THE MEASUREMENT OF GAS PRODUCED BY ELECTRICAL POWER ARCS IN INSULATING OIL

Thesis by

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ABSTRACT

This thesis presents a study of the factors which influence the gas rate (volume of gas produced per unit arc energy) in insulating oil. Such data are fundamental to the design of oil circuit breakers. It is found that the gas rate varies with electrode length, location of arc on the surface, duration of current and material of arcing surface. The gas rate is higher for the longer gap length (3/4 inch) than for the shorter gap length (1/4 inch). An arc on the center of the surface generally gives a lower gas rate while that on the edge a higher gas rate. For arcs occurring on the center, copper surface has a higher gas rate while steel and silver elkalite (alloy used in practice) surfaces have approximately the same lower rate. A high gas rate results in the short duration arc of 1/2 cycle and nearly equal low gas rates are obtained for durations of 2 cycles and 3 1/2 cycles. No appreciable change in gas rate is observed as the magnitude of current peak varies from 400 to 800 amperes.

With the method used in this research, steel surfaces have the desired character that arcs always occur on the center. For 600 amperes and 2 cycle duration, the gas rate of flat steel surfaces referred to 760 mm and 25°C is 74, 133 and 175 cubic centimeters per kilowatt second at 1/4, 1/2 and 3/4 inch gap lengths respectively.

Because the gas rate for silver elkalite and steel surfaces are about the same with arcs on the center, the effect of current magnitude is small and the arc duration in most circuit breaker operation about 2 cycles, the total volume of gas produced in actual operation of a circuit breaker can be calculated approximately by correlating the above figures with field test records of arc energy and electrode travel.

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I. INTRODUCTION

Circuit breakers on power system perform the functions of circuit switching during normal conditions and current interruption during faults or over loads under abnormal conditions. Two principle types of interrupting media are used, namely oil and air. For voltage ratings below 34.5 kv, both air and oil circuit breakers serve the purpose equally well, the choice depending on the service requirements such as indoor or outdoor, power rating, etc. For voltage ratings above 34.5 kv, oil circuit breakers predominate (1) although air blast and oil-poor breakers are making impressive progress (2), (3), (4).

The design of oil circuit breakers has evolved from simple configurations in which a pair of plain contacts opens in oil to the more complicated design of multi-contacts with arc quenching chambers. It is generally recognized (5), (6), (7), (8), that the introduction of fresh oil into the arc helps to extinguish it. One method of forcing fresh oil into the arc is to put the contacts in a semi-enclosed chamber with two or more arcs in series. The pressure of the gas formed at one arc forces fresh oil to flow across the other arcs. This provides more rapid arc quenching. One basic design parameter therefore is the amount of gas produced by the arc. In addition, the knowledge of the amount of gas produced is useful in determining the required air volume above the oil surface of a circuit breaker.

Due to the difficulty of directly measuring the gas and the factors affecting its quantity in the actual operation of a circuit breaker, an alternative procedure is to measure the gas rate (volume of gas produced per unit arc energy) in a more ideal laboratory configuration under various arc conditions. It will be demonstrated that with the gas rate known, the amount of gas produced in the field test of a circuit breaker can be approximately calculated from the arc energy record so that improvement in the design of circuit breakers may be achieved.

In the actual operation of a circuit breaker, the gap length between electrode surfaces is not a fixed value but varies as the electrodes move. With the information available to the author, the maximum separation is about 3/4 inch during arcing time. In general the arcing time is about 2 cycles. The current to be handled ranges from several hundred to tens of thousands of amperes. Due to the large number of combinations of possible arcing conditions, it is desirable to study the effect of each variable by varying it over a desired range while each of the other variables is fixed at a selected value deemed to be the mean or most desirable value. The only convenient method in the High Voltage Laboratory to vary power current duration below three cycles is through the use of ignitron tubes which have a maximum current rating of about 800 amperes. This magnitude of current is far below the high fault current of many thousands of amperes that a circuit breaker is required to handle. However, previous researches on circuit breakers (9), (10) indicate that the critical gap length for arcing, the arc energy distribution and the arc temperature are independent of current variations in the approximate range of 200 to 2000 amperes for copper electrodes. It was likewise found early in this research that the variation of current magnitude from 400 to 800 amperes (peak value) had negligible effect on the gas rate. Furthermore, in most of the field tests, no appreciable change was found for silver elkalite arcing surfaces generally used in circuit breakers even when the highest current of many thousands of amperes was interrupted. In view of these facts, it seems reasonable to use the data obtained at low current magnitudes to calculate the gas produced in the actual circuit breaker operation when high current magnitudes are encountered.

Since the arcing surfaces of present day circuit breakers are mostly made of silver elkalite, data corresponding to silver elkalite surfaces are of most importance. However, in this research arcing surfaces made of silver elkalite, steel and copper were tested. Steel surfaces were used because it was found that among the five materials considered namely: aluminum, brass, copper, silver elkalite and steel, surfaces made of steel gave results with the least deviation when repetitions of tests were made. This helps to show the effect of each variable. On the other hand, copper contacts were also used because previous researches on circuit breakers were conducted mostly with copper surfaces. It is therefore desirable to have data tested on copper surfaces in this research in order that the results obtained in this thesis may be compared with that of previous investigations.

As mentioned earlier in this introduction, the effect of each variable was investigated by varying the particular variable concerned over a desired range while each of the other variables was fixed at a selected value deemed to be the mean or most desirable value. The factors to be investigated and the selection of values for the parameters are as follows.

(a) <u>The effect of current magnitude</u> — The duration of current was fixed at two cycles since circuit breaker arcing times are in general about two cycles. The electrode gap length was fixed at 1/4 inch which is approximately the mean separation during arcing time in the actual circuit breaker operation. The current was then varied from 400 to 800 amperes, the latter being the maximum rating of the ignitron tubes for the current duration control. Gas rate was found to be practically independent of the current magnitude.

(b) <u>The effect of arc duration</u> — The electrode gap length was fixed at 1/4 inch as above and the current at 600 amperes (peak value) while the duration was varied from a half cycle to three and a half cycles.

(c) <u>The effect of electrode gap length</u> — The current used was 600 amperes and the duration two cycles. The electrode gap length was varied from 1/4 to 3/4 inch, since as mentioned earlier, the maximum electrode separation is 3/4 inch during arcing time.

In the above three cases flat electrodes (generally called butt type) 1 1/4 inch in diameter were used. This dimension is typical in circuit breakers over a wide range of ratings.

(d) <u>The effect of arcing surface shape and size</u> — In addition to the flat surfaces of 1 1/4 inch diameter, three other types of surfaces were used. These were flat surfaces of 3/4 inch diameter, hemispherical surfaces of 1 1/4 inch diameter and hemispherical surfaces of 3/4 inch diameter. In this case, the gap length was fixed at 1/4 inch, the current at 600 amperes and the duration 2 cycles.

(e) The effect of arcing surface material – As mentioned earlier, steel, copper and silver elkalite were used as materials for the arcing surface. To obtain information on this effect, tests in (a), (b), (c) and (d) were repeated for each of these three types of arcing surfaces.

II. DESCRIPTION OF TEST APPARATUS AND SEQUENCE

Since this research is based on experimental results, a detailed description of the test technique used is desirable so that improvement of the test technique and comparison of the results can be made by other investigators in the future.

The function of the test apparatus is twofold: (a) to produce a controlled arc in oil and to record the arc current and voltage, (b) to collect and measure the gas dissociated from the oil.

The apparatus for the first purpose is primarily of an electrical nature and that for the second purpose mechanical. In the following, the electrical and mechanical apparatus employed, together with their sequence of operation, will be described.

2-1 Electrical Elements of System

For clarity, a schematic block diagram of the electrical circuit is shown on figure 1. However, in order to describe the operation of the test, it is desirable to show the complete circuit and this is given in figure 2.

It is necessary to use fixed electrodes with adjustable gap length so that the effect of each variable may be separated, particularly the effect of gap length. With the electrodes fixed, a method of initiating the arc is required. A surge generator, (figure 3), was found to be suitable for this purpose, after certain insulation coordination problems were solved as described later and it was established that the surge current itself did not produce any measurable gas.

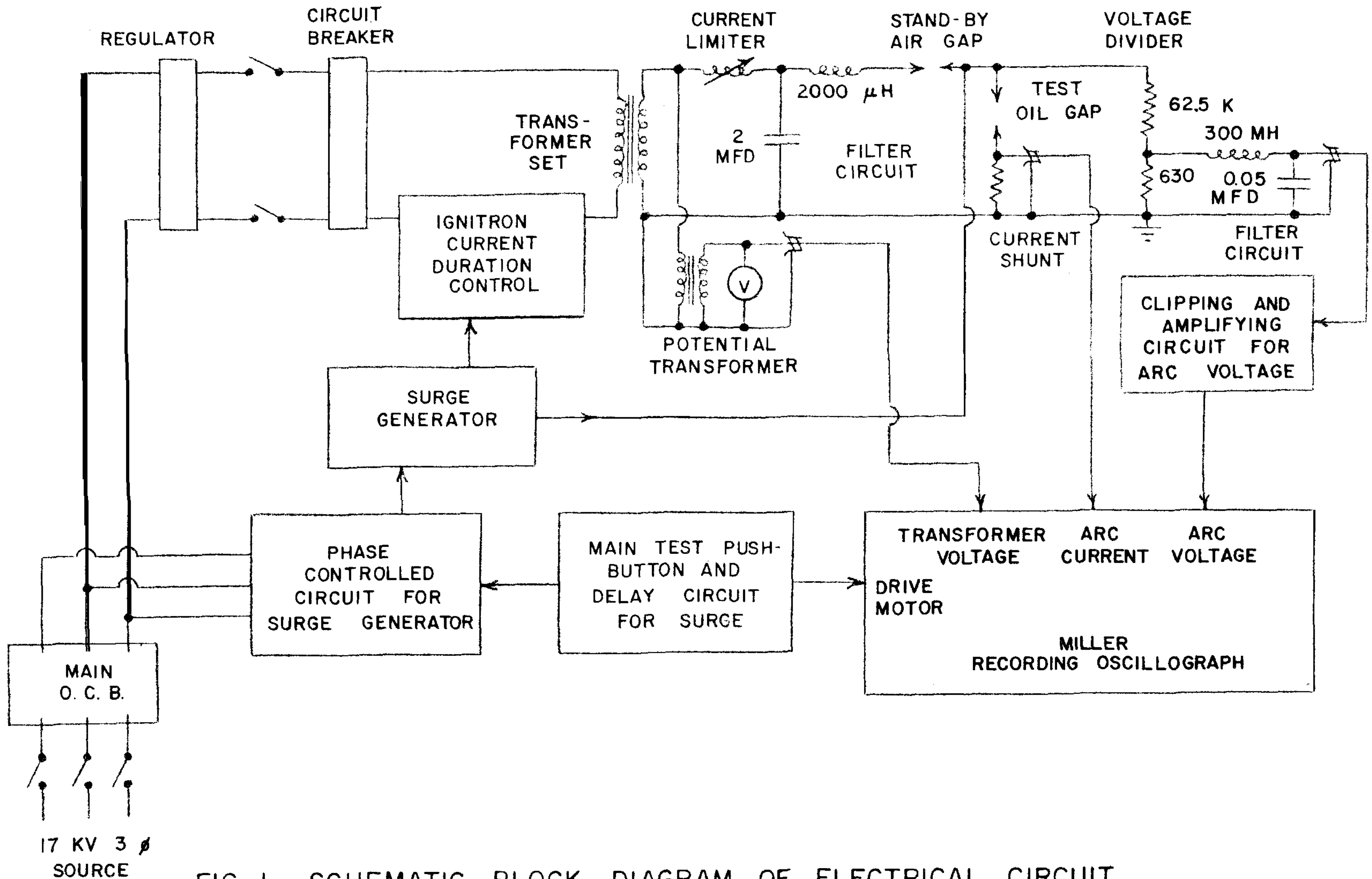

FIG. I SCHEMATIC BLOCK DIAGRAM OF ELECTRICAL CIRCUIT

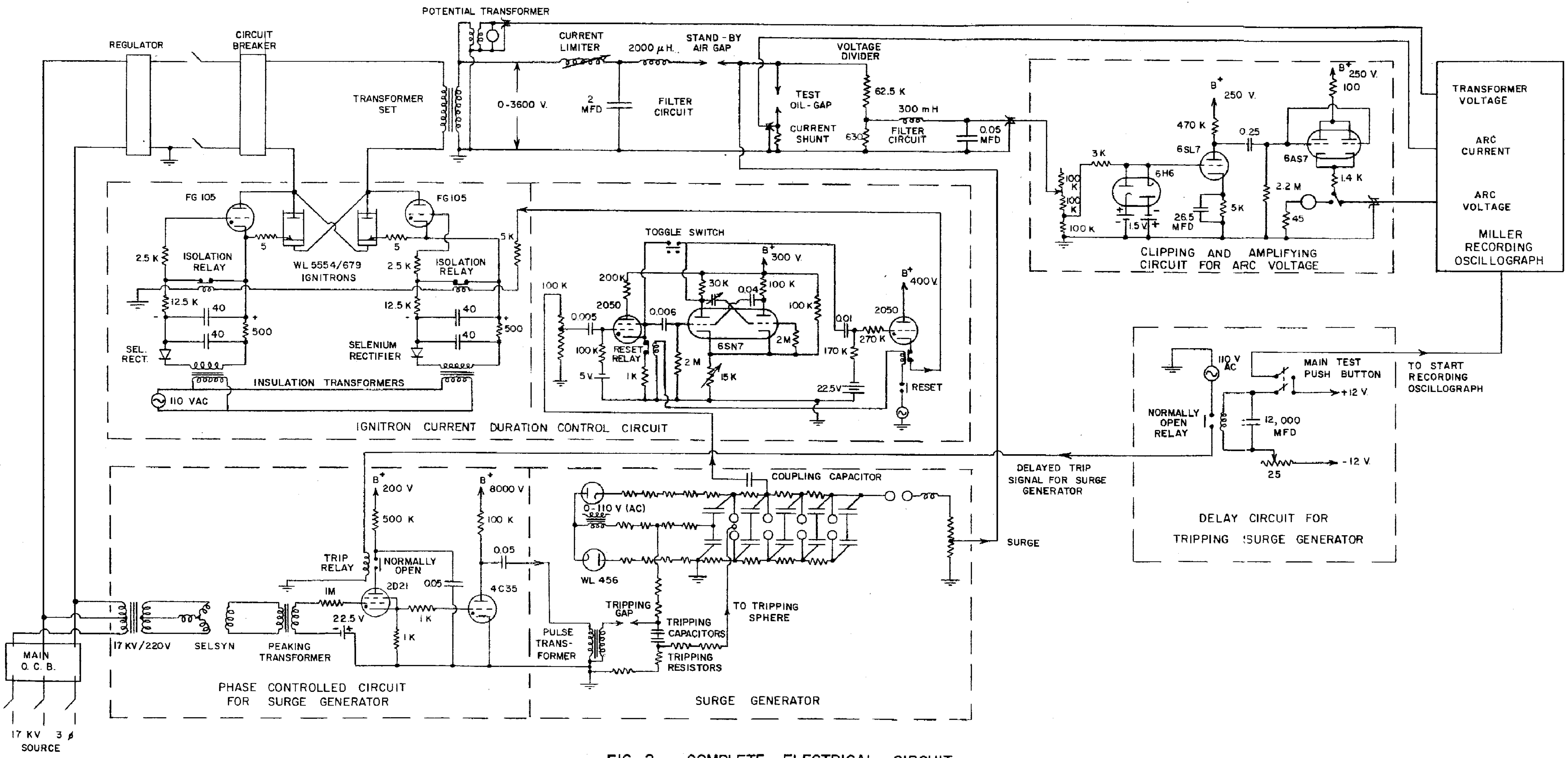

FIG. 2 COMPLETE ELECTRICAL CIRCUIT

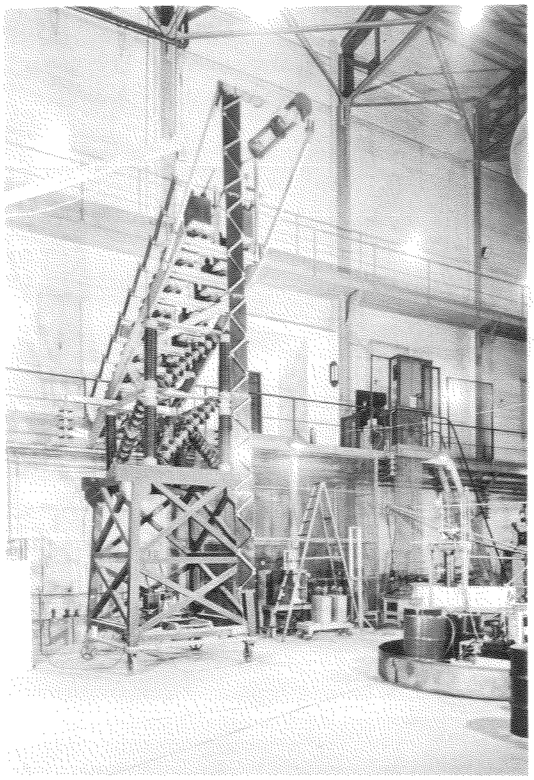

Fig. 3. Photograph of Surge Generator

Referring to figure 2, the 17 kv, 3-phase source supplies a line to line voltage to a voltage regulator with a variable secondary voltage of 0-3600 v. A set of four transformers and a current limiter (figure 4) were used to supplement the voltage regulator for current magnitude control. The duration of the current was controlled by the ignitron circuit. A filter circuit was used to protect the transformers from the high surge voltage necessary for initiating the arc through the test oil gap. A small stand-by air gap isolated the 60 cycle voltage from the test gap in order to reduce the power ratings of the shunt resistor of the surge generator and the arc voltage measuring equipment. The latter consists of a voltage divider, a filter circuit, and a clipping and amplifying circuit. The secondary voltage of the transformers, the arc current and the arc voltage through the amplifier were recorded on a Miller magnetic oscillograph. The arrangement in figure 2 was chosen to utilize as much as possible the equipment available in this laboratory. The specific electrical apparatus built for this research is the arc voltage measuring equipment mentioned above.

Prior to each test, the transformer voltage was set to a desired value by adjusting the voltage regulator providing the proper 60 cycle voltage at the stand-by air gap. After the surge generator has been charged for one minute, the test is initiated by operating the main test push-button on the delay circuit for tripping the surge generator. Due to the RC delay circuit, the above operation first starts the camera of the Miller magnetic oscillograph and then energizes the trip relay in the phase controlled circuit for the surge generator. The phase controlled

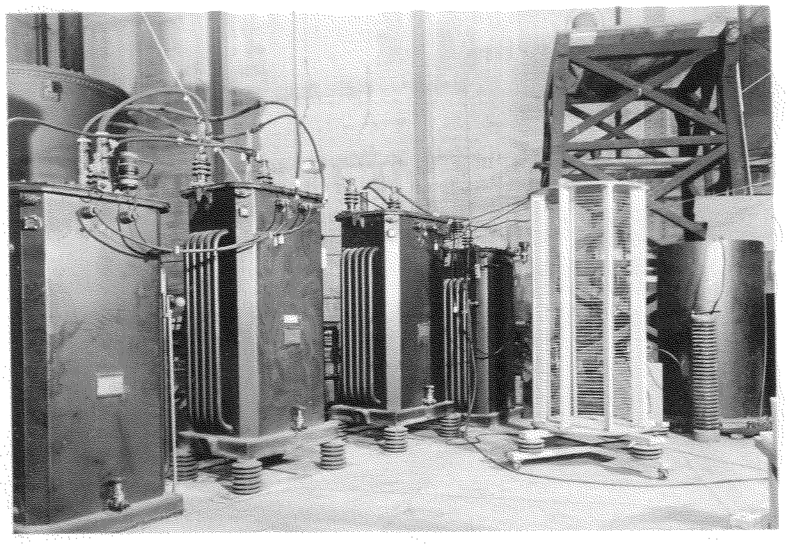

Fig. 4. Photograph of Transformers, Filter Inductance Coil, and Current Limiter.

circuit makes it possible to fire the surge generator at the proper instant so that a symmetrical arc current is obtained. The phase controlled circuit consists of a selsyn, a peaking transformer and two thyratron tubes (2D21 and 4C35). After the plate supply contact is closed by the trip relay, the 2D21 thyratron tube fires when its grid voltage reaches its critical value. The instant at which this critical value is reached depends on the setting of the selsyn. The voltage drop developed across the cathode resistor (1K) of the 2D21 thyratron tube in turn fires the 4C35 thyratron tube. A pulse voltage of 8 kv is thus applied to the pulse transformer of the surge generator. The 30 kv output of the pulse transformer breaks down the tripping gap and causes the tripping capacitors to discharge. The resulting voltage developed across the tripping resistors is applied to the tripping sphere and causes the surge generator to fire.

A portion of the surge voltage developed across the shunt resistor of the surge generator is used to break down both the stand-by air gap and the test oil gap. The breakdown of the stand-by air gap connects the 60 cycle voltage to the test oil gap while the simultaneous breakdown of the latter gap by the surge voltage initiates the desired power arc.

In order to control the duration of the arc current, a signal voltage obtained from the surge generator by capacitor coupling is applied to the ignitron current-duration control circuit. When the surge generator fires, the short circuit of the first sphere-gap, where the tripping sphere is located, connects the first four capacitors in series and thus suddenly raises the voltage on the surge generator side of the coupling capacitor. This in turn causes the grid voltage of the 2050 thyratron tube to be above its critical voltage and start conducting. When one half cycle of arc current is desired, the toggle switch is positioned so that the upper contacts are shorted. In this case, the voltage drop developed across the cathode resistor (1K) of the first 2050 tube is directly applied to the grid of the second 2050 tube. The subsequent conduction of this tube energizes the isolation relays. The opening of the relay contacts applies negative pulses to both grids of the FG 105 thratron tubes. This prevents the conduction of the FG 105 tubes and thus isolates the ignitron rods. The ignitron tube then would extinguish at the end of the half cycle since application of a voltage to the rod is necessary for the ignition of the tube.

In case current durations of more than half cycle are desired, the toggle switch is set in the downward position. The voltage drop developed across the cathode resistor (1K) of the first 2050 thyratron tube is now applied to the grid of the 6SN7 tube of a multivibrator circuit. After the proper time delay determined by the adjustable timing capacitor, the output pulse then fires the second 2050 thyratron. This in turn prevents the ignitron tube from being reignited as described in the case for one half cycle.

A sample magnetic oscillogram is shown in figure 5. In addition to the required arc voltage and current, the transformer voltage is also recorded simply for checking purposes. The transformer voltage and the arc current are supplied to the oscillograph by means of potential

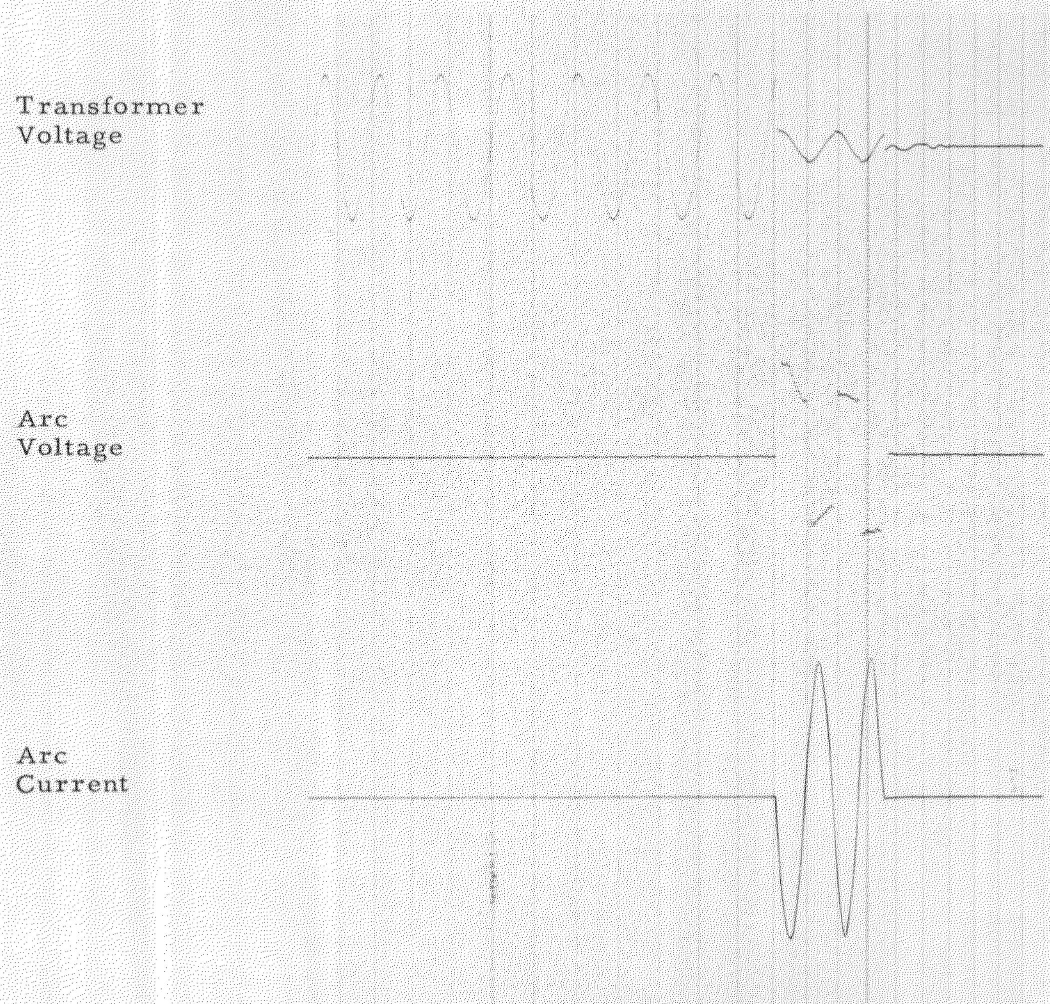

Fig. 5. Typical Oscillogram Showing Transformer Voltage, Arc Voltage and Arc Current.

transformer and a current shunt respectively. In order to record the arc voltage, it was found necessary to use a filter circuit and a clipping and amplifying circuit. Since these circuits do not effect the test sequence, they are described in the appendix.

2-2 Mechanical Elements of System

In order to collect the gas produced by the arc, the electrodes were placed inside a closed steel tank partly filled with oil. Steel was chosen as the tank material for its high strength in view of the turbulent motion of the oil during arcing time and possible high pressures in the closed tank. Although the resultant pressure can be minimized by providing a large initial air volume above the oil, it is desirable to use a reasonably small air volume so that the gas produced by the arc can be measured more accurately. The steel tank body was built to withstand 300 pounds per square inch.

Figure 6 shows pertinent details of the steel tank and figure 7 the front view of the steel tank. The tank is three feet long and six inches in diameter, with a wall thickness of 0.28 inch. One foot up from the bottom, a window for changing electrodes has been created by welding on a short section of steel pipe of four inch diameter. The tank is threaded at both ends and at the window pipe. Steel flanges are then screwed on. Attached to the top and window flanges are two inch thick circular pieces of plexiglass. The top piece is drilled and tapped to provide the outlet to the gas measuring apparatus and a second outlet for a pressure gage which is used to measure the static pressure after arcing and to check the possibility of leakage by pressurizing the tank

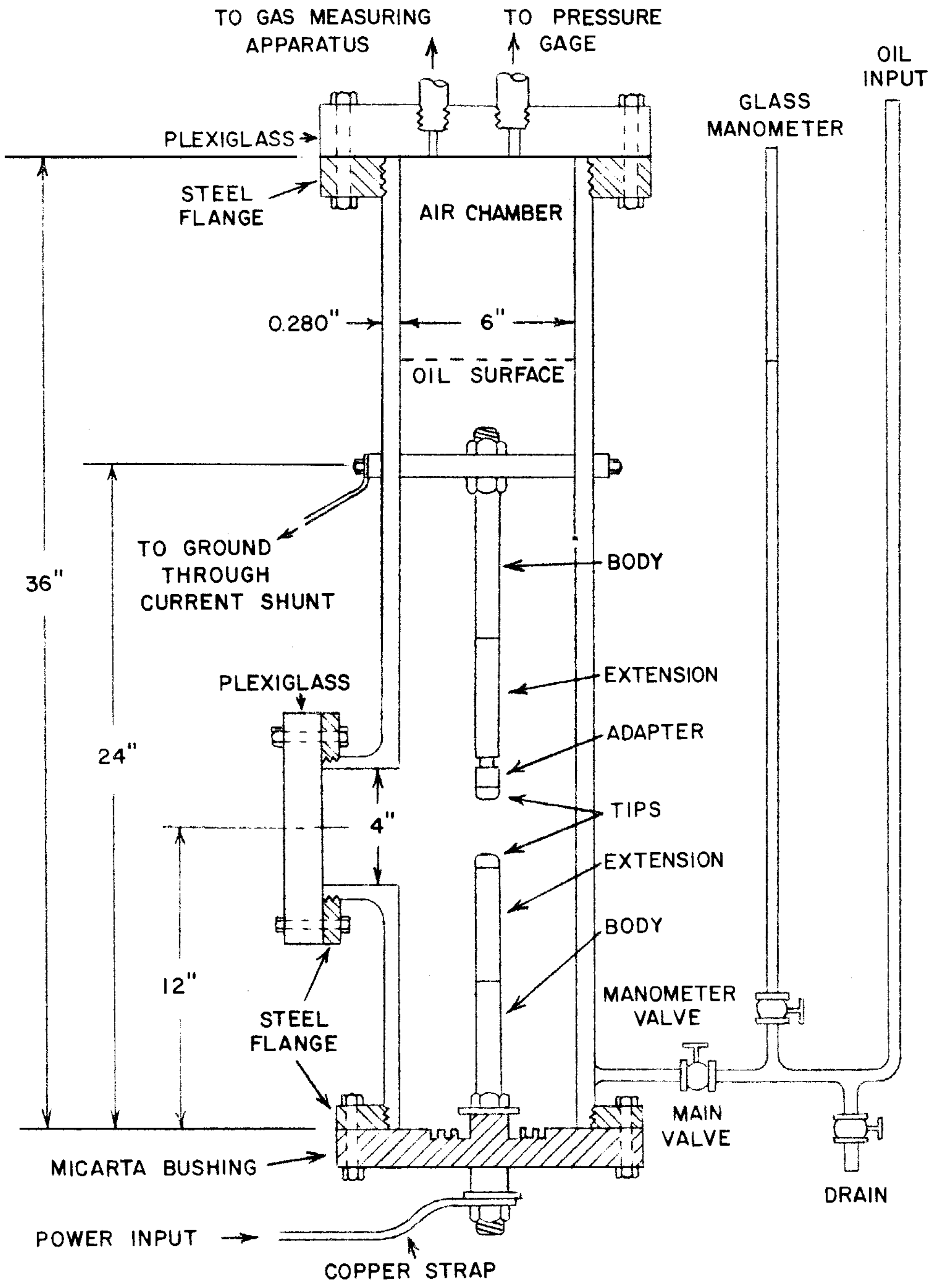

FIG. 6. STEEL TANK WITH AUXILIARIES

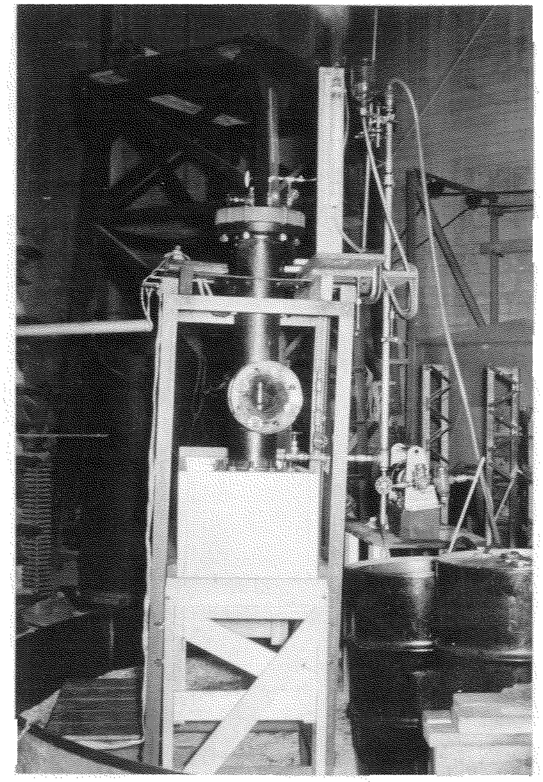

Fig. 7. Photograph Showing Front View of Steel Tank.

and observing any pressure drop. The plexiglass for the window allows direct observation of the arc.

Attached to the bottom flange is a two inch thick micarta plate (figure 8) which acts as a bushing for the bottom electrode. The incoming power is supplied to the bottom electrode through a copper strap submerged in an oil box (figure 9). This method of introducing the incoming power to the bottom electrode is necessary, since a surge voltage of more than 400 kv is employed to initiate the arc when the electrode gap length is 3/4 inch.

As shown in figure 6, the upper electrode is supported by a copper crossbar which is attached to the tank by means of bolts. At one of the bolts, the tank is grounded through the current measuring shunt (comparing figure 2 and figure 6).

In an earlier mode, the electrodes were so constructed that each of the upper and bottom electrodes had a movable extension screwed to the electrode body which was supported by the upper cross-bar or the bottom bushing. This facilitated replacement of the electrodes. It was soon found however that the burning on the electrode surface after a power arc rendered the electrodes useless for a second test because the data were always different when new and burned electrodes were tested. This is especially true for copper and steel electrodes. To have accurate results it was thus found necessary to replace electrodes after each test.

In view of the enormous number of tests to be made and the fact that only the arcing surface is damaged, it was decided to replace

Fig. 8. Photograph of Micarta Bushing with Bottom Electrode in Position.

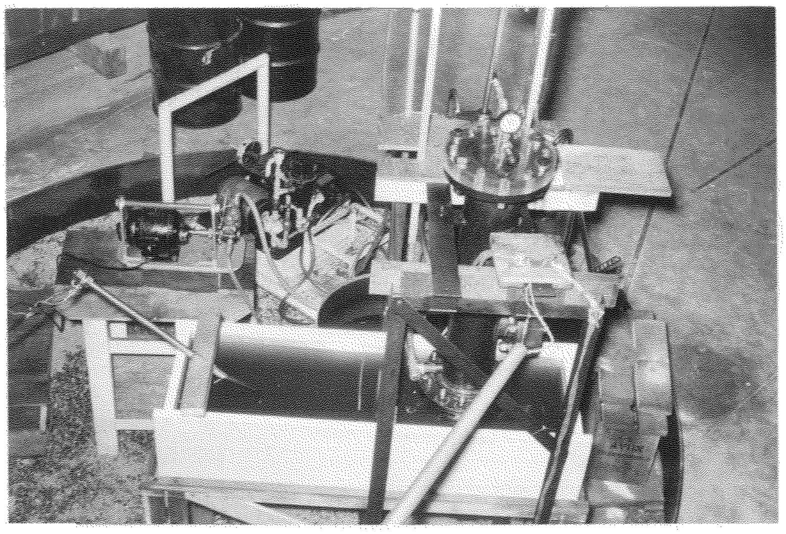

Fig. 9. Photograph of Oil Box with Incoming Lead.

only the section of electrode near the arc. This is achieved by using the replaceable tips shown in figure 10. The larger flat and hemispherical tips are 1 1/4 inches in diameter and the smaller ones 3/4 of an inch. The large flat tips are used in all tests except in the study of the effect of electrode shape and size. In the latter case, the other types of tips are used.

Referring to figure 6, the bottom electrode consists of a body of 1 1/4 inch diameter copper rod fixed on the bushing, a movable extension, and a tip. The upper electrode has an adapter (figure 11) in addition to the above parts. Figure 12 shows the two movable extensions; figure 13, the same parts with the adapter attached to the upper extension and figure 14 the electrode assemblies with tips in position. It is now clear from figure 14 that the adapter is desired for changing tips when the required arc gap is smaller than the thickness of the tip. Also, the adapter makes possible a minor adjustment of gap length which is varied by rotating the movable extensions. It is worthwhile to mention here that this complicated construction of the electrode did not cause the results to be different from that obtained with the simpler form mentioned before.

The tank is partly filled with oil. The oil surface inside the tank is indicated by a glass manometer which is calibrated to show the height and volume of air column above the oil surface. The apparatus used to measure gas production is pictured in figure 15 and consists of a calibrated glass cylinder and oil reservoir connected by a plastic hose. The oil reservoir is free to move vertically and can be locked in any

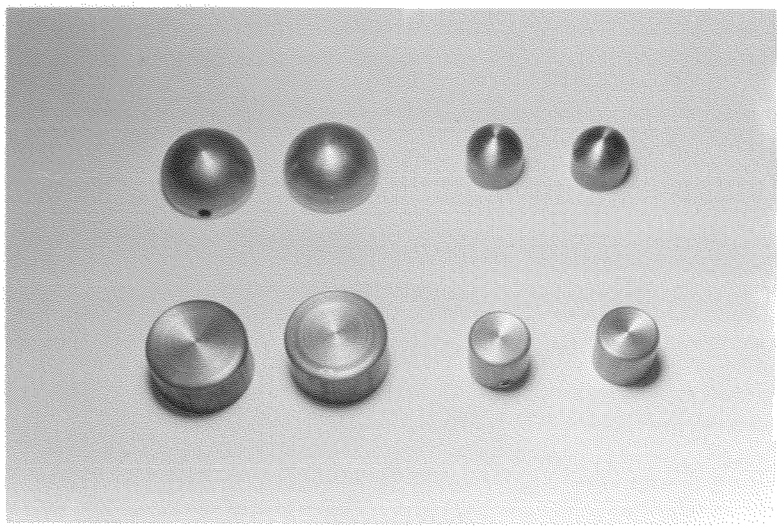

Fig. 10. Photograph of Electrode Arcing Tips.

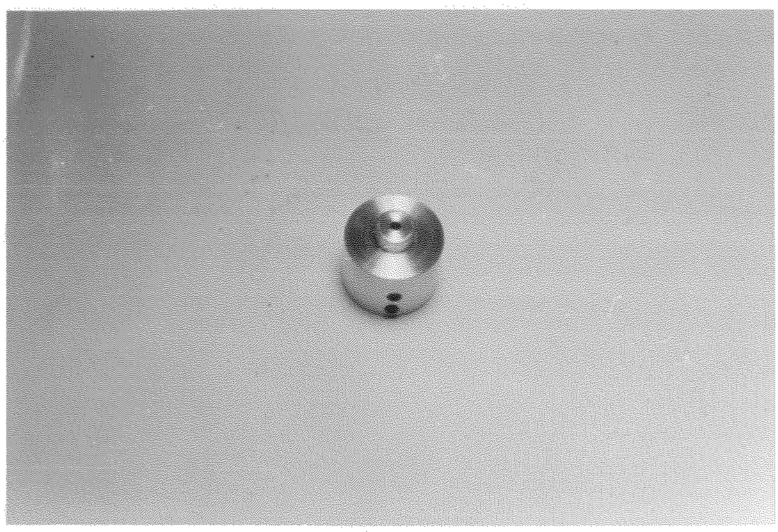

Fig. 11. Photograph of Electrode Adapter.

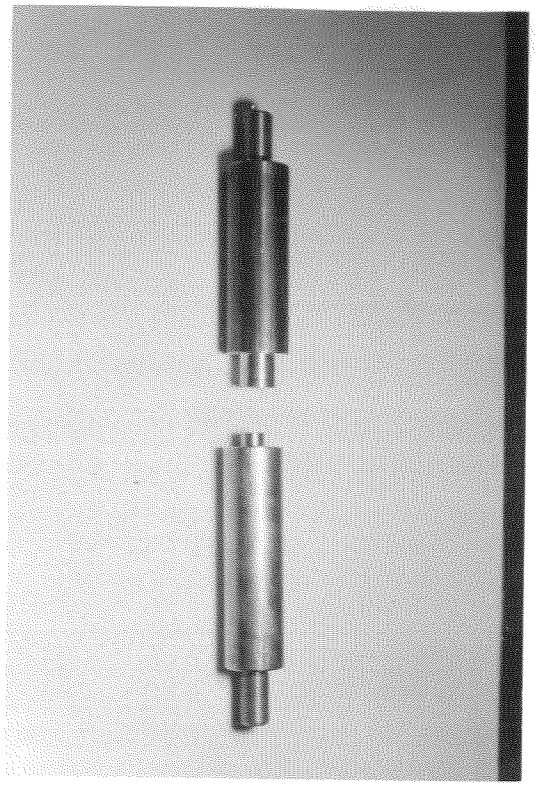

Fig. 12. Photograph of Electrode Extensions.

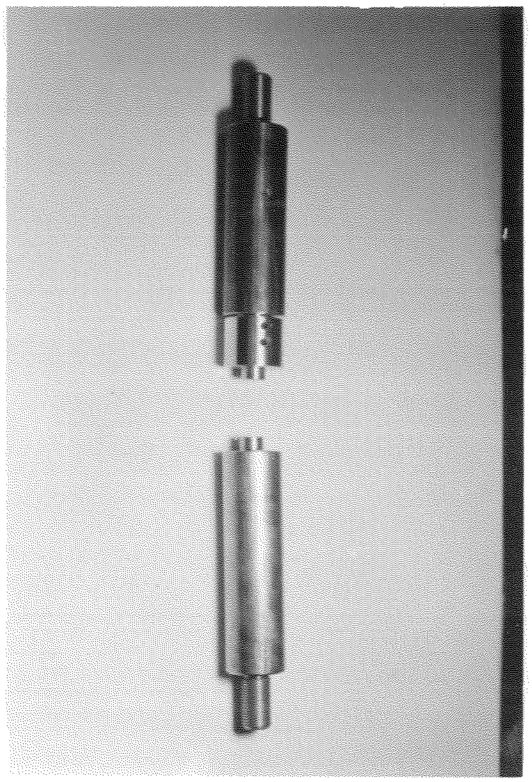

Fig. 13. Photograph of Electrode Extensions with Adapter in Position.

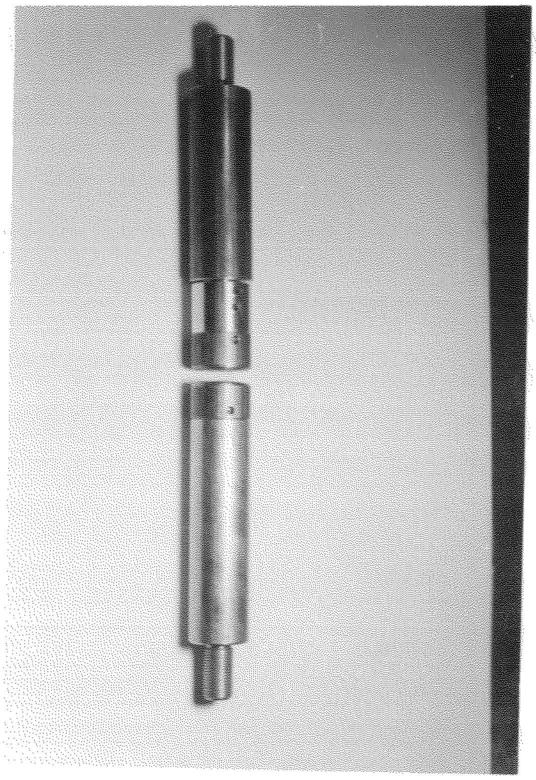

Fig. 14. Photograph of Electrode Extensions with Adapter and Tips in Position.

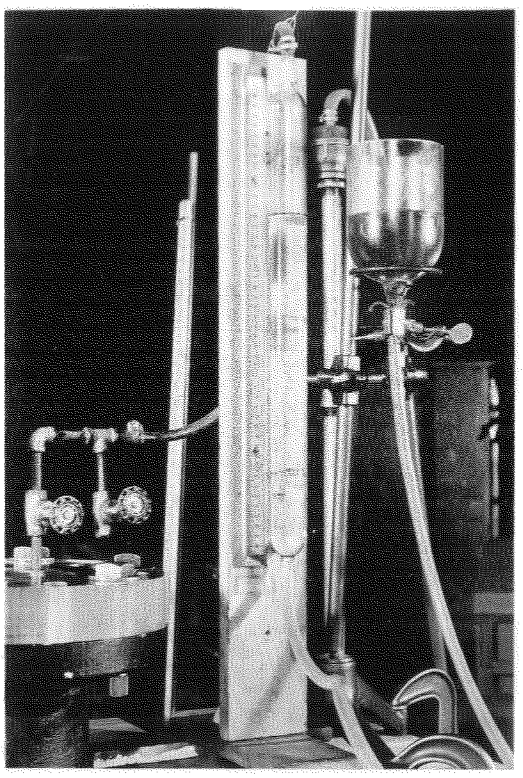

Fig. 15. Photograph of Gas Measuring Apparatus.

position. The top of the glass cylinder is connected to the gas outlet in the plexiglass of the steel tank by a second plastic hose through a valve. The other valve shown in figure 15 is a release valve whose function is self-explanatory from the following description of gas measurement and method of changing oil.

Prior to the test, both the gas outlet and the release valves are turned to open position. The oil surface in the glass cylinder is set near the top by locking the oil reservoir at a suitable position. The valves are then closed during the arcing time. After the arcing is over, the gas outlet valve is opened. Since the pressure inside the tank is now higher than atmospheric pressure due to the additional gas produced by the arc, the oil surface in the glass cylinder is displaced downward. The oil reservoir is then lowered until a new level between the oil surfaces of the glass cylinder and the oil reservoir is reached. The displacement of the oil surface in the glass cylinder multiplied by the cross sectional area of the cylinder gives the volume of gas sought. After the gas measurement is recorded, the release valve is opened to allow draining of oil in order to change tips for the next test.

The complete mechanical apparatus is enclosed in a 12 foot diameter circular pan as shown in figure 16. In addition to the steel tank, the oil box and the gas measuring glass apparatus already mentioned, the equipment contained in this pan consists of an oil filter, an oil pump and oil drums. The oil is filtered after arcing and pumped back to the tank when new tips are in position. It should be mentioned here that the filtered oil was used only after careful investigation showed

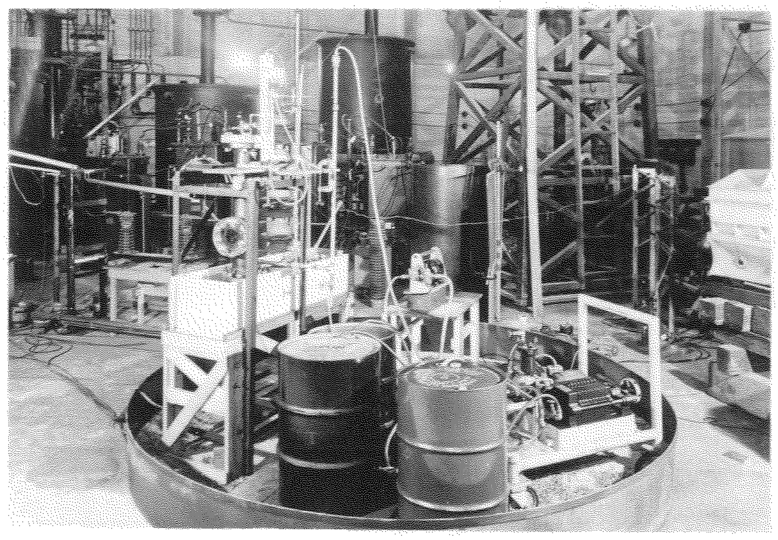

Fig. 16. Photograph of Complete Mechanical Equipment.

that no difference is observed in results between new and filtered oil. Generally speaking, it took about forty minutes for each test run, including fifteen minutes for the oil to settle down after it was pumped into the tank.

III. METHOD OF CALCULATION AND EXPERIMENTAL RESULTS

The basic information from this investigation is the gas rate (volume of gas produced per unit arc energy). However, in defining gas volume, it is necessary to specify the associated temperature and pressure. It has been customary, mainly for comparison purposes, both in published and unpublished articles in this field to state the volume of gas at 760 mm and 25°C. This convention is followed in presenting the results of this research by applying a correction factor to the volume of gas measured. Let

V = volume of gas produced during test (cubic centimeter)

t = temperature of gas (centigrade)

T = absolute temperature of gas in degrees Kelvin = 273 + t

P = barometric pressure recorded (millimeter)

V_c = volume of gas referred to 760 mm and 25°C

T_c = absolute temperature in degrees Kelvin corresponding to 25°C = 273 + 25 = 298

P_c = 760 mm.

From

$$\frac{V_c}{V} = \frac{T_c}{T} \times \frac{P}{P_c} \qquad (1)$$

$$V_c = V \times \frac{T_c}{T} \times \frac{P}{P_c} = V \times \frac{T_c}{P_c} \times \frac{P}{T}$$

$$= V \times \frac{298}{760} \times \frac{P}{273 + t}$$

$$= V \left(.392 \times \frac{P}{273 + t} \right)$$

we have

$$\text{the correction factor} = .392 \times \frac{P}{273 + t} \qquad (2)$$

Originally the temperature of the gas in the air chamber was measured by a thermocouple and a thermometer attached to the inside of the top plexiglass. Both measurements show that the resultant gas temperature does not differ by more than one degree (centrigrade) from the room temperature due to the cooling effect of oil above the arcing gap and the relatively small volume of gas produced as compared with the volume of the air chamber. In order to speed up the test, the room temperature is recorded instead of the temperature inside the air chamber and is used in the above formula for obtaining the correction factor.

One way to find the arc energy from the oscillogram (figure 5) is to plot on a linear time base the product of corresponding current and voltage ordinates and measure the area bounded by the resultant watt curve and the time axis. The area so obtained is a measure of the energy. However, due to the enormous amount of data to be calculated and the slight non-linear time base in the oscillograph, the work involved is tedious although not impossible. In view of the nearly constant arc voltage in each half cycle, a simpler approximate method of calculating arc energy from the oscillogram is used in this research and is explained below.

Referring to figure 17(a), since the current has a sinusoidal shape, it can be represented by $i = I_m \sin \omega t$ where I_m = peak value of the current wave and $\omega = 2\pi f = 2\pi \times 60$ radians per second.

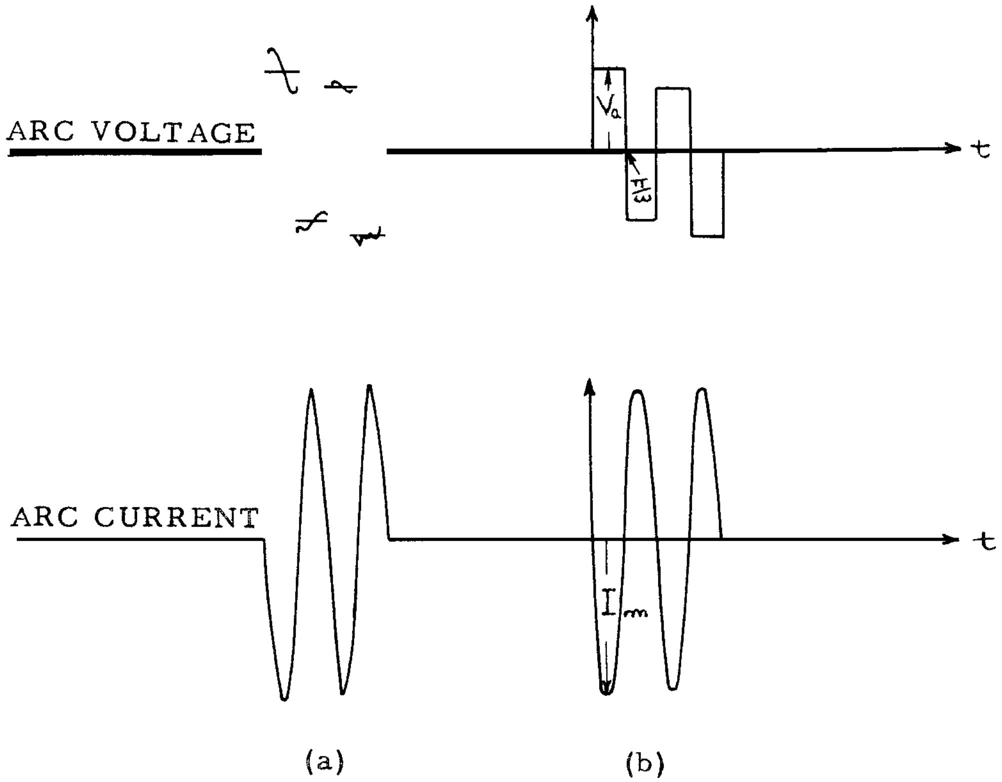

Fig. 17. (a) Reproduction of Arc Voltage and Current from Figure 5 with Horizontal Line Added Representing the Average Arc Voltage.

(b) Plot of Arc Voltage and Current From (a) Using the Average Value of Arc Voltage and a Linear Time Base.

Let v represent the instantaneous voltage then we have the arc energy in the first half cycle $= \int_0^{t=\pi/\omega} v \, i \, dt$

$$= \int_0^{t=\pi/\omega} v \, I_m \sin \omega t \, dt$$

If v is taken as a constant V_a equal to the average value of the voltage ordinates in the first half cycle, then the arc energy in the first half cycle

$$= I_m V_a \int_0^{t=\pi/\omega} \sin \omega t \, dt = \frac{I_m V_a}{\omega} \int_0^{\omega t=\pi} \sin \omega t \, d(\omega t)$$

$$= \frac{I_m V_a}{\omega} \Big[-\cos \omega t \Big]_{\omega t = 0}^{\omega t = \pi} = 2 \frac{I_m V_a}{\omega} = \frac{2 I_m V_a}{2\pi f}$$

$$= 5.31 \times 10^{-3} I_m V_a \qquad (3)$$

Although derived for the first half cycle, equation 3 applies equally well to the second half cycle, the third and fourth etc. provided that the values I_m and V_a are obtained from the corresponding half cycles. The total arc energy is obtained by adding the energy in each half cycle.

Figure 17(b) is a plot of arc voltage and current from figure 17(a), using the average value of arc voltage in each half cycle and a linear time axis. This is done in order to make equation 3 more clear.

To simplify matters further, the average value V_a in each half cycle is obtained by drawing a horizontal line on the voltage curve such that equal areas result on both sides of the line. The height of this line above the time axis multiplied by the calibration factor gives the average voltage in volts for the corresponding half cycle. An evident error associated with this method of obtaining the average value results from the slight non-linearity of the time base. However, it has been shown that an arbitrary displacement of 0.5 mm in one direction on the ordinates of the horizontal lines representing the average voltages does not change the total arc energy by more than 5 $^{o}/o$ since the height of each horizontal line is on the order of 10 mm. In view of the small variation of the voltage wave in each half cycle, the difference between the ordinate of the average height obtained in this method and its true value is always smaller than .5 mm. Thus the overall accuracy in the gas rate calculation is within 5 $^{o}/o$. Since this method of obtaining the average voltage generally gives a higher value than its true value, a higher arc energy is obtained, resulting in a smaller value of gas rate since the latter is inversely proportional to arc energy. In other words, the gas rate data calculated by this method is on the conservative side.

The experimental results calculated by the above mentioned method are plotted in figure 18 through figure 22 inclusive. Each data point shown in these figures is an average of five test runs. A total of about 200 tests were made for the results shown. This research including calculation and preparation of equipment required about two man years of effort.

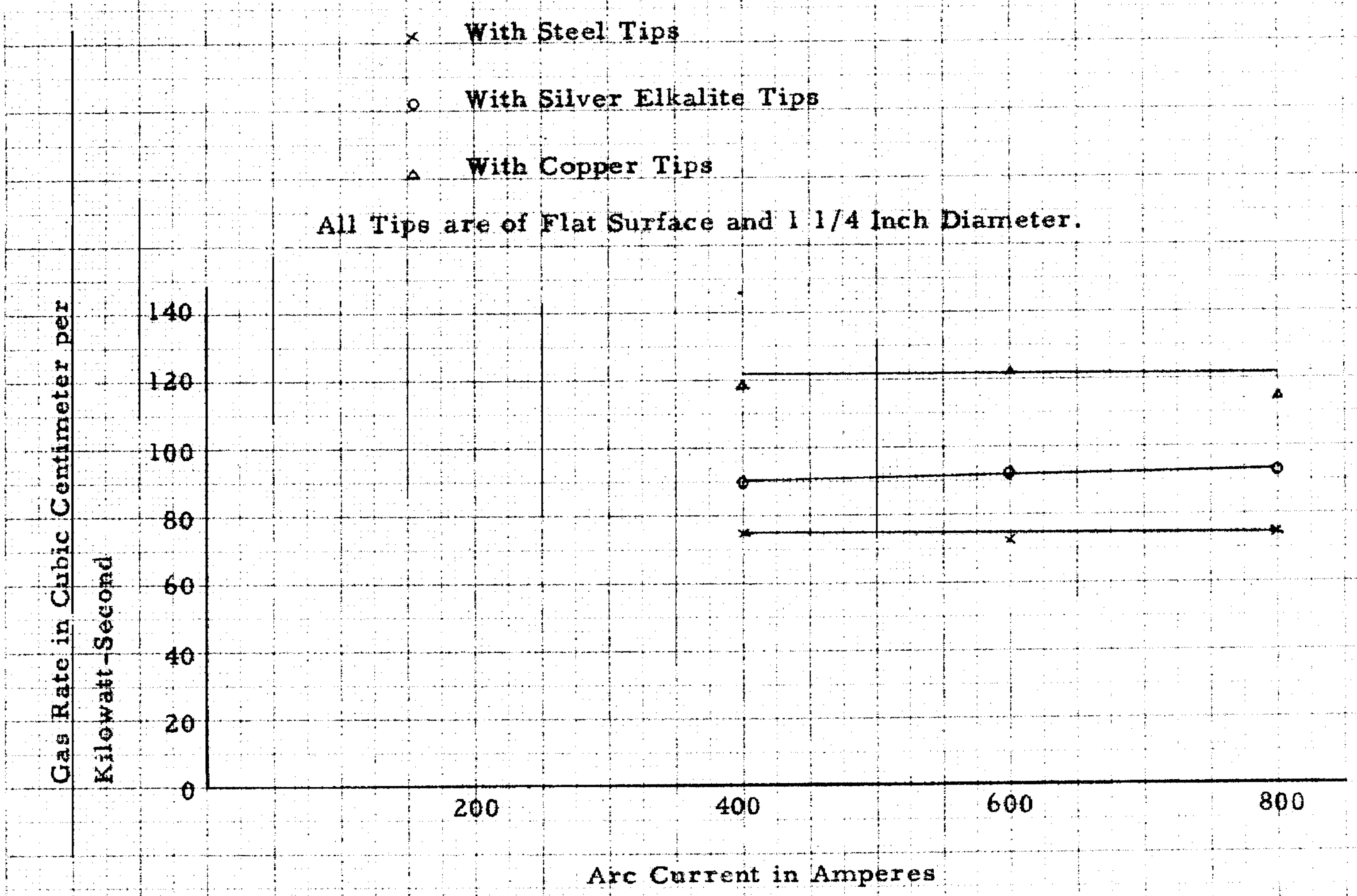

Fig. 18. Curves Showing the Effect of Current Magnitude on Gas Rate with Two Cycle Arc Duration and One Quarter Inch Electrode Gap.

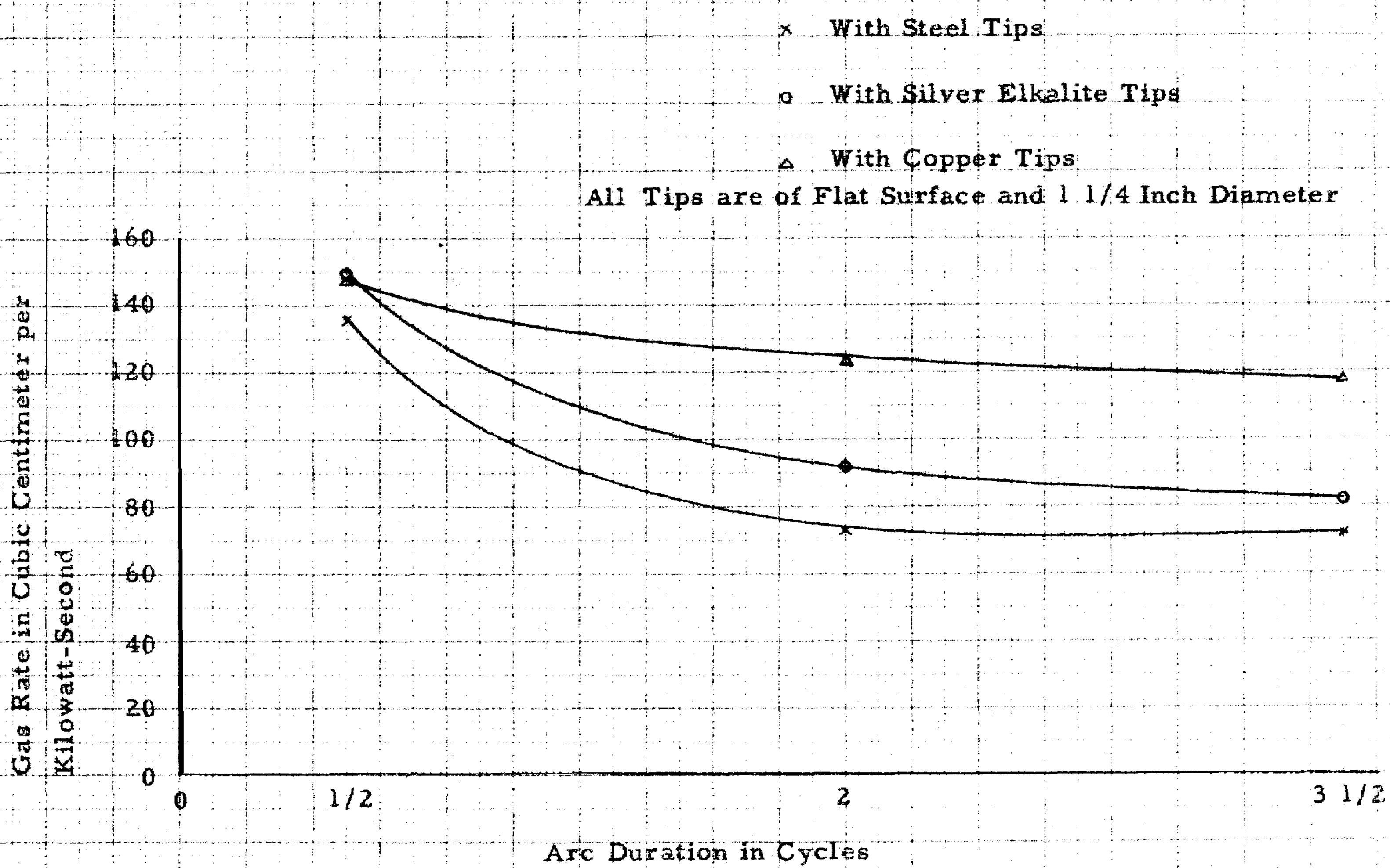

Fig. 19. Curves Showing the Effect of Current Duration on Gas Rate with 600 Amperes and One Quarter Inch Electrode Gap.

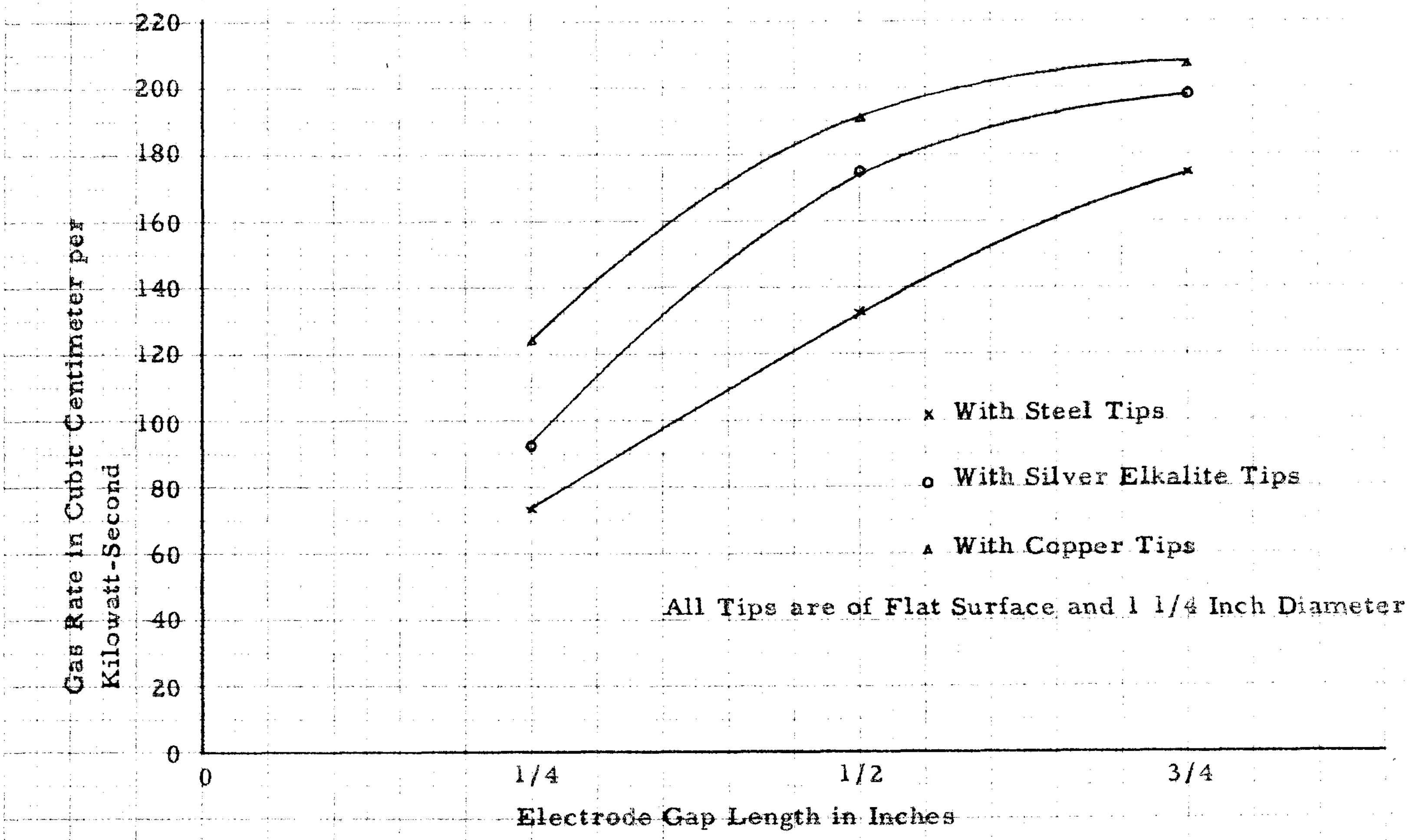

Fig. 20. Curves Showing the Effect of Electrode Gap Length on Gas Rate with 600 Amperes and Two Cycle Arc Duration.

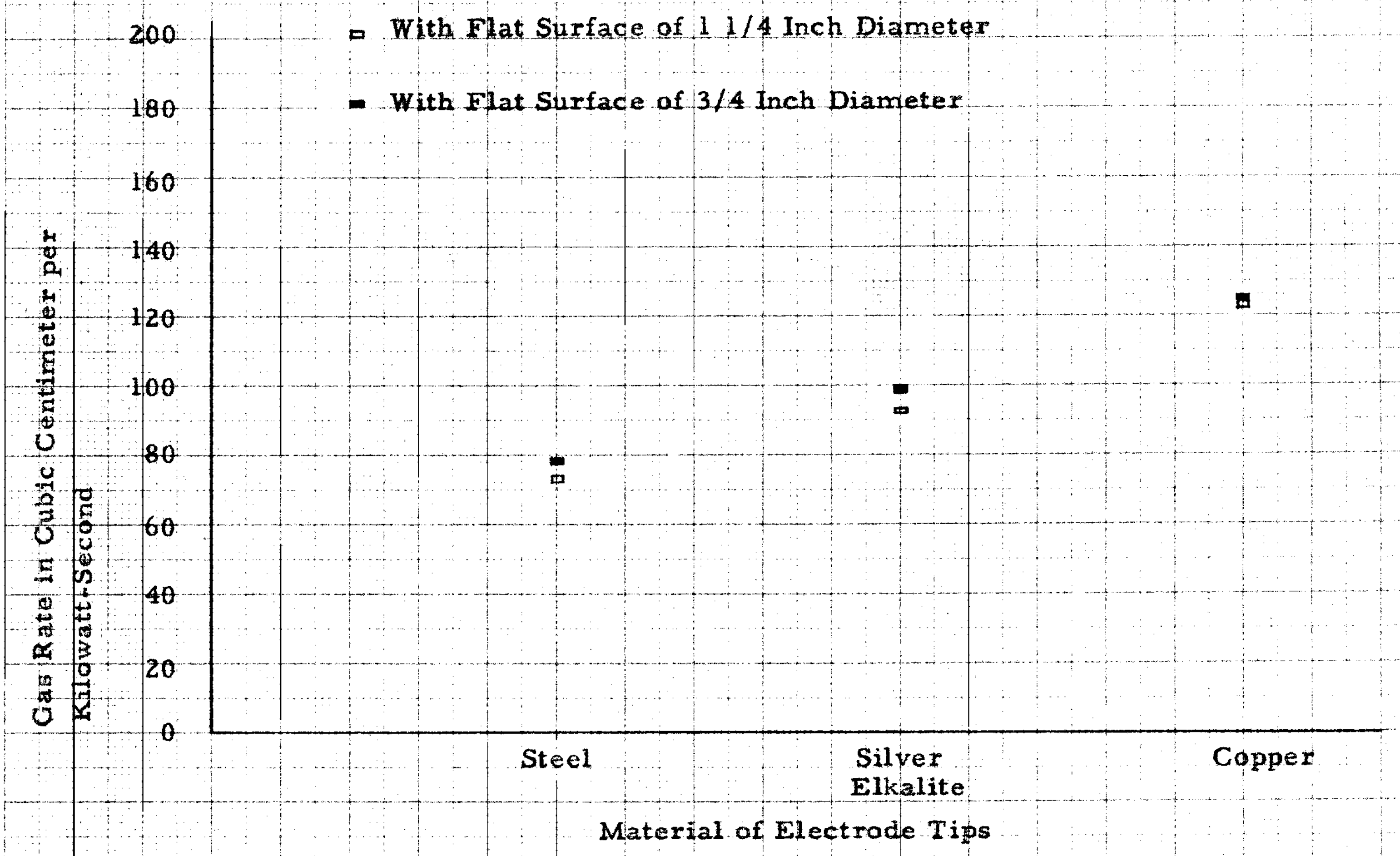

Fig. 21. Data Showing the Effect of Electrode Size (Flat Surface) on Gas Rate with 600 Amperes and Two Cycle Arc Duration at One Quarter Inch Electrode Gap.

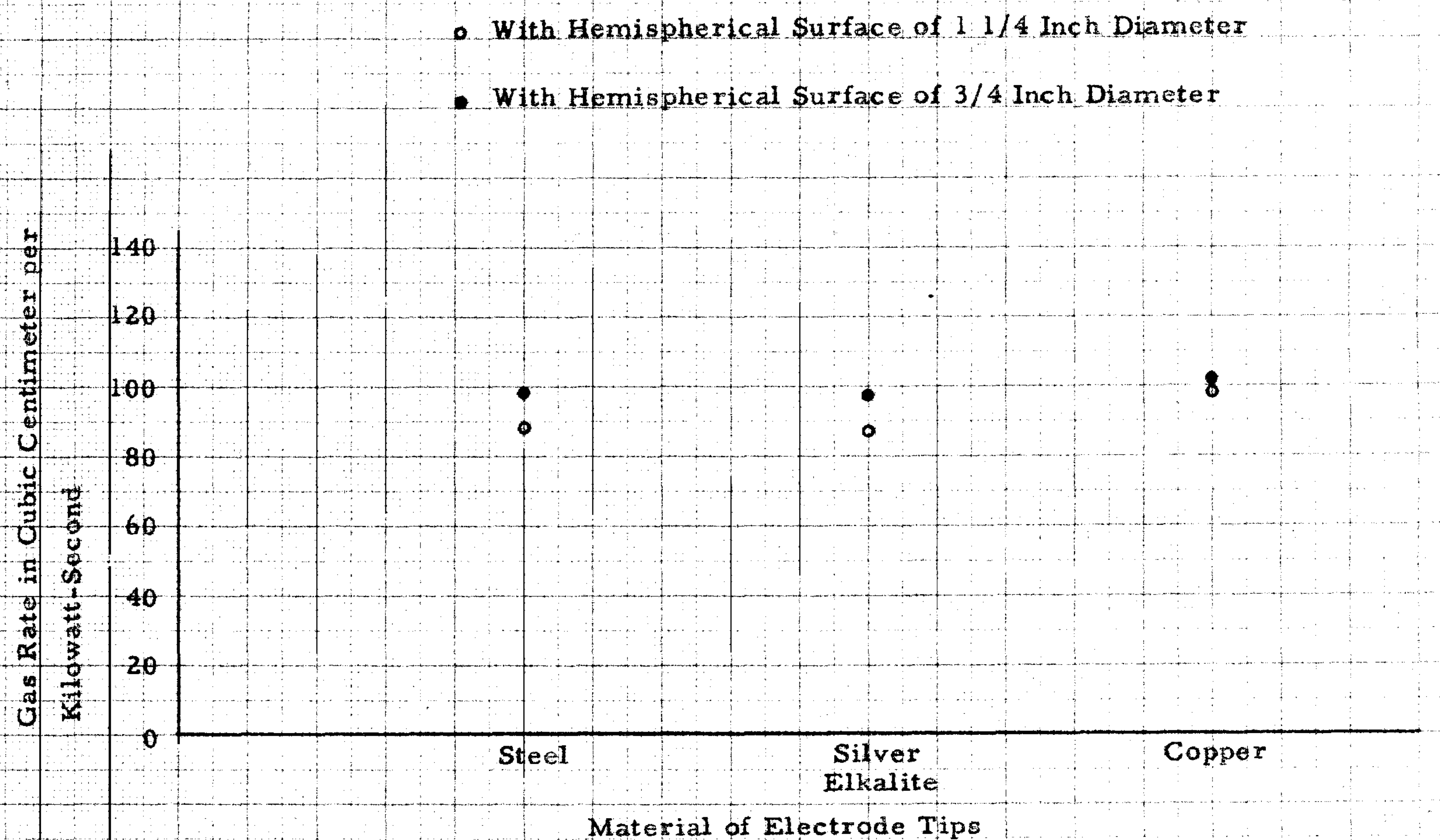

Fig. 22. Data Showing the Effect of Electrode Size (Hemispherical Surface) on Gas Rate with 600 Amperes and Two Cycle Arc Duration at One Quarter Inch Electrode Gap.

IV. DISCUSSION

4-1 Percent Deviation

It was mentioned in the last section that each data point shown in figures 18 through 22 was an average of five test runs. It is worth while to show the deviation of the results in an individual test run from the average data point. Table 1 shows the percent positive and negative deviation of individual test results at all data points. The percent positive deviation is the difference between the largest value of gas rate among the five tests and the average value divided by the average value. Similarly, the percent negative deviation is the difference between the smallest value of gas rate among the five tests and the average value divided by the average value. It is shown in this table that steel surfaces gave the least deviation with a maximum of 16.1 °/o and in general the deviation was within 10 °/o. For silver elkalite surfaces, the maximum deviation was 30.9 °/o while in most tests, the deviation was within 15 °/o. The variation of results obtained in the individual test runs for both steel and silver elkalite surfaces should be considered as small in view of the wide variations generally encountered in the study of arc characteristics either in air or in oil (11), (12) and (13). This is best appreciated from the following quotation (10).

> "The energy calculated for about 80 individual tests in the open tank switch from the mean values of the constants involved, including the arc temperature, agrees with the observed values with a maximum deviation of about ± 40 °/o, the mean percent deviation being only 12 and 13 percent respectively for the two assumptions made as to the state of dissociation of gases at the arc. This must be regarded as satisfactory, considering the wide range of variations generally found in pursuing quantitative measurements on the arcs. It is well known that under identical external conditions, wide variations of performance

TABLE 1

PERCENT DEVIATION*

Referring to	Steel	Silver Elkalite	Copper
Fig. 18 - Magnitude Effect (flat 1 1/4 inch dia., 2 cycles, 1/4 inch gap)			
400 Amperes	+ 3.1	+ 17.9	+ 16
	- 3.1	- 11.5	- 16.9
600 Amperes	+ 10.7	+ 13.3	+ 51.5
	- 9.9	- 10.7	- 34.4
800 Amperes	+ 2.7	+ 30.9	+ 17.7
	- 1.2	- 27.8	- 25.4
Fig. 19 - Duration Effect (flat 1 1/4 inch dia., 1/4 inch gap, 600 amps.)			
1/2 Cycle	+ 3.5	+ 10.9	+ 7.9
	- 4.9	- 11.4	- 12.8
2 Cycles	+ 10.7	+ 13.3	+ 51.5
	- 9.9	- 10.7	- 34.4
3 1/2 Cycles	+ 6.84	+ 18.8	+ 50.7
	- 8.24	- 24	- 37
Fig. 20 - Gap Length Effect (flat 1 1/4 inch dia., 2 cycles, 600 amps)			
1/4 Inch Gap	+ 10.7	+ 13.3	+ 51.5
	- 9.9	- 10.7	- 34.4
1/2 Inch Gap	+ 16.1	+ 12.5	+ 22.3
	- 15.3	- 9.2	- 24.8
3/4 Inch Gap	+ 14.3	+ 4.8	+ 8.14
	- 11.7	- 4.2	- 18.7

* See page 41 for explanation.

TABLE 1 (Continued)

Referring to	Steel	Silver Elkalite	Copper
Fig. 21 - Size Effect (flat surface, 1/4 inch gap, 2 cycles, 600 amps)			
1 1/4 Inch Diameter	+ 10.7	+ 13.3	+ 51.5
	- 9.9	- 10.7	- 34.4
3/4 Inch Diameter	+ 2.2	+ 12.3	+ 29.8
	- 3.9	- 12.1	- 29.2
Fig. 22 - Size Effect (spherical surface, 1/4 inch gap, 2 cycles, 600 amps)			
1 1/4 Inch Diameter	+ 7.4	+ 22.1	+ 20.2
	- 4.7	- 15.9	- 7.5
3/4 Inch Diameter	+ 9.8	+ 12.8	+ 26.7
	- 7.8	- 15.3	- 14

are observed, even in repeated tests due to fortuitous variations in the form and activity of the arc itself, of the moving oil etc. ..."

The data obtained with the copper surface had the highest deviation with a maximum value of 51.5 °/o and in most cases were of the order of 20 °/o and were chiefly due to the effect of the location of the arc as explained in the next section.

4-2 Effect of the Location of the Arc

It was found that an arc on the center of the surface generally gave a lower gas rate while that on the edge a higher gas rate (figure 23). This situation occurred, of course, only on flat surfaces. Since the data on figures 18 to 21 were all taken with flat surfaces and since each data point was an average of five tests, the location of the arc evidently effected both the result and the percent deviation. This deviation due to the location and hence partly due to the path of the arc was also observed by Ellis (12). While there is no way to control the location of an arc, it was observed at the beginning of this research that for steel surfaces, all arcs occurred on the center and thus gave results with least deviation. This was the chief reason for using steel surfaces as it helped to show the effect of each variable. For silver elkalite surfaces most of the arcs occurred near the edge while some were on the center. This caused the deviation to be slightly high. Since for arcs on the center, both steel and silver elkalite surfaces had about the same gas rate, the higher results for silver elkalite surfaces as compared with that for steel surfaces (figures 18 through 21) must be considered as mainly due to the effect of the location of the arc. In the case using

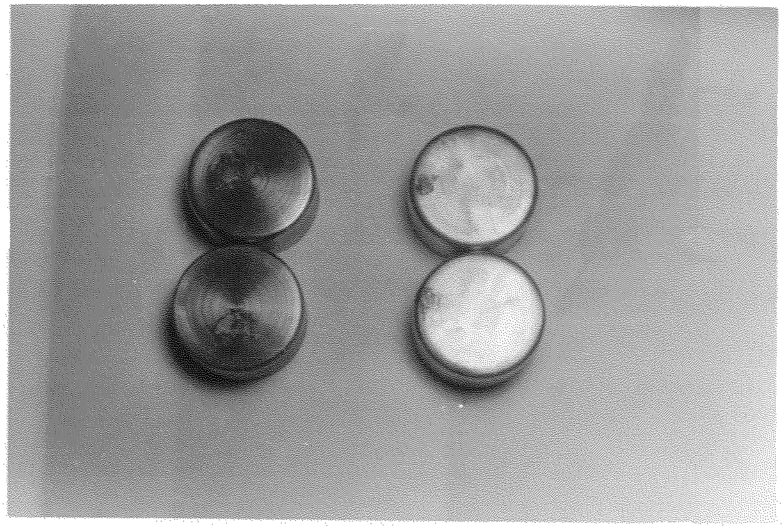

Fig. 23. Photograph of Silver Elkalite Tips with Arc Spots on the Center and Near the Edge.

copper surfaces, most of the arcs occurred right at the edge with some on the center. The difference between results with arcs at the edge and those on the center was more prominent than in the case of silver elkalite surfaces and hence the highest deviation was obtained. Since the result using copper surfaces was always the highest even when the arc occurred on the center, it is safe to conclude that the material used for the surface does effect the gas rate with copper giving the highest value.

4-3 Test Temperature and Volume of Air Above Oil Surface Inside Tank

All the tests for the data shown in figures 18 to 22 were conducted at room temperatures between 13°C to 25°C. No appreciable effect on results was observed due to the difference in temperature within this range.

The air volume above the oil surface was kept at 1000 cc in all the above tests. Check tests were made using an air volume of 3000 cc. No appreciable effect on results was observed. In this connection, it may be mentioned here that the gas produced with copper surfaces ranged from 24.1 cc (1/2 cycle, 1/4 inch gap, 600 amperes) to 718 cc (2 cycles, 3/4 inch gap, 600 amperes).

V. CONCLUSION

Before stating the conclusions derived from the test results shown in figures 18 through 22, it should be reiterated that the data for both copper and silver elkalite surfaces were obtained mostly from arcs occurring on and near the edge of the electrodes. This evidently gives results higher than that produced by arcs on the center or on the entire surface, the latter being closer to the actual practice. Therefore the data for copper and silver elkalite should be considered as too high for practical use. However since the arc for steel electrodes always occurred at the center of the surface and the gas rate for silver elkalite electrodes for arcs in the center was almost equal to that for steel electrodes, calculations of the total gas produced from actual circuit breakers using silver elkalite electrodes can be made from the steel electrode data of this thesis. Since copper surfaces are no longer used in practice, the inability to obtain accurate data for arcs occurring at the center seems to be not too important, although the original attempt to compare the results obtained in this research with that found by previous investigators is made difficult. In this connection, it may be mentioned here that a previous investigation (9) gave an average gas rate of 70 cc/kw-sec. using an open tank and copper surfaces. The data for copper surfaces shown on figures 18 through 22 range from a minimum of 99 cc/kw sec. to a maximum of 208 cc/kw sec. One of the causes for having the higher value of gas rates has been mentioned to be the edge effect. No attempt will be made to judge further the accuracy of this research or of the previous investigation. However, the fact that the results in this research have the same order of magnitude as those obtained by the previous investigation should provide the design engineer with an approximate range of values.

5-1 Factors Influencing the Gas Rate

(a) Current Magnitude - Figure 18 shows that the gas rate is not effected by the variation of current magnitude in the range between 400 to 800 amperes. This conclusion may be extended to much higher current magnitudes as discussed on page 2.

(b) Duration of Current - Figure 19 shows that a high gas rate results in the short duration arc of 1/2 cycle and nearly equal low gas rates are obtained for durations of 2 cycles and 3 1/2 cycles.

(c) Gap Length - Figure 20 shows that the gas rate increases as the gap length varies from 1/4 inch length to 3/4 inch length.

(d) Electrode Size - For flat surfaces of the same material (figure 21), the difference between the results using 1 1/4 inch diameter and 3/4 inch diameter surfaces is small in view of the possible deviation of the data. For hemispherical surfaces of the same material, (figure 22), the slightly higher results of the 3/4 inch diameter surfaces compared to that of 1 1/4 inch diameter is partly due to the enlargement of the gap resulting from the burning of the hemispherical top. This seems to agree with the phenomena in (c) in which the gas rate was shown to increase with the gap length. For steel tips, the enlargement of the gap for hemispherical surfaces is the main reason for having a higher gas rate than for flat surfaces (comparing figures 21 and 22). However for silver elkalite tips, the edge effect of flat surfaces compensates for the effect due to the enlargement of the gap using hemispherical surfaces. Thus nearly identical results were obtained with hemispherical and flat surfaces. For copper tips, the edge effect is most prominent, and a higher gas rate is obtained for flat surfaces than for hemispherical surfaces.

5-2 Suggested Method of Calculating Gas Volume Produced in an Actual Circuit Breaker

The arcing surfaces of present day circuit breakers are mostly silver elkalite. In the actual operation of a circuit breaker, the area of the arc core is always large enough to occupy the entire electrode surface. Due to the inability in this reasearch to obtain a complete set of data for silver elkalite surfaces with arcs on the center, the data obtained with steel surfaces are used instead since as mentioned above the two gave approximately the same gas rate for arcs on the center of the electrode surface. Owing to the fact that the effect of current magnitude is small and that the arc duration in practice is about 2 cycles, an approximate method of calculating the volume of gas produced can be made by considering the gap length as the only variable. The necessary information for this calculation can be obtained from the records of arc voltage, arc current and the contact travel. It is suggested that a mean gap length for each half cycle of arcing be measured from the contact travel record. Corresponding to the measured mean gap length, the gas rate desired can be obtained from the curve for steel surfaces in figure 20. The gas rate for each half cycle multiplied by the corresponding arc energy gives the volume of gas produced in each half cycle. Thus the total gas referred to 760 mm and 25°C is given as the sum of that produced in each half cycle.

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APPENDIX

Arc Voltage Measuring Equipment

The arc voltage as well as the arc current and transformer voltage is recorded on a Miller magnetic oscillograph using galvanometers. A galvanometer with a natural frequency of 3200 cycles per second is suitable for the measurement of the 60 cycle arc voltage. The sensitivity of this type galvanometer is 50 milli-amperes per inch deflection. A peak deflection of about a half inch in each direction of the 60-cycle arc voltage is desired in order to have a fair accuracy for scaling. To give this deflection, a current of 25 milli-amperes (peak) in the galvanometer element is necessary. Since the non-inductive resistance of the galvanometer element is 45 ohms, the applied voltage to the element should be on the order of one volt (peak). If an external resistance is connected in series with the element, the range of the applied voltage to the combination may be varied.

Now referring to figure 2, normally with the application of the surge voltage at the test oil gap, both the test gap and the stand by air gap break down simultaneously, resulting in the desired flow of arc current. The voltages applied to the voltage divider at the test oil gap are of two types namely the surge voltage of about 450 kv and the 60 cycle arc voltage of 50 to 300 volts, depending upon the gap length. However, since it is desirable to keep the surge voltage to a minimum value required for breaking the oil gap in order to avoid insulation problems, (especially when longer oil gaps are tested), it is found that occasionally the surge voltage breaks down the stand by air gap but not the oil gap. This phenomenon for parallel arc gaps is not uncommon in high voltage works. Under this condition, the voltages appearing at the voltage divider are the surge voltage of 450 kv and the 60 cycle transformer open circuit voltage of about 3000 volts. In other words, there are possibly three different values of voltage at the voltage divider and we are interested only in the measurement of the arc voltage which is between 50 to 300 volts (peak volts). The surge voltage can be filtered out by the use of an L-C filter circuit. A clipping circuit using a 6H6 twin diode may be used to clip the 60 cycle open circuit voltage while the lower magnitude arc voltage is allowed to flow. However in order to keep the load impedance high at the output of the L-C filter circuit, the range of the series resistance for the Miller galvanometer circuit is limited. To coordinate these circuits, an amplifier with a cathode follower is used. The choice of the circuits for the arc voltage measurement shown in figure 2 is two fold. In the first place, a wide range of arc voltage can be recorded on the oscillograph with the desired size of deflection and, secondly, the elements for the circuits especially the inductance coil and capacitor for the filter are easily obtained. The function of the arc voltage equipment is described below.

For a surge voltage of 450 kv at the test oil gap, the voltage applied to the input of the filter is 4,500 volts since the voltage divider has a ratio of 100 to 1. The output surge voltage of the filter is about 600 volts calculated by the Laplacian transform method. This magnitude of surge voltage is to be considered as safe for the apparatus used.

For the 60 cycle open circuit voltage of 3000 volts (rms), the 100:1 voltage divider cut this voltage down to 42 volts (peak). Although the filter circuit does not effect the 60 cycle voltage, this peak voltage of 42 volts is clipped by the 6H6 tube.

For the arc voltage of 50 - 300 volts to be recorded. The 100:1 voltage divider gives an input voltage of 0.5 to 3 volts at the filter circuit. This voltage is in turn applied to the grid of the 6SL7 amplifier tube through a second voltage divider. This second voltage divider is used for convenience in adjusting the input voltage to the amplifier and has fixed tap ratios of 2:1, 3:1 etc. The output voltage of the amplifier drives the cathode follower which in turn passes a current of about 20 ma to 40 ma through the galvanometer element. The complete voltage measuring circuit is calibrated corresponding to the tap setting of the second voltage divider. Since the cathode follower tube (6AS7) is operated with a quiescent current of 50 ma, a switch and a 45 ohm resistor are used to replace the galvanometer element when arcing test is not in progress in order to reduce the burden on the galvanometer. An ammeter is also used to indicate that the cathode follower circuit is in proper operative condition.