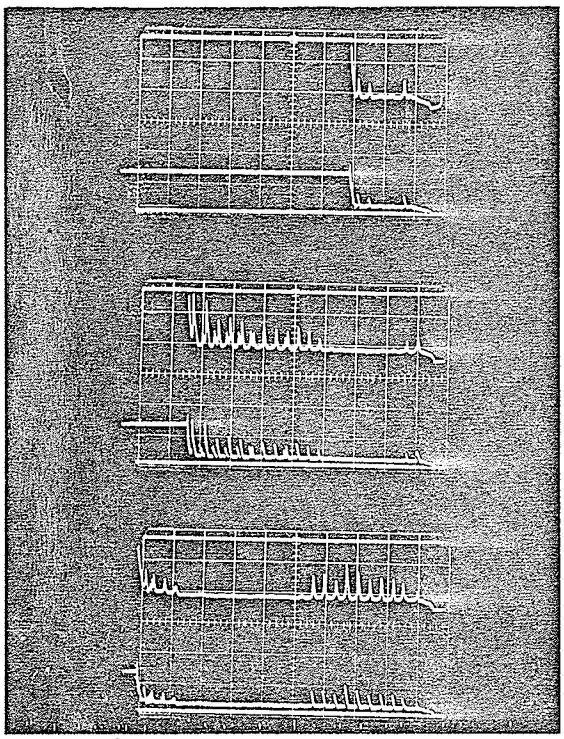
time = 50 m.sec., current = 1 ampere   time = 0.2 sec., current = 2 amperes

FIGURE (21)

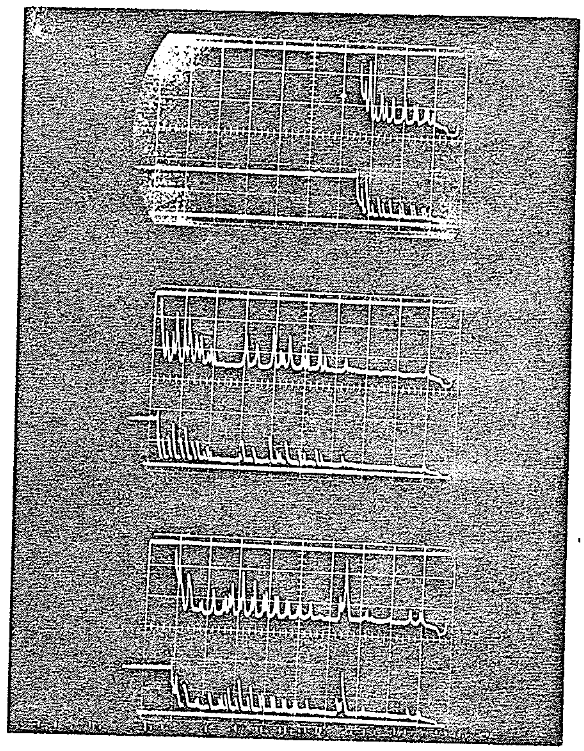
Arc Characteristics in SF_6 Gas for 1/2" Contact Opening

voltage = 20 volts/division

Applied Voltage = 225 volts



Applied Voltage = 275 volts



Top oscillograms show arc current.

Bottom oscillograms show arc voltage.

<u>FIGURE (22)</u>

Arc Characteristics in SF_6 Gas for 1/4" Contact Opening

Scale per Division

time = 50 m.sec.
current = 1 ampere
voltage = 20 volts

TABLE (13)

The relation between applied voltage, arc voltage, current and arc resistance in SF_6 for a contact opening of 1/4 of an inch.

Applied Voltage (volts)	Arc Voltage (volts)	Arc Current (amperes)	Arc Resistance (ohms)
200	50	17	2.95
225	50	19	2.64
250	50	21	2.4
275	50	23	2.16
300	50	26	1.92

Figure (23) shows the relation between arc resistance and arc current for a contact opening of 1/4 of an inch. When the contact opening was changed to 1/8 of an inch, the arc voltage dropped to 40 volts. As far as the arc time duration is concerned, it was found that for a contact opening of 1/4 of an inch the arc duration was 340 m.sec. and the arc characteristics were unstable. The by-products of the arc were highly corrosive and affected to a large extent the performance of the contacts and the solenoid in the sense that after each set of readings for the same gap setting, the contacts were changed.

The values of the arc voltage obtained in this experiment were higher than those obtained by Swarbrick (5) for the same contact opening. This difference is probably because the arc voltage included large electrode drops and also because the arc in this experiment was not stabilized while in Swarbrick's work effective stabilization was obtained by forcing the arc to burn in a cylindrical column of discs.

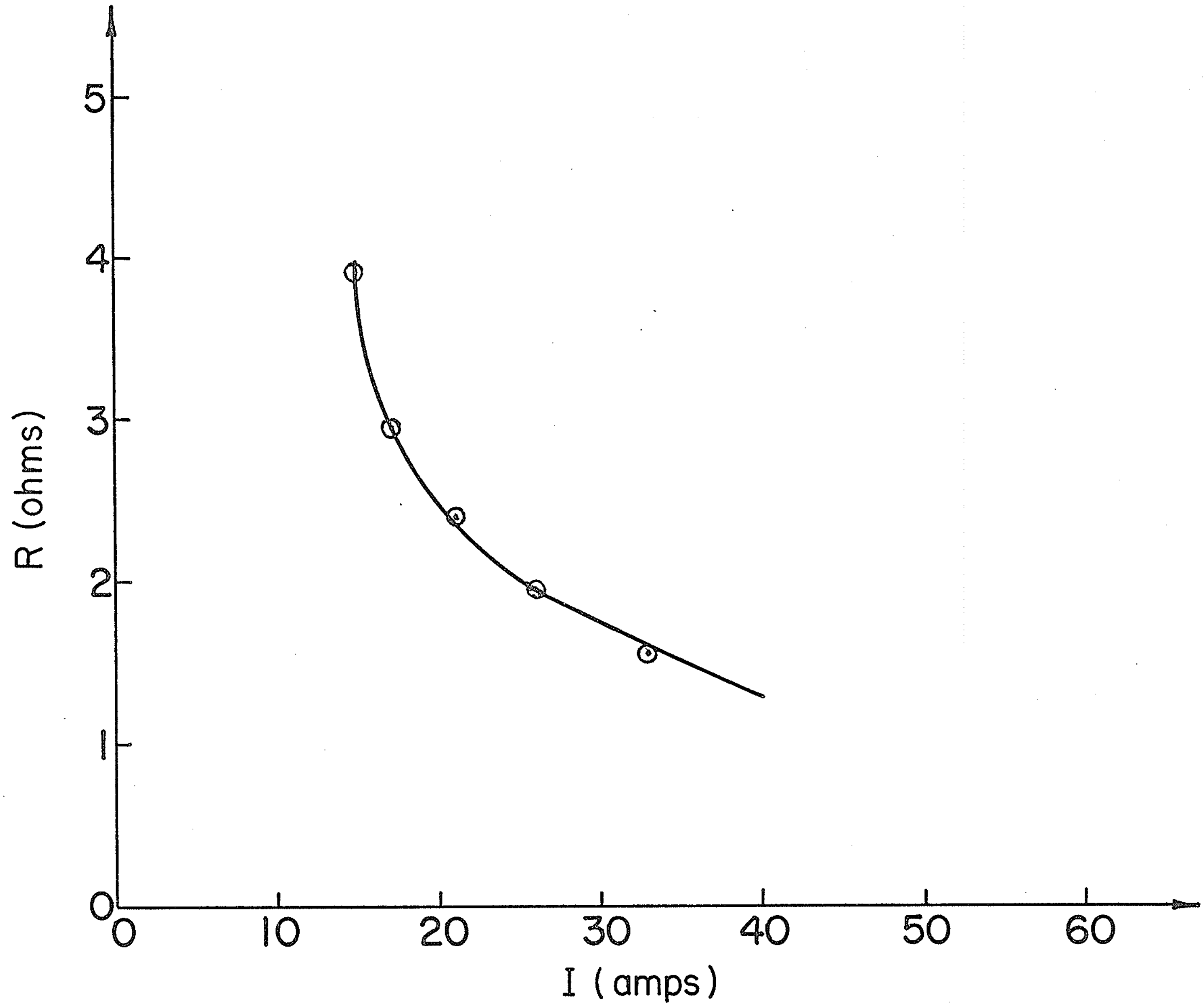


FIGURE 23 [SF_6 ARC RESISTANCE AGAINST CURRENT AT 1/4" GAP]

4.

4.1 DISCUSSION OF RESULTS

The present investigations in both FC 75 and transformer oil showed that the average arc voltage remained constant and did not change with variation of the applied voltage. The value of the average arc voltage was found to be higher in transformer oil than in FC 75. On the other hand, the average arc current in both cases increased with increase in the applied voltage. When the arc voltage at the instant of arc initiation was measured for both compounds, it was found that the value was the same and equal to 10 volts. In the two liquids the instantaneous arc resistance was calculated by dividing the arc voltage by the corresponding value of the arc current

$$R_a = \frac{V_a}{I_a}$$

Since V_a was constant, this equation represents a rectangular Hyperbola as shown in Figures (8) and (13).

The arc duration time in both cases showed considerable scatter and this was probably due to the change of the condition of the liquid from one rest to another. This was mainly because of the deterioration of the liquid and to the effect of the by-products of the arc. It was noticed that the arc average time duration in FC 75 was longer than that in transformer oil, in spite of the fact that the thermal conductivity of FC 75 is much higher than that of transformer oil.

At higher values of current, it was noticed that before the arc was completely quenched, both liquids tended to quench it several times, but it restriked before the quenching had been completed. These instabilities might be due to the recovery of the liquid dielectric strength but before it was completely recovered, breakdown occurred again. These instabilities affected the value of the arc voltage at the instant of arc extinction.

When the products of the arc, in the case of transformer oil, were examined, it was found that the remaining compound was completely black due to the presence of carbon while, in the case of FC 75, it consisted of two immiscible compounds with a very thin layer of carbon between them.

The a-c breakdown strength of the two liquids before and after the experiment indicated that the breakdown strength of transformer oil did not decrease due to deterioration while on the other hand, that of FC 75 decreased from 31 KV. to 12 KV. The chemical effect of the arc products on the cell and its components, in the case of transformer oil, was mild while, in the case of FC 75, this effect was stronger due to the presence of Fluorine in the liquid and its by-products were highly corrosive.

4.2 COMPARISON BETWEEN LIQUIDS AND SF_6 GAS AS ARC QUENCHING MEDIA

From the experimental results obtained, it was clear that the arc voltage in the two liquids was higher than that in SF_6, but the arc time duration was shorter. If typical values are considered, the arc voltage in transformer oil was 80 volts, for FC 75 it was 60 volts, while for SF_6 it was 50 volts (all the values correspond to an opening of 1/4 of an inch). For the same contact opening, the arc time durations were 92, 97 and 340 m.sec. respectively. The chemical effect of the arc products on the cell and its components was mild in the case of the two liquids compared to the effect in the case of SF_6 gas. It was noticed that the upper contact was always more affected than the bottom one in the three media. Due to

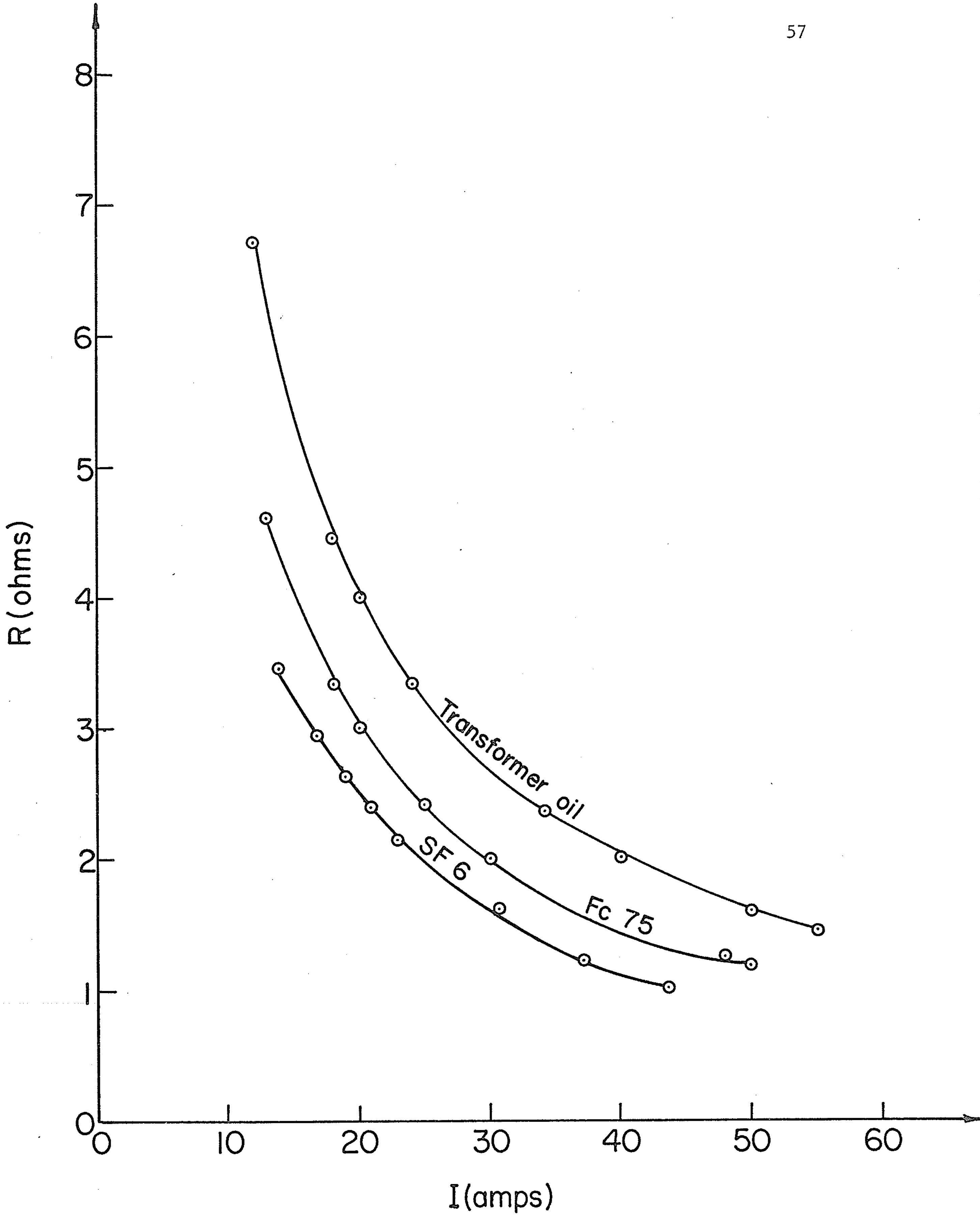


FIGURE 24 [THE RELATION BETWEEN ARC RESISTANCE AND ARC CURRENT FOR A CONTACT OPENING OF AN $\frac{1}{4}$ INCH IN TRANSFORMEROIL, Fc 75 and SF_6]

the fact that SF_6 arc is very filamentary, and hence suffers greatly from instabilities, it makes the free burning arc characteristics difficult to be measured exactly.

The growths of the instability in FC 75 with the increase in arc current is shown by the oscillograms presented in Figures (5), (6) and (7). This phenomena reveals itself also in the case of SF_6.

It should be noted that the accuracy of the results obtained in this experiment is within ±20% error depending on the precision of reading the values of arc voltage, arc current and arc duration from the oscillograms, but the results can be considered comparable to each other since the measuring technique involved was the same for the three media.

4.3 CONCLUSION

The studies presented in this thesis provided a comparison between the d-c arc characteristics in fluorinated cyclic ether (FC 75), transformer oil and sulphur hexafluoride (SF_6) gas.

The results obtained for the arc voltage showed that it had a lower value in the case of SF_6, about 50 volts which increased to 60 volts in FC 75, while in transformer oil it reached 80 volts for a contact opening of 1/4 of an inch.

The measured values of the d-c arc time duration showed considerable scatter, presumably due to the deterioration of the compounds and the by-products of the arc. The values of the arc voltage obtained for SF_6 were high compared with the values obtained by Swarbrick. It is likely that the present values included large electrode drops. From the oscillograms obtained for the arc characteristics, it was noticed that in all three media the arc was quenched and before it extinguished completely, it re-striked again due to the rise of dielectric strength after the current reached nearly zero value. This caused instabilities in the arc characteristics. Although the thermal conductivity of FC 75 is much higher than that of both transformer oil and SF_6, and it was anticipated that FC 75 would quench the arc more readily than the two former media, experiments showed otherwise.

REFERENCES

1. B. P. Baker and H. M. Wilcox, "The Use of Oil in Arc Rupture with Special Reference to System Stability", AIEE Trans. Vol. 49, 1930, pp. 431 - 446.

2. D. C. Prince and W. F. Skeats, "The Oil Blast Circuit Breakers", AIEE Trans. Vol. 50, 1931, pp. 506 - 512.

3. Joseph Slepian, "Displacement and Diffusion in Fluid-Flow Arc Extinction", AIEE Trans. Vol. 60, 1941, pp. 162 - 167.

4. J. Slepian, "Extinction of a Long A-C Arc", AIEE Trans. Vol. 49, 1930, pp. 421 - 430.

5. P. Swarbrick, Ph.D. Thesis, University of Manchester, 1965, "An Investigation of the Characteristics of an Arc Discharge in an Electronegative Gas SF_6".

6. S. Fukuda and T. Ushio, T. Ito and T. Miyamoto, "Recent Studies on Arc Behaviour Around Current Zero in SF_6", International Conference on Large High Tension Electric Systems, 1968 session.

7. T. E. Browne Jr., "A Study of A-C Arc Behaviour Near Current Zero by Means of Mathematical Models", AIEE Trans. Vol. 67, Part I, 1948, pp. 141 - 153.

8. H. J. Lingal, A. P. Strom, T. E. Browne Jr., "An Investigation of the Arc Quenching Behaviour of Sulphur Hexafluoride", AIEE Trans. Vol. 72, Part III, 1953, pp. 242 - 246.

9. B. J. Calvino and P. Pezzi, "Interruption Characteristics of an SF_6 Self-Extinguishing Circuit Breaker", International Conference on Large High Tension Electric Systems, 1968 session.

10. H. J. Lingal and J. B. Ownes, "A New High Voltage Outdoor Load Interruptor Switch", AIEE Trans. Vol. 72, Part III, 1953, pp. 293 - 247.

11. Tsuneo Ushio and Toshio Miyamoto, "Dynamic Behaviour of Arcs in Sulphur Hexafluoride Gas", Mitsubishi Denki Laboratory Reports Vol. 3, No. 2, Apr. 1962, pp. 141 - 164.

12. Technical Information by 3M Company, Chemical Division, on Fluoriner Brand Electronic Liquids.

13. Frank M. Clark, "Insulating Materials for Design and Engineering Practice", Wiley, 1962, pp. 233-238.

14. B. W. Swason and R. M. Roidt, "Boundary Layer Analysis of an SF_6 Circuit Breaker Arc", IEEE Summer Power Meeting, July, 1970.

15. K. H. Yoon and H. E. Spindle, "A Study of the Dynamic Response of Arcs in Various Gases", AIEE Trans. Vol. 77, Part III, 1958, pp. 1634 - 1642.

16. W. M. Leeds, T. E. Browne, A. P. Strom, AIEE Trans. Vol. 76, Part III, 1957, pp. 906, "The Use of SF_6 for High Power Arc Quenching".