The behaviour of a thyristor assisted commutator

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The Behaviour of a Thyristor-Assisted Commutator.

by

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A Thesis submitted for the Degree of
Master of Science in the University of Durham.

Engineering Science Department

May 1968.

ABSTRACT

Development of machines in which sliding contact commutation is assisted by thyristors has led to a need for more knowledge about the behaviour of carbon brushes sliding on slip rings when the current is applied in pulses instead of continuously. Of particular interest is the question of relative wear of those parts of the rings that carry current relative to those that do not, the maximum current density at which they can work under pulsed conditions, and the uncertainty of such contacts when a brush is sitting partly on a "conducting" segment and partly on a "non-conducting" segment.

To look at the above in a relatively simple way, some rings were rotated and current passed in pulses, of both sine wave and rectangular form. An attempt was made to detect excessive wear or damage on the rings, together with any significant time lag between application of voltage and flow of current. Photographic evidence of the above is presented.

To look at the effect of current flow when the contact is uncertain, as is the case when a brush is only partly sitting on a segment, a split ring was used, and current passed to a brush as it passed across the split.

The switching method adopted was by using thyristors, and the appropriate circuity is described.

A great deal of published literature concerns the study of contacts and wear. A survey of this literature is presented as background material to this thesis. There is no satisfactory theory of current flow under pulsed conditions, but it is quite possible that the existing literature on steady flow of current is applicable to some extent to pulsed conditions, and a knowledge of this theory is an essential starting point to an understanding of what is going on.

ACKNOWLEDGMENTS

I am particularly grateful to Professor J. J. Bates for supervising the work described in this thesis, and for his suggestions which made this work possible. I would also like to record my thanks to Dr. E. C. Salthouse for his interest in the progress of this work.

I am indebted to Dr. C. Preece for many discussions and his continued encouragement throughout the period of the work.

I would also like to thank the technicians of the Engineering Science Department of The University of Durham for their part in the construction of the experimental equipment.

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NOTE: All current densities quoted in this thesis are peak values.

1. INTRODUCTION

1.1. Use of Direct Current

The study of a.c. motors in which the speed of rotation can be easily controlled has been a major concern of electrical machine engineering for half a century or more. The need for variable speed a.c. motors arose because until recent times no cheap and efficient rectifying devices were available. Had the semiconductor diode been available at the beginning of the century, the problem of variable speed from a.c. supplies would probably have been solved by the use of d.c. machines operating through rectified supplies. It is quite likely that much more research effort would then have been devoted to the perfection of the commutator, which is the only really troublesome feature of d.c. machines.

With the advent of the semiconductor diode, the d.c. machine, fed through diodes from an a.c. supply with some means of voltage control, has become a very efficient form of variable speed drive, but the sliding contact commutator continues to be a source of weakness, and limits the combinations of speed and power possible. Some recent work has been directed towards using thyristors to assist the process of commutation in d.c. machines.

1.2. Previous work on Thyristor Commutation Machines.

"Thyristor-Assisted Sliding Contact Commutation" is a scheme for using thyristors to assist the process of commutation in d.c. machines. By using thyristors to assist the process of commutation in d.c. machines. By using a sliding contact commutator to distribute the tappings on a closed winding to a pair of thyristors, which then do the actual switching, required in commutation, it is possible to get an improved performance from a machine which justifies the additional cost of the thyristor equipment.

The work with thyristor commutation machines was undertaken by Bates and Sridhar (1966). The scheme is shown in Fig. (1.4.) and described in (1.4.). Instead of a single commutator there are two parts commutators C_1 and C_2, the coils being connected to alternate segments. There are four brushes to feed current in, two on each commutator. The pairs of brushes are in parallel, and connected to the ends of a commutating transformer T_r, through Thyristors T_1 and T_2.

Bates and Sridhar pointed out that the results so far were sufficiently encouraging for this development to be vigorously pursued to produce a number of proto-type machines, and to prove their advantages and their reliability in a number of motor and generator applications. They also suggested that a considerable amount of development work remained to be done on such matters as contact behaviour under pulsed current conditions.

1.3. Differences Between this Sort of Commutation and Previous Types.

In conventional commutators there is a necessarily large degree of subdivision of the armature winding and the large number of commutator segments means that the mechanical construction of the commutator is a difficult and expensive process. Additional disadvantages are that the commutator will be heated considerably by the winding losses due to the large number of tappings from the winding to the commutator and that a damaged segment cannot be replaced because of the rigidity of all the segments together in one structure. In thyristor assisted commutation the number of segments is reduced to only eight or so. Rigidity of segments can be achieved separately without replying on the presence of adjacent segments. Commutator diameters will also be less. In a conventional commutator the contact is very sensitive because a brush must make good contact simultaneously with two adjacent commutator segments, and any small difference in surface level makes it difficult to achieve this condition of simultaneous contact. Also because of the uncertain nature of the brush contact, it is difficult to ensure an exact balance between the interpole induced e.m.f. and commutating e.m.f.s. at all instants. In a thyristor machine the brush has no longer to make simultaneous contact with two adjacent segments. The brush is arranged to be on a single segment when it changes from the inactive to the active condition. Electromagnetically, the interpole need not provide an exact balance of voltages in the commutating coil but need only supply just more than the limiting value of volt-seconds for commutation.

1.4. The present work.

The investigations described in this thesis concern the brush slip-ring contact characteristics as applied to the thyristor-assisted commutator machines. The waveform of brush current in the thyristor machine will approximate to a pulsed triangular wave. However in these initial studies the wave form of the pulse is not too obviously important and half sine waves and square wave pulses are likely to be just as informative and lend themselves to easier experimental rigs.

The experiments were made in order to obtain information on the relation between brush and commutator or slip ring surface damage with current in pulses. Studies were carried out to determine the maximum current density at which a brush can be worked when the current is passed in pulses and how the maximum current density is related to the duration of the pulse. An important question to be answered in this investigation is what time lag occurs between the firing of the thyristor and a flow of current from the brush to the slip ring. The importance of time lag in the successful operation of thyristor assisted commutation machines is shown below. Fig.(1.4.) shows a scheme for thyristor-assisted commutation which was designed and built by Bates and Sridhar (1966). There are two part commutators C_1 and C_2 instead of a single commutator, the coils being connected to alternate segments. The number of segments has been reduced to eight on each commutator. There are four brushes to feed current in, A_1 and A_2 on commutator C_1 and B_1 and B_2 on commutator C_2. The brushes are connected to the ends of a commutating transformer T_r. The current is supplied to the thyristors T_1 and T_2 via this commutating transformer. When running, the thyristors are fired in turn and the commutation sequence as quoted from Bates and Sridhar (1966) is as follows. "In the position shown on Fig,(1.4.), the thyristor T_1 would be fired and would feed current into the armature via brushes A_1 and A_2. As the commutator moves to the left, A_2 will leave segments C_{11} and enter segment C_{12}, but there will be no change in current in coil 12, as current will still be entering through A_1. When A_2 is just fully on segment C_{12}, thyristor T_2 will be fired. Current will now start to flow into the armature through brush B_2 and commutation will commence. It is important that commutation should not start until B_2 is firmly established on segment C_{22}. There is no need for simultaneous contact of a brush with two adjustment segments, with its consequent difficulties due to small differences in surface level. Commutation will now proceed under the action of an interpole induced e.m.f. in coil C_{12}. The interpole strength must be sufficient for the current through thyristor T_1 to be brought to zero before A_1 leaves segment C_{11}".

Thus the brush does not have to break the current. If there was a time lag between the application of voltage and the passage of current, the current would flow only for part of the time available for commutation on the segment. In other words, the time available for commutation would decrease and would limit the maximum operating speed of the machine.

Studies were also carried out into the erosion caused to the segment when a brush is turned on early, i.e. when the brush sits partly on an active and partly on an inactive segment of a slip ring.

In 1951 McLaughlin investigated the deterioration at brush and commutator surfaces in d.c. machines. He concluded that if a brush running on a short-circuited commutator is required to carry only a steady direct current then its current rating can be increased to many times the normal value. For the brush grades tested, EG12 and EG14 , McLaughlin pointed out that the rating could almost certainly be increased from 60 amps/sq.in. to 800 Amps./sq.in. for a period of 36 hours. McLaughlin was one of the first who investigated the damage of brush and commutator with current in pulses. His conclusion in this concern was that the high rate of rise of a current pulse might cause slight damage to the commutator if the pulse current flowed from the commutator to the brush. Whereas damage was observed with a pulse amplitude of 600 amps/sq.in. and rise time of 10 micro-seconds, no damage was observed if the pulse currents flowed from the brush to the bar and had an amplitude of 600 amps/sq.in.

The aim of the present programme of tests was to make a preliminary examination of some contact difficulties that arose in the construction of proto-type thyristor assisted commutator machines and to see what influence these problems will have on their development.

2. AN OUTLINE OF THE EXPERIMENTAL WORK

The purpose of the experiments to be described was to study the effect on brush and ring surfaces of the passage of current in pulses. One of the variables investigated was the current passing in pulses between brushes sliding on a slip ring. The pulses were repeated on the same parts of the ring. With this arrangement the wear of the brush and the behaviour of the ring can be accurately measured. The rate of pulsing was 50 pulses per second as shown in Fig.(2.1).

The ring was mounted on a shaft of a motor running synchronously. The brushes studied were from the EG series of electrographitic brushes, and from the CM series of metal-graphitic brushes. They were of 0.75 inch x 0.5 inch section. The aim of using different types of brush was to investigate the relationship between the types of brush and the effect of current pulses. Metal-graphitic brushes are used for non-commutating conditions; i.e. pure current collection. The positive and negative brushes travelled on the same track of a 10 inch diameter, brass slip ring running at 4000 ft./min. The mechanical pressure of the brushes was fixed at 2 lbs/sq.in. for the duration of the experiments, and the experiments took place under normal atmospheric conditions.

According to the types of current applied to the brushes, the experimental work can be divided into four sections:-

(1) Experiments with half sine wave current pulses.

(2) Experiments with square wave current pulses.

(3) Experiments with direct current.

(4) Experiments without current.

2.1. Brush and Surface Behaviour with Half Sine Wave Current Pulses.

Sine wave is a good approximation to the waveform of current at brushes in a thyristor machine, so the first experiments were carried out using current pulses as half sine wave. These are particularly simple to generate.

The main object of these experiments was to investigate the behaviour of brush and slip ring which occurred due to the passage of this type of current, and the particular time lag between the application of the voltage and the passage of current from the brush to the slip ring.

The current was supplied from a current transformer through a diode, Fig.(3.1.1.).

An experimental test was carried out for 168 hours to obtain a general idea of the behaviour of the brush and the ring. Several experiments each of a period of 100 hours were made by increasing the current gradually to determine the maximum current density that could be worked without any damage to the slip ring. The current densities applied were of the range 55-380 Amps./sq.in. Additional tests, again for 100 hours each, were carried out with current density of 400 Amps./sq.in. in order to determine the relationship between current density and wear.

2.2. Brush and Surface Behaviour with Square Wave Current Pulses.

In these experiments the brushes were fed from a d.c. battery, using thyristors to apply the current in pulses as shown on Fig.(3.2.1.). The object of these experiments was also to investigate the time lag between the application of voltage and the passage of current, where the pulse wave here is sharper and there is more possibility of any time lag which might appear being obvious.

Brush wear due to the passage of current in sharp edged pulses was also investigated, and the voltage drop between the brushes was observed.

Several tests in the ranges of 55-380 Amps/sq.in. were carried out for the time duration of 100 hours each.

The investigations were extended to a split ring and tests were carried out to show the erosion occurring when the brush is turned near the edge of a commutator segment. This condition approaches that found in the thyristor machine.

2.3. Brush and Surface Behaviour with Direct Current.

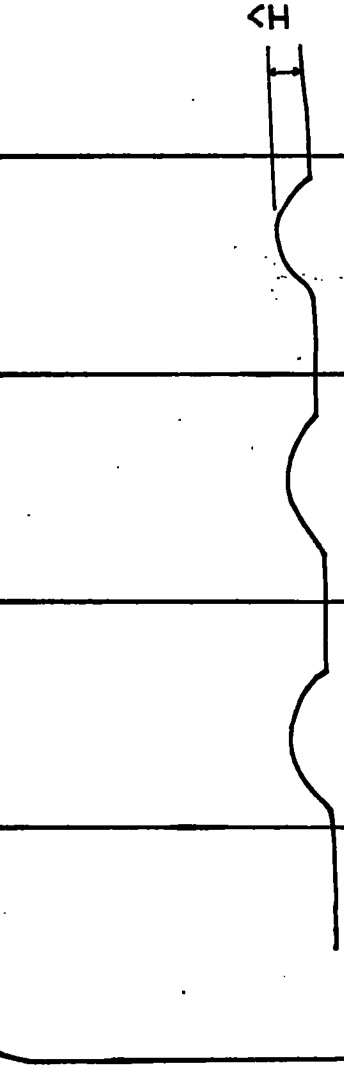
Tests were carried out with current density of 55 Amps/sq.in. for 100 hours each, and also with 80 Amps/sq.in. for 168 hours.

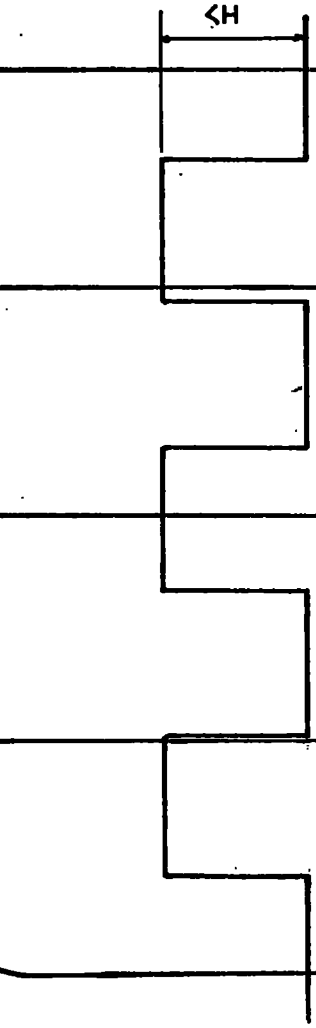
The purpose of these experiments was to compare the effects of the two above types of pulsed current with those of steady currents applied between brushes and a brass ring.

2.4. Brush and Surface Behaviour Without Current.

These series of tests were carried out to determine the rate of wear of an electro graphitic and metal-graphitic brush on brass due to purely mechanical considerations. Brush types EG11S, EG16 and CM3H were investigated for 100 hours duration each. Mechanical wear tests were also carried out on the segmented ring.

The following tables show summaries of the tests carried out in these investigations.

Test	peak Current Density (Amps/ sq.in.	Duration of Test (Hours)	Brush Area (sq.in)	Brush Grade	General Observations.
	110	168	0.375	EG11S	Blackening on the brush track. No damage. Fig. (4.4.10)
	55-380	5 tests 100 each	0.375	EG11S	Blackening and colour mark. No damage to ring.
	55-380	5 tests 100 each	0.375	EG16	No damage to ring. Slight darkening of track.
	400	2 tests 100 each	0.375	EG11S	Colours marks tends to grey. Sparking on the negative brush. No real damage to ring but excessive brush wear
	400	2 tests 100 each	0.375	EG16	Blackening and colours. Sparking on the negative brush. No damage but excessive brush wear.
	400	2 tests 100 each	0.375	CM3H	Craters and grooves on the brush track. Blackening on the positive brush surface. Heavy brush wear. Fig. (4.4
	55	100	0.375	CM3H	No damage to ring. Slight marking on the track.

Test	peak Current Density (Amps/sq. in.	Duration of test (Hours)	Brush Area (sq. in.)	Brush Grade	General Observations.
	55 and 110	4 tests 100 each	0.375	EG11S and EG16	Mark and no damage.
	55	100	0.375	CM3H	Slight marking on brush track.
	150-380	4 tests 100 each	0.09	EG11S	No damage. Marking and blackening on the brush track.
	150-380	4 tests 100 each	0.09	EG16	Blackening on the brush track. No real damage to ring.
	380	100	0.09	EG11S	Marking on the brush track tends to grey. No damage to ring.
	380	100	0.09	EG16	No damage to ring. Blackening on the brush track. Fig.(5.2.6.)
	380	100	0.09	CM3H	Fig. (5.2.8) Craters and grooves on the ring. Blackening, and fine powder on the brush surface.

Test	peak Current Density (Amps./sq. in.)	Duration of test (Hours)	Brush Area (sq.in.)	Brush Grade	General Observations.
Segmented ring.	300	2 tests 20 each	0.09	EG16	Fig.(6.5.1.) Erosion and marking tends to grey on the active segment.
	zero	2 tests 20 each	0.09	EG16	Slight blackening on brush track.
	zero	2 tests 100 each	0.375 and 0.09	EG11S	Slight blackening on brush track. Fig.(4.4.14).
without current	zero	2 tests 100 each	0.375 and 0.09	EG16	Slight blackening on brush track.
	zero	2 tests 100 each	0.375 and 0.09	CM3H	Slight brush wear.
	zero	2 tests 100 and 20	0.09	EG16	Slight blackening on brush track.
Segmented ring	zero	2 tests 100 and 20	0.09	EG16	An increase of brush wear due to the split of the ring.

Test	Current Density (Amps./ sq.in.	Duration of test (Hours)	Brush Area	Brush Grade	General Observations.
Direct Current	80	168	0.375	EG11S	Fine grooves on brush track with grey colour. Fig.(4.4.13.)
	55	100	0.375	EG11S	Blackening on brush track. No damage to ring.
	55	100	0.375	EG16	Blackening on brush track. No damage to ring.
	55	100	0.375	CM3H	Marking and fine grooves on the brush track.

3. DESCRIPTION OF THE EQUIPMENT

The equipment required for half sine wave current consisted of:

- A voltage transformer to change the input voltage of the transformer gradually according to the required current density.
- The main current transformer built to provide high rates of current.
- A current transformer to reduce the current from 100 Amps. to 100 m.Amps., connected with a meter to enable the measurement on the main transformer to be used.
- The diode used to cut off half the sine-wave was the BYX14(800). Fig. (3.1.1.) illustrates the circuit.

The equipment required for square wave current consists of two thyristors used as a simple on-off switch, turning off with a capacitance to allow the current to be applied in pulses. Current flows from the brush to the slip ring only when thyristor (1) is fired. Fig.(3.2.1.)

The thyristors used had a maximum peak ~~reverse~~ forward current rating of 1000 Amps. and a maximum peak reverse voltage of 500 volts. (Mullard BTY99-500 R) (see 9.1 and 9.2.)

Two double beam cathode ray oscilloscopes were used for observing the waveforms of voltages and currents and also to enable observations to be made of the delay of current and the change of the voltage drop against time. Photomicrographic records were taken of the slip ring wear.

The three rings made of brass* of 1 inch width, and 10 inches diameter, were mounted on the shaft of the synchronous motor and isolated from each other by tufnol discs 1/4 inch thick.(see photograph)

For the segmented ring tests two brass rings 9/16 inch thick and 10.5 inches diameter, were divided into four segments isolated from each other by tufnol 1/8 inch thick.

The gate pulsing auxiliary contact was made of alternate copper-tufnol segments, and was also mounted on the shaft. It was designed to fire the thyristors alternatively twice for each revolution.

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*The choice of brass was purely one of convenience. It is possible of course that the alloy metals in the brass may introduce additioanl complications, but in this early study this was not regarded as too significant.

4. EXPERIMENTS WITH HALF SINE WAVE CURRENT PULSES.

4.1. General

This series of experiments was made in order to determine the maximum density of half sine wave current that could be carried continuously by EG11S, EG16 and CM3H brushes, under normal conditions, without causing damage to the brush or the slip ring.

The time lag between the application of voltage and the passage of current was also investigated, and the voltage drop between the brushes was observed. The experiments comprised a series of 100 hour tests in which a range of current densities from 55-400 Amps/sq.in. was used. An additional experiment for a longer period(168 hours) at a current density of 110 Amps/sq.in. was also undertaken.

4.2. Classification of Sparking.

The following classification of sparking was used by McLaughlin (1951) to describe the sparking observed in his investigation, and it will be used in the present work.

Grade I Sparking.

Intermittent sparking between brush and

commutator. The sparks are inaudible and have a bright bluish green appearance. They wander at random along a contact edge or edges, and only a few, or sometimes none, are visible at a given moment.

Grade II Sparking.

This is more intense than Grade I sparking, but the individual sparks appear to be of a similar type. The general effect is that the sparks appear to be flickering, rather than wandering.

Grade III Sparking.

This type of sparking is audible as a sharp crackling noise, which varies considerably in intensity. The brightness and the cross-sectional area of the sparks is greater than those of Grade I and II. Individual sparks appear intermittently or continuously at definite spots near the brush edge.

Grade IV Sparking.

This type is similar in appearance to Grade III sparking except for its colour which is reddish, as distinct from bluish green.

4.3. 100 Hours Tests.

EG11S, EG16 and CM3H brush grades were tested for a range of densities between

55 and 400 Amps/sq.in. at a brush pressure of 2 lbs./sq.in. and a slip ring peripheral speed of 4000 ft./min.

The two brushes were run on the same ring. In each experiment a constant current was passed from one brush "the positive" through the slip ring and out through the other brush "the negative". Three tests were carried out with a current density of 55 Amps/sq.in. to observe the delay of current. This is the order of current density to be expected in Thyristor Assisted Commutation Machines. Also three tests were carried out with current density 400 Amps/sq.in. to investigate the effects of very high current densities.

A brush with a constant area of 0.375 sq.in. was used throughout these tests. After each test the slip ring and the surface of the brushes were examined for damage, measured, cleaned and replaced.

4.4. Observations.

4.4.1. Tests on EG11S brushes.

No damage was observed to the slip ring surfaces at current density of 400 Amps/sq.in. but excessive brush wear was observed. At this density there was sparking at the trailing edge of the negative brush which could be observed by the naked eye after 50 hours run. The sparking observed was of Grade I and II. At the positive brush sparking was also observed but after a longer time this was less intense than at the negative brush. The sparking was only of Grade I. The brush appeared smooth, and fine grooves were observed on the brush and brush track.

In this test any time lag between the application of the voltage and the passage of current was negligible in comparison with the period of the wave. Fig. 4.4.1 shows the wave form of the voltage applied to the brush and the contact voltage drop.

The above results were observed with smooth, clean ring surfaces. In a particular case when the surface was rough, due to poor machining, a time lag was observed. This time lag was variable and depended entirely on the current density. It became smaller with high density and became zero with a current density of 150 Amps/Sq.in. Graphs of current densities against time lag for rough surfaces are shown in Fig.(4.4.2b). Fig.(4.4.2.a.) shows the wave form of the current and the contact voltage drop with rough surfaces where time lag was observed. The degree of smoothness required for no time lag to be observed was of the order of 60. μ in. C·L·A.

Brush voltage drop characteristics were obtained from the above series of tests. These are shown diagrammatically in Fig.(4.4.3.) plotted against the time , and in Fig.(4.4.4.) plotted against current densities. Fig.(4.4.5.) shows the change of the wave form of the contact voltage drop and current due to the deterioration of contact surfaces after 100 hours run with current density of 400 Amps./sq.in.

In general, with high current densities there was an increase in the wear of the brush. This may be due to the attendant increase of heat. Brush characteristics were plotted as the wear of the brush against current density in Fig.(4.4.6.) and against time in Fig. (4.4.7.).

Since the current was passing through the diode and the rings were rotating synchronously at a speed of 1500 r.p.m. (25 revolution per second), the current frequency being 50 cycle/sec., it is clear that the current passed through the brushes twice during each revoltuion of the rings, causing two bars to be marked on the slip ring track.

The blackening of the ring track was observed in all the experiments and its thickness depended on the current density. With a current density of 55 Amps/sq.in. only a slight blackening was observed, but with a current density of 400 Amps/sq.in. a rather thicker film was observed. The film was coloured, almost tending to bluish-grey, this may have been due to oxidation or burning caused by the high contact heat and sparking. But no damage was observed on the ring track or brush surface. For current densities of the range of 55-380 Amps/sq.in. the blackening was usually associated with coloured portions.

Fig.(4.4.8.) shows the brush track of EG11S grade after 168 hours run on the brass ring and at a current density 110 Amps/sq.in. at the end of an active wave current Fig.(4.4.9) shows the same conditio at the beginning of an active current wave Fig.(4.4.10) shows the brush track for the same condition, but at the middle of an active current wave ,and Fig.(4.4.11) at the middle of an inactive current wave where no current is passing. Fig.(4.4.12) shows the brush track of EG11S grade after 100 hours run with 400 Amps/sq.i. current density. The brush track of

EG11S grade using direct current is shown in Fig. (4.4.13) for 168 hours run with current density 80 Amps/sq.in. The brush track of EG11S grade for 100 hours run without current is shown in Fig.(4.4.14).

4.4.2. Tests on EG16 brushes

A series of tests similar to those described above was repeated with a pair of EG16 brushes. The performance of the two brush grades proved to be very similar with the EG11S brushes no significant time lag was observed between the application of voltage and the passage of current. But the contact voltage drop between the brushes was smaller with the EG16 brushes. Fig.(4.4.4.) shows diagrammatically the voltage drop between the brushes against current densities, and Fig.(4.4.15) against time. Fig. (4.4.16) shows the change of the wave form of the contact voltage drop and current due to the deterioration of contact surfaces after 100 hours run with current density of 400 Amps/sq.in.

For current density of 400 Amps/sq.in. sparking was observed by the naked eye at the negative brush after about 60 hours run.

No real damage was observed on the bars of the slip ring. Only marking of different types of colour film was observed on the ring track dependent on the current density, and due to the high surface temperature and sparking. Brush wear plotted against current densities is shown diagrammatically in Fig.(4.4.6.) and against time in Fig.(4.4.7)

4.4.3. Tests on CM3H Brushes.

No time lag was observed between the application of the voltage and the passage of current Fig.(4.4.17). But heavy wear was observed on the ring track with 400 Amps/sq.in. After 100 hours run the ring appeared rough and heavily pitted on some of the active parts of the ring where current passed. This damage was observed on the last 25 hours. No damage or marking was observed on those areas where no current was passed. Grooves were observed on the brush track and the brush in the direction of motion. Also some pitting and roughness were observed on the trailing edge of the negative brush. Blackening was noted on the leading edge of the positive brush.

The voltage drop between the brushes was 4-5 times smaller than that observed with the electrographitic brushes. Fig.(4.4.4) show the contact voltage drop against current densities. Also Fig. (4.4.7) shows the wear of the brush against time. Fig.(4.4.8.) shows the brush track of CM3H grade for 100 hours run with current density 400 Amps/sq.in., and Fig.(4.4.19) shows the change of the shape of contact voltage drop and current due to the deterioration of the contact surfaces.

4.5. Examination of Brush Track and Brush.

At the conclusion of each test with electrographitic brushes EG11S and EG16 with 400 Amps/sq.in. the brush track was examined under a microscope with a magnification of 20 times. The major portion of the brush track appeared as a number of alternate dark and light bands. The colour of these bands varied from that of slightly oxidized copper, through reddish brown to black. The bars which appeared black to the naked eye also had a striped appearance under the microscope, Fig.(4.4.12.). The bands were in this case of a brown or black colour. Under the microscope the brush surface appeared as a smooth surface sparsely covered with fine reddish brown powder.

4.6. The Wear/Time Curve

The experiments with current density of 400 Amps/sq.in. was repeated for the three types of brushes, to investigate the gradual wear of the brush with time, before and after the observation of sparking. The brushes were removed every 25 hours, measured, and replaced. Fig.(4.4.7.) shows the wear/time curve, which demonstrates that the rate of wear

~~of the brush increases~~ of the brush increases rapidly after the appearance of sparking for both polarities and the three types of brushes.

Fig.(4.6.20) shows the wear/time curve, for EG11S, EG16 and CM3H brushes running without current with contact ~~area~~ curve 0.375 sq.in. for 100 hours. The almost linear area demonstrates that the wear of the brush without current is much smaller than with current, where this wear is due almost entirely to friction and mechanical abrasion.

4.7. Results.

The above series of tests with half sine wave current pulses indicates results which may be summarized as follows:-

1. Investigations with brushes of EG11S, EG16 and CM3H showed that they can be used at normal brush pressure, 2 lbs/sq.in. with 400 Amps/sq.in. for, in the case of the EG11S and EG16 brushes, considerable periods (100 hours, (and probably much longer), and in the case of the CM3H brush, 50 hours, without any significant damage occurring to the slip ring, but there is excessive brush wear.

2. There is no significant time lag between the application of voltage and the passage of current with EG11S, EG16 and CM3H brush grades and clean, smooth surfaces.

3. The wear of the brush increases as the current density increases. With electrographitic brushes, the wear on the negative brush is greater than that on the positive brush, and the reverse is the case with metallic brushes. Also, when sparking occurs, it causes a rapid increase of brush wear.

4. The wear of the brush is much smaller with half-sine wave current than with direct current for either polarity using the three types of brushes.

5. Wear of the EG11S brush grade is smaller than that for brushes of grade CM3H and greater than that for brushes of grade EG16, for the same ~~duration of~~ current densities.

6. Investigations with EG11S, EG16 and CM3H brushes grades showed that greater wear occurred running the brush with current than in running the brush without current.

7. The formation of a black or colour film on the slip ring can be continuous and may occur due to the contact heat and sparking.

4.8. Discussion of the Results.

The above results show that with the three types of brush grades, there is no appreciable time lag between the application of voltage and the passage of current. To show to what extent this fact will affect thyristor assisted commutation machines the following calculation is cited. In a thyristor machine of 10 inches diameter, and 16 tappings, if the speed is 3000 r.p.m. the time of commutation will be t_c, where

$$t_c = \frac{1}{50 \times 32} \text{ sec.}$$

$$= \frac{1000,000}{1600} \ \mu.\text{sec.}$$

$$= 625 \ \mu.\text{sec.}$$

If the speed is 6000 r.p.m. then the time of commutation will be only t_c', where

$$t_c' = 312.5 \ \mu.\text{sec.}$$

Any reduction in commutation time due to time lags on switching on, reduces the current commutating ability of the machine.

The tests indicate, however that there is a time lag with rough ring surface. This may be due to ~~a slow build up~~, the time required for contact to be established. This time lag may be eliminated by giving the brush very high mechanical pressure, but excessive brush wear will also ensue. It follows that the surface should be kept as smooth as possible. In theory it might be expected that time lag would be caused by the eventual formation of film on the surface, but in practice this did not happen, and no real delay was observed after 100 hours run, Fig. (4.4.5.), Fig. (4.4.16) and Fig. (4.4.19).

The results of the above tests with both types of electrographitic brushes show that there was a reduction in wear of EG16 brushes compared with that of the EG11S brushes. This reduction is explained by the sparking which appeared to the naked eye after 60 hours run with EG16 and only after 50 hours with EG11S type. Also sparking at the negative brush appeared to be more severe with EG11S than with EG16 brush grade. This suggests that EG16 brushes should be used to avoid wear and damage due to sparking.

The brush wear caused by direct current was much greater than that caused by half sine wave current for both polarities and the three types of brushes. The results show that the ratio of wear of direct current to half sine wave current is of the order of 3 or 4:1 for the three brush grades. It was also found that with EG11S, EG16 and CM3H grade brushes running without current on a brass ring, the brush wear was much smaller than that observed with the same grade brushes carrying current under the same conditions. For example, for 100 hours tests with 400 Amps/sq.in. the wear with EG11S would be greater - about 12 times in the negative brush and about 8 times in the positive brush. With EG16 this ratio would be of the order of 9 times in the negative brush and 7 times in the positive brush. With CM3H the ratio would be of the order of 6 times in the negative brush and 8 times in the positive brush.

The brush wear without current is clearly due entirely to friction and mechanical abrasion. But with current tests, additional factors such as sparking must be considered. Fig.(4.6.20) shows the almost linear wear/time curve with currentless tests and contact area 0.375 sq.in.

The wear/time current with current tests shows that sparking caused excessive brush wear. This can be reduced by increasing the brush pressure, but then there will be overheating from frictional losses and excessive wear by mechanical abrasion; consequently it is necessary to operate in a zone within which losses and wear are not affected to any major degree by the brush pressure.

Finally, the results show that the brushes can be run with 400 Amps/sq.in. for 100 hours without damaging the ring. Thus it may be said that the brushes can be run on a thyristor machine with a peak density equal to this. ~~Thus the part brushes on the thyristor machine are equally capable of passing a given current into an armature as a single brush four times the width of each part brushes.~~

5. EXPERIMENTS WITH SQUARE WAVE CURRENT PULSES.

5.1. General

The object of this series of tests was to determine whether the application of high current density pulses with high rates of rise would cause appreciable damage to the surface of EG11S, EG16 and CM3H brushes on slip ring bars.

The thyristor switch was designed to allow the pulses of current to be applied twice during each revolution of the rings, that is, to pass through two of the four quadrants of the ring. The wear of the brushes was studied and the delay of the current following the application of voltage was also monitored during the tests.

The experiments consisted of four tests of 100 hours each using EG11S and EG16 grades at current densities of 55 and 110 Amps/sq.in. A brush with a constant area of 0.375 sq.in. was used in the experiment. Four tests for 100 hours each were carried out with current densities in the range of 150-380 Amps/sq.in. using EG11S brushes and EG16 brushes. Also another three tests were carried out with EG11S, EG16 and CM3H brushes for 100 hours each and 380 Amps/sq.in. For these tests brushes of contact area

0.09 sq.in. were used. This reduction in area was necessary in order to obtain these high current densities with the available current supplies. In order to affect the stability of the brushes as little as possible only their length and not their width was reduced. The brush pressure was 2 lbs/sq.in. for the duration of all the experiments, and the slip ring peripheral speed 4000 ft./min. After each test the ring and the brush were examined for damage, measured, cleaned and replaced.

5.2. Observations.

5.2.1. Tests on EG11S Brushes.

No ~~real~~ significant time lag was observed between the application of voltage and the passage of current. Like the half sine wave, the current starts to flow immediately upon the application of voltage. This is shown in Fig.(5.2.1.) which shows the wave form of current applied to the brush and the contact voltage drop.

No damage was observed to either brush or slip ring at current density of 300 Amps/sq.in. At 380 Amps/sq.in. fine grooves were observed on the brush track in the direction of motion. Also after this test all the pulsed bars showed appreciable blackening, but no real damage was observed to slip ring surface. The bars that were not pulsed were unmarked.

After 100 hours run the brush appeared smooth and finely grooved, and was covered with a fine reddish brown powder. Sparking of Grade I and II was observed, on both positive and negative brush. ~~It is possible that this was due to overloading of the current rating.~~ For current density below 300 Amps/sq.in. the marking observed on the brush track was of a colour between black and reddish grey.

In general, there was an increase of brush wear with higher current densities due to an increase of heat and sparking. Fig.(5.2.2.) shows the wear of the brush plotted against current densities. Brush voltage drop characteristics were also obtained from the above series of tests. These are shown diagrammatically in Fig. (5.2.3) against time and Fig.(5.2.4.) against current density.

5.2.2. Tests on EG16 Brushes.

No time lag was observed between the application of voltage and the passage of current. Also no damage was observed to either brush or slip ring at current density of 380 Amps/sq.in. At this density colour marks of a reddish grey appearance and fine grooves were observed on the brush track. The brush was smooth and covered with a fine powder.

Sparking of Grade I and II was also observed on both positive and negative brushes. Fig.(5.2.2.) shows the wear of the brush against current densities. Fig.(5.2.4.) and Fig.(5.2.5.) show the contact voltage drop against current densities and against time.

Fig. (5.2.6.) shows the brush track of EG16 grade brush for 100 hours run with current density of 380 Amps/sq.in.

5.2.3. Tests on CM3H Brushes.

As with EG11S and EG16 grade brushes, no time lag was observed between the application of voltage and the passage of current with this type of brush, Fig.(5.2.7.). But after testing at 380 Amps/sq.in. 100 hours, the ring was rough and heavily grooved. Also ~~puncturing~~ pitting was observed in some of the ring bars where current passed. No marking was observed where no current passed. The damage was observed in the last 25 hours. The brush also appeared grooved and covered with a fine powder.

Fig. (5.2.8.) shows the brush track of CM3H grade for 100 hours with current density of 380 Amps/sq.in.

5.3. Results.

The above series of tests with square wave current pulses produced results which may be summarized as follows:-

1. The brushes of the EG11S and EG16 grades studied can be run with 380 Amps/sq.in. for 100 hours (and may be much longer) without any damage occurring to the slip ring but there is excessive brush wear.

2. Brushes of CM3H grade investigated can likewise run with 380 Amps/sq.in. for 50 hours without any damage occurring to the slip ring but again there is excessive brush wear.

3. No significant time lag was observed between the application of voltage and the passage of current with the three grades of brushes.

4. The wear of the brush with square wave current is much smaller than with direct current for either polarity and the three types of brushes.

5. The formation of a black or colour film on the slip ring is continuous and may be due to the high contact heat and sparking.

6. Investigations with EG11S, EG16 and CM3H brush grades showed that running the brush with

square wave currents caused much greater brush wear than running the brush without any current.

7. The wear of the brush increases as the current increases. It is greater with EG11S than with EG16, and smaller than with CM3H. Also with electrographitic brush the wear on the negative brush is greater than that on the positive brush and the reverse is the case with the metallic brush.

5.4. Discussion of the Results.

In thyristor machines the brushes are fed with current in pulses. The commutator consists of active segments and inactive segments. Thus the time lag between the application of voltage and the passage of current, and also the wear of the brush with this type of current, must be taken into consideration.

The results with square wave currents show that with EG11S, EG16 and CM3H grade brushes tested no time lag was observed between the application of voltage and the passage of current. As mentioned previously this is important factor with regard to thyristor machines because a maximum commutation time can thereby be achieved. The only time delay in the circuit is thus the firing time turn-off of the thyristor. This time is of the order of 5 μ.sec. for the thyristor (BTY 99 500R) which was used. As this turn-on time is constant for any current it can be accounted for in the setting up of the machine.

The above results show that the brush wear caused by direct current is much greater than that caused by square wave current for the three types of brushes used. It was expected that the ratio of wear due to direct current to wear due to square wave current would be of the order 2:1 since the square wave current passes for only half of the time. In fact this was not so. The results showed that this ratio of wear is of the order of 3 or 3.5:1 for the same duration and current density. This may be due to increased sparking and raising the surface temperature.

The results indicate that the brush wear with square wave current is more than that with sine wave current for the same duration and peak current densities. This is shown diagrammatically in Fig.(5.4.1.) plotted as a ratio wear against peak current density. The curves show that the ratio of wear increases as the current density increases. This increase of brush wear is due to the longer duration of the peak current, in the case of square wave. It is more likely in thyristor machines that less brush wear is caused by sine wave currents since the current pulses applied to the brush in thyristor machines are triangular and not square wave as has been shown in (1.4.). With average current density this ratio will drop and the brush wear will be almost the same as shown in Fig.(5.4.2.).

In comparison, tests made without current have shown much less brush wear than in those tests made with square wave current, for the same grades and the same duration.

The film which was observed on the brush track, may be due to oxidation or burning due to the high contact heat and sparking, and the wear of the brush, may be due to melting by friction and sparking.

With 380 Amps/sq.in. current density, and after 100 hours run, the pulsed bars showed appreciable blackening and marking, particularly at the beginning of each pulse. This may be due to the high rate of rise of the pulse current, as has been suggested by McLaughlin (1951).

6. SPLIT RING TESTS

6.1. General

In the thyristor machine there are alternate active segments and inactive segments, Fig.(1.4.). Current is passed only when a brush is fully in contact with an active segment. The commutating time is determined by the difference between the segment width and two brush widths, and not by the brush width only. In small thyristor commutators, if the width of the segments is for instance 1 inch, and the width of the brush 1/2 inch, Fig.(6.1.1.), then the time of commutation is very limited, particularly with high speeds. The time of commutation could be increased by turning the current on before the brush was fully on one segment and turning it off after the brush had started to leave. A brush sitting partly on an active, and partly on an inactive segment gives rise to a very uncertain contact. The tests described in this chapter were made to determine the erosion that occurs when a brush is used under these conditions.

For the experiment a split ring was made of brass 3/4 inch wide and 10.5 inch in diameter. The ring consisted of four segments separated from each other by air gaps. Two opposite segments were connected electrically together to pass current. The width of the gaps were of the order of 1/16 of an inch. The ring was mounted on the shaft of the motor. The experiments consisted of three tests for 20 hours duration each.

6.2. 20 Hour Tests

EG16 brush grades were tested with a current density of 300 Amps/sq.in., a brush pressure of 2 lbs./sq.in. and a slip ring peripheral speed of 4100 ft./min. A test was carried out for 20 hours without current to investigate the brush wear occurring due to mechanical abrasion and friction. The two brushes were run on the same slip ring.

A brush with an constant area of 0.09 sq.in. was used in the experiments. After each test the slip ring and the brushes were examined for damage, measured, cleaned and replaced. Fig.(6.2.1) shows the wave form of the current applied to the brush and the contact voltage drop. The current was turned off by the thyristor switch before the brush reaches the end of the active segment.

6.3. Observations.

After 20 hours run with a current density of 300 Amps/sq.in. and early firing, darkening was observed on the active segment destributed along the contact area. At the beginning of the active segment where the brush was turned on, heavy erosion was observed. The marking tended to grey and there seemed to be burning due to sparking. This marking was associated with surface puncturing and roughness. Slight blackening was also observed on the inactive segment. The brush appeared smooth, but roughness and puncturing were also observed on the leading edge of the positive brush. It was observed that after 20 hours run without current, transferred graphite was destributed along the contact area.

6.4. Summary of Above Results.

1. Heavy erosion and burning is caused to the brush and segment due to sparking when a brush is turned on early, i.e. when a brush is sitting partly on an active, and partly on an inactive segment.

2. An increase of mechanical wear occurs to the brush due to the split in the ring.

6.5. Discussions of the Results.

The above results show that heavy erosion is caused to the segment due to arcing when a brush is turned on before it is fully on the active segment. In sliding contact, the brush only touches the ring at a few spots. Morganite Ltd.(1961) suggest that the mechanical contact points which are not initially conducting may also carry current once the potential between them due to the passage of current through the constriction resistance at the conducting spots becomes sufficiently high. This is the sort of condition which occurs in thyristor machines, where the turn-off volts can be as high as 100 V in a machine of a few hundred horse power rating. It is to be expected that arcing will occur across this small gap, and in fact there was erosion (roughness) of the ring. Fig.(6.5.1.) shows this erosion. That this erosion may be due to arcing is suggested by the results of the following tests:

(i) Using a plate of metal (brass) and brush, insulated from each other by tissue paper, the circuit was complete through a thyristor, d.c. supply resistance and switch as shown in Fig.(6.5.2.). After switching the current on and off several times, and changing the position of the brush, the plate was puncutred by the arcing. This puncturing appeared under the microscope to be similar to that which occurred on the active segment.

(ii) By reducing the turn-on voltage for the same current, and repeating the test for several voltage levels, a voltage was reached where no arcing occurred and hence no damage. This voltage was of the order of 7 volts.

(iii) By switching the current on through an inductive circuit, Fig.(6.5.3.), the build up time of the current was then sufficient to allow the brush to be fully on the segment before the arcing voltage is exceeded. No arcing thus occurred, and hence no damage was observed.

It has been attempted industrially to assist the process of commutation in d.c. machines by using semiconductor diodes instead of thyristors, which were used on the experiment illustrated by Fig.(1.4.). The above results show that erosion occurs due to early turn-on. It is therefore argued that the current must only be turned on when the brush is fully on the segment, and must not be turned on before this condition is reached. The current must also be brought to zero before the brush leaves the active segment in order to avoid erosion and damage occuring to either brush or ring due to sparking. These conditions can only be ensured by the use of thyristors. With diodes the time of establishing the current cannot be controlled and in low speed machines if a current density of the order of 400 Amps/sq.in. is used then in one instant when the brush is half on an active segment, the density will rise to 800 Amps/sq.in.

or so, and this overloading of current will increase the erosion and sparking.

The adjustment between two adjacent commutator segments is a matter of importance in thyristor commutators. The experiments show that brush wear caused by running the brush without current on the segmented rings can be double or more than that caused by similar running on smooth rings. To effect reduction of the mechanical wear caused by abrasion and friction, good adjustment must be made between the adjacent commutator segments.

The length of the gap between segments must be taken into consideration. If this is too short, contact debris might form a conducting path between two adjacent segments; if too long, it will give rise to a very uncertain contact. Both these factors must be taken into careful consideration when commutator design is undertaken.

7. GENERAL SURVEY OF LITERATURE APPROPRIATE TO SLIDING CONTACTS.

7.1. The Nature of the Brush-Slip Ring Contact, and Current Transfer.

Sliding surfaces damage cannot be defined without specifying ambient conditions which influences the results. It is necessary therefore to give an idea of the nature of contact.

Among the conditions which have to be considered are:

(1) The area of sliding contact.

(2) Temperature.

(3) Pressure.

(4) Contact resistance.

(5) Films on surfaces.

(6) Current transfer.

7.1.1. The area of sliding contact.

If the surface is viewed under a microscope and if the microscope is focused carefully on the individual grains, they are found to differ in height by several ten thousands of an inch; that is there are certain very small areas that are high or protruding and others that are lower or depressed. As the brush is pressed at first very lightly against the ring surface, only the high point or points of the brush face will bear on the ring, as has been suggested by Baker (1934).

In 1936 Bowden and Ridler pointed out that although the surfaces were carefully prepared they could never be perfectly flat. They show the conditions of contact represented diagrammatically as shown in Fig.(7.1.1.). They suggested that, only the areas in contact A_1B_1, A_2B_2, etc. are heated directly by friction, and it is only these areas which constitute the thermo-junction. The areas α, β are not heated by direct friction. Even the rubbing areas will not necessarily all be at the same temperature.

In 1939 Bowden and Tabor suggested that when two surfaces are placed together the area of intimate contact must be very much less than the apparent area. Even if the surfaces are very carefully polished and are made as flat as possible hills and valleys will still be present on the surface. The upper surface will be supported on these irregularities, and large areas will be separated by a distance which is great compared with the dimensions of a molecule. In 1950 the same authors again suggested that the real area of contact is almost independent of the size of the surface and is determined by the load, since, under the intense pressure at the localized points of contact, plastic deformation and flow of current occur until the area is sufficiently great to support the load.

Holm (1946 and 1958) has distinguished between the apparent contact area A_a, the load bearing area A_b and the electrical contact area A_c, Fig.(7.1.2.).
In 1964 Barker, in restating that the real area of contact is very much smaller than the apparent area; showed that if a load 1 Kg. is applied to two tungsten surfaces in apparent contact over 1 cm^2, the real area of contact might be as low as 10^{-5} cm^2.

With this knowledge of the roughness in the contact we can understand the manner in which the contacting surfaces come together.

7.1.2. Surface Temperature in Sliding Contacts.

When sliding takes place all the friction occurs over the very small areas and we may expect the surface temperature at these points of rubbing contact to be high.

A recent experimental study of the friction between two bodies in sliding motion has been undertaken by [illegible]. Bowden and his collaborators, who have shown that there is strong evidence for the belief that the force of friction is entirely due to the exceedingly minute points of the two surfaces in actual contact and that the friction is such that the action of sliding quickly raises these points to the melting temperature but never above this temperature, and consequently that these surface points are in a state of continuous plastic deformation.

Heat is generated near the interface of a sliding electrical contact both by the friction and flow of electric current. The frictional heat is generated at the surface of the contacting members, but the electrical heating occurs wherever the current flows. In the case of a brush running on a commutator or slip ring the heat produced is caused by the friction loss at the rubbing surface and the electrical loss due to the contact voltage drop. The temperature rise is a function of the brush grade, slip ring material, and the cooling surface of the slip ring in relation to the current passed, and the amount of ventilation as suggested by Morganite Ltd. (1961).

In 1936 Bowden and Ridler demonstrated that the temperature reached by sliding surfaces depended upon the load, speed, coefficient of friction and thermal conductivity, and that in sliding contacts there were cahnges in the areas of contact and the surface temperatures.

In 1949 Soper suggested that an increasing current must create a rising temperature at the contact points. For the normal operating current the heat input is equal to the dissipation. On increasing the current, however, the heat input is raised but the cooling is not instantaneously increased, so that the temperature becomes greater; this increase of temperature leads to further plastic deformation and thus a greater contact area.

It is clear that the temperature at the contact surface of a brush will always be materially higher than that of the body of the brush. Hunter-Brown (1919) suggested that the thermal conductivity has a very definite bearing upon the performance of carbon brushes, as relatively very large amounts of heat are generated in very small volumes of material and unless the heat escapes rapidly a destructive temperature rise is the result.

Morganite Ltd. (1961) suggested that heat conduction away from the contact points is limited and it is possible for instantaneous local temperatures to approach the melting point of the surface material.

This is how one surface can polish another.

7.1.3. Pressure Between Surfaces, and Air Pressure Under Brush.

One of the most important factors affecting the behaviour of brushes is the pressure applied to the brushes in order to maintain contact with the moving surface of the commutator or slip ring. It is necessary that contact shall be maintained right across the contact face from the leading to the trailing edge of the brush.

Morganite Ltd. (1961) suggested that because of the irregularity of the sliding surfaces, the pressure existing between brush surface and slip ring is not uniformally distributed over the surface and the centre of pressure is changing all the time. It is also noted that brush pressure must be kept in reasonable limits. If pressure is too low there will be overheating from electrical losses and excessive wear by burning. If it is too high there will be over heating from frictional losses and excessive wear by mechanical abrasion. Fortunately there is a zone in which losses and wear are not affected to any major degree by brush pressure.

When the rubbing speed is high, as it generally is for a carbon brush rubbing on the rotating part of an electrical machine, there is another factor to consider. The moving surface carries with it a film of air, held to it by the viscosity of the gas.

In 1926 Stine in his investigations of brush friction found that the pressure of air under a brush on a rotating commutator is not atmospheric. In this case his general conclutions were that, if the brush tends to ride on its leading edge, the air pressure under the brush is less than atmospheric, but if it tends to ride on its trailing edge the air pressure is greater than atmospheric.

Such changes in air pressure under a brush must cause corresponding changes to the effect of the brush pressure and hence to the size and number of contact spots.

Morganite Ltd. (1961) suggest that this film of air is drawn under the brush contact surface. It tends to separate the brush and commutator or slip ring surface and to act like a fluid lubricant. It also permits the entry of wear debris between the two surfaces. In the electrical conduction process this air film acts as an additional rectifier barrier, modifying the voltage/current characteristic.

Mayeur (1959) suggested that most of the mechanical brush load is supported on an air film which hydrodynamically lubricates the brush. Mayeur indicated that the contact gap was between 1 and 5 microns and that the spherical grains would be slowly dragged across the brush face by the motion of the slip ring, in whose surface they formed shallow scratches.

7.1.4. Constriction Resistance and the Coherer Bridges ; The Tunnel Effect.

The term electrical contact resistance refers to the resistance occurring between any two contact points in electrical applications. Holm (1946 and 1958) applied the concepts of "constriction resistance" to explain the action of electric contacts in general, and also specifically to the contact between a graphite brush and a commutator. He maintains that the resistance is due to the fac~~e~~t that the lines of current flow, are forced to converge in order to pass through the relatively small area of intimate contact.

Like Holm, Shobert (1954), Morganite Ltd. (1961) and others considered the existance of constriction resistance and distinguished between the mechanical contact and the conducting contact.

In the case of a clean metal contact with no disturbing film in the contact, Holm and Shobert suggested that the contact resistance is simply a constriction resistance. If a film is present, the contact resistance consists of the constriction resistance and the film resistance.

Holm also suggested that the film acts as an insulator for some time, i.e. only a very slight current flows. But as soon as the so called puncturing voltage is reached at the film, the current suddenly rises because of an abrupt drop in the contact resistance. The described change is called the Coherer action.

He pointed out that the coherer action begins with a puncturing or breakdown of the film, producing a channel in it, which fills with molten metal, finally solidifying. As long as the bridges consist of molten metal it grows because the RI^2 heat supplies new molten metal from the electrode. This is drawn into the channel until the bridge is large enough to endure the current in the solid state. Then the growth ceases. Holm also suggested that since the metal ions are smaller than the oxygen ions, they are more mobile. Thus the metal ions and not the oxygen ions diffuse through the oxide layer. He claims that the coherer action is of great importance in practical engineering. It is responsible for the conduction from the graphite brush through the black commutator film to the copper ring.

Holm offered a suggestion to explain the behaviour of the voltage drop by the coherer action. He pointed out that if a slip ring which has been kept still for a long time begins to rotate under a current carrying brush, its collector film acts as an insulator at first. But the contact area becomes studded with coherer bridges giving a limited conductance. Through the coherer action, metal bridges are formed in the punctured holes just large enough to carry the current without melting, and this state is indicated by the contact voltage called bridge voltage. He put forward a reason for increasing the bridge voltage under certain conditions. The bridges do not remain undamaged indefinitely, and their sliding surfaces gradually obtain a thin tarnish film. The film voltage is added to the normal bridge voltage. Often the contact voltage must assume higher values in order to produce new bridges. He suggested that the observed increase in contact resistance under negative brushes at low oxygen pressures was due to an increase of the coherer bridges.

The Tunnel Effect.

Shobert (1954) described the tunnel effect as the passage of electrons through a potential barrier whose height is greater than the energy of the electrons passing through.

Holm (1946 and 1958) also suggested that because of the tunnel effect the electric current passes thin films without practically perceptible resistances and that the tunnel effect is responsible for the current transmission through the films. He indicated that the effective wave length for the tunnel effect is the de Brogle wave length of the electrons and that they have a finite probability of passing through potential barriers whose heights correspond to an energy greater than their own. The effect is particularly significant if the barriers are narrow, as for thin surface films. The tunnel effect implies a transmission of an electron wave, i.e. of electrons, through potential barries, if their thickness is of the same order as the electrons' wave length; the electrons do not thereby loose energy.

7.1.5. Films on the Ring Surface.

The film on a commutator or slip ring, which plays such an important part in brush behaviour must not be regarded as static, but as a dynamic thing which is constantly changing under the opposing effects of factors which build it up and those which destroy it.

In 1934 Baker suggested that the non-linear volt/ampere characteristic of carbon brushes on copper slip rings was probably due to the presence of a film of copper oxide, on which he considered the sliding to take place. Baker suggested that if formed, a copper oxide film would be broken down by the passage of current, thereby offering an explanation for the observed decrease in contact resistance with increasing current. He supposed a breakdown or reduction in resistance of the semi-insulating oxide film. Baker ascribed the almost linear volt/ampere characteristic of the contact in nitrogen to the absence of an oxide film.

In 1935 Hessler mentioned the conditions of the brush and slip ring surfaces as factors determining the contact resistance for a given current.

Hessler and Savage (1939) considered the increased rate of oxidation of copper with temperature to be due to the greater diffusion of oxygen through the existing oxide, but pointed out that the copper oxide would be diminished locally by the abrasive or polishing action of the brush.

In 1944 Van Brunt and Savage reported that they had succeeded in stripping 90% of the film formed by running an electrographite brush on a copper slip ring. The results for a typical film are given in table 7.1.5..

In 1954 Shobert pointed out that the copper oxide film grows at a rate determined by the motion of copper ions through the film. Thus the motion of these ions, and hence the rate of oxidation, would be accelerated by the electric field under a negative brush and retarded by that under a positive brush. Also he suggested that a water film appears to operate hydrodynamically and to present a thin film-tunnel resistance when the contacts are running. This resistance disappears at stop indicating that the film is essentially removed. Holm (1958) suggested that this water film acts as a lubricant to reduce sliding wear.

In 1959 Holm suggested that the films which are produced by carbon brushes on the copper collector during sliding are highly resistive and that conducting spots through them are necessarily produced by a kind of electrical breakdown called "fritting". These spots are metallic under the brush but do not remain so when they are exposed to air,

Table 7.1.5.

	Percentage	Weight g/cm^2	Average thickness	
			mm	A^o
Cu_2O	65.8	1.27×10^{-5}	2.1×10^{-5}	210
C	22.1	0.42×10^{-5}	3.3×10^{-5}	330
Residue:				
SiO_2, Al_2O_3, Fe_2O_3, CaO.	12.1	0.24×10^{-5}		
Totals	100.0	1.93×10^{-5}	5.4×10^{-5}	540

at least portions of them quickly become covered by resistive films and these require elevated voltage for new frittings as they arrive under the brush again.

Wide ranging experiments by Morganite Ltd. (1961) have shown that with graphite sliding on copper, the skin largely consists of a mixture of the oxides of copper together with graphite. This mixture together with a number of impurities coming from the brush material and from the atmosphere, whether as part of the film or adding to the surface, can modify the contact. Because of the presence of this skin only perhaps one tenth of the mechanical contact points between brush and copper surface will be electrically conducting.

The most important factors influencing the film thickness, as shown by Morganite Ltd., are the sliding temperature which influences oxidation rate, and brush current density which influences the rate at which the oxide is reduced to metal by chemical reaction with the carbon when under the brush surface.

Lancaster (1962) pointed out that the amount of oxidation depends on the time available between repeated contacts on the copper, and hence upon the area of the brush and the diameter and speed of the slip ring.

7.1.6. Current Transfer

It is clear from the above section that in most contacts applications the current does not pass through the entire apparent contact area.

Holm (1946 and 1958) offered an explanation of current transfer. He suggested that the oxide film on a copper slip ring was insulating but was broken down electrically by localised points of contact by "fritting", thus forming small conducting regions or contact spots. He suggested that fritting served to enlarge the contact area until the available voltage could no longer support a further increase, thereby giving rise to a non-linear relation between current and voltage. Holm suggested that the coherer action is responsible for the conducting of current from the graphite brush through the commutator film to the copper ring. If the film were thin enough, Holm atributed conduction to the wave mechanical "tunnel effect".

In 1946 and 1949 Soper offered his ideas on current transfer in sliding electrical contact stating that this occurred by auto-electric emission (field emission), or by thermionic emission, or by a combination of both. He also recognised that the wave mechanical tunnel effect could account for the transfer of "relatively small current" across the contact. Soper in his suggestions used the principle that all conductors contain free electrons which posses energies up to the Fermi energy. In order to extract these free electrons from the conductor without the application of an external field, they must be given an extra energy, called the "work function". In 1955 Schroter developed a theory of current transfer in sliding copper graphite contacts which was based on the semi-conducting properties of cuprous oxide. Like Holm, he assumed current to flow over part of the areas of mechanical contact between the brush and the ring but through a relatively thick oxide film. And in 1959 Mayeur suggested that conduction occurs through carbon wear debris under the brush.

The Field Emission

The results of carbon-brush contact investigations all suggest the existence of "emission centres" from which electrons are drawn because of a high field strength at the point of contact. Soper (1959) suggested that although the brush must at all the instants make mechanical contact with the ring in at least three points, it does not follow that electrical contact is consistent at all the points. Electrons will, most probably, be extracted from only one point at any instant, and from that point at which the field strength is greatest; this follows since the emission is sensitive to changes in the field strength.

The emission area is much greater for the polished ring; this is to be expected, as the "granular" nature of the rough surface will produce a greater field intensity and thus require a much smaller emission area. Both the effective contact spacing and the total emitting area are dependent on the roughness of the surface, as suggested by Soper.

Soper assumed that there is an effective contact spacing of the order of 10^{-8} cm, and an emission area of the order of 10^{-7} cm^2. In a brush commutator contact, Soper suggested that only one small area will be emitting electrons at a given moment, but that over a short interval most of the contact surface will be utilized.

For a given current transfer, Soper suggested that, the contact drop depends upon the effective contact spacing and the emitting area. The mechanical pressure, the speed of sliding, the humidity, and the coefficient of friction only control the value of the contact drop in so far that they modify the values of the emission area and contact spacing. Thus an increase in the value of the brush mechanical pressure will decrease the voltage drop as a result of an increase in the size of the emission area and a decrease in the contact spacing.

The Electrical Characteristics of the Contact.

The electrical characteristics of the contact may be summarized as follows:-

1. There is a voltage drop across the contact of the order of 1 volt, when the electrographite brush is carrying current at normal current densities (about 50 Amps/sq.in.).

2. The V-I curve has a characteristic shape, the contact drop (V) increases rapidly with current (I) at low current densities, and much more slowly at higher current densities. ~~and much more slowly at higher current densities.~~

3. The contact drop of voltage is usually higher if the current flows from the commutator to the brush, than if it flows in the opposite direction.

4. The contact drop of voltage decreases immediately with an increase of brush pressure.

5. The voltage contact drop is greater if the commutator is rotating than if it is stationary, and increases slightly with an increase of speed.

6. There is a time lag of several minutes before the voltage contact drop reaches a stable value

corresponding to a new value of current density.

7.2. Wear of Sliding Contacts

7.2.1. Wear and Friction

Wear as a general phenomenon is usually very complex. This is partly because the sliding conditions may change the nature of the surfaces either by work-hardening them, changing their roughness, or by producing new phases or alloys at the interface, as suggested by Bowden and Tabor (1950).

Archard (1953) discussed mechanisms of wear in terms of various models of real surfaces and deduced a relationship between the wear rate and the load. He assumed that wear was caused by elastic or plastic deformation, and concluded that wear was due to lump removal from contact areas which had been formed by plastic deformation.

It is now well understood that the contact between the rubbing surfaces occurs at a number of small areas and that the true area of contact, formed by the sum of these small areas, constitutes a small proportion of apparent area of contact. The friction and wear is therefore caused by the contact and deformation of two protuberances of the opposing surfaces.

Wear rates and coefficients of friction have been measured with a pin and ring machine for a range of material combinations by Archard and Hirst (1955). Archard and Hirst show in their results that the rates of wear cover a range of nearly 10^5 but the coefficient of friction varies by less than five to one.

Holm (1958) first assumed the removal of so many atoms per atomic encounter, but later considered material to be removed in layers. Holm also suggested that only the number of contact areas varied with load.

Archard (1953) concluded that the wear rate was proportional to the load, and independent of the apparent area of contact. He also concluded that the wear rate would be independent of the speed of sliding, providing the probability factor and flow pressure remained constant.

Like Archard, Bowden and Tabor (1964) indicated that the wear was dependent on load, but unlike Archard they suggested that the rate of wear was dependent on speed and area of contact. They concluded that the wear was almost entirely due to melting by friction. The main effect of speed on wear arises from the increased surface temperature generated at the points of rubbing contact. At high speeds of sliding, surface melting may take place and this is often accompanied by low friction and wear, and the main effect of load may be due to an increase in number and/or area of contact points.

7.2.2. Wear of Sliding Contacts Without Current.

The behaviour of sliding contacts without current has not played much part in the experimental investigations in the past. Recently attempts have been made to understand this behaviour.

Folm (1957) suggested that the amount of graphite transferred during sliding increased in proportion to the surface roughness.

Holm (1958) reported that in the case of brush running without current on copper ring, the rate of wear was very small. So small that it often was neglected, and in 1961 Hirst and Lancaster indicated that, as the speed increases the rate of wear decreases to a minimum at about 100 cm/sec. and then begins to increase.

In 1962 a substantial experimental study was made by Lancaster to determine to what extent the rate of wear of an electrographitic brush on copper depends upon the conditions of sliding. Lancaster's results show that when an EG11 brush slides without current on a copper slip ring, the rate of wear decreases with time to a limited value. Examination of the surfaces of the wear tracks on the copper at various stages after the sliding showed that the changes occurring at light and at heavy loads were very different. Lancaster concluded that a transfer layer produced at a heavy load cannot be maintained when the load is reduced below a critical value. This suggests that the transferred layer in the severe wear regime was in a state of dynamic equilibrium. Moreover, the fact a transferred layer cannot be formed at all when the load is below a critical value leads to the conclusion that the changes which occur on the surface of the copper at light loads directly affect transfer of graphite rather than wear.

Lancaster showed curves which indicated that the rate of wear increases continuously with load and that the increase is not directly proportional to it, although large loads produced proportionally greater wear. They also indicated that the rate of wear was only influenced by the apparent area of the brush when significant changes occur in the composition of the surface film generated on the copper. Lancaster pointed out that very little Cu_2O or Cu was present on the surface. Also with increasing diameter of the ring, i.e. with increasing time available for oxidation, he suggested that contact resistance increased and the rate of wear decreases as expected.

The tests described in this thesis confirmed that, with EG11S, EG16 and CM3H grade brushes running without current on a brass ring, the wear was much smaller than that observed with the same grades of brushes carrying current under the same conditions.

7.2.3. Wear of Sliding Contacts with Current.

The experimental work on electrical sliding contact all suggested that wear can be almost entirely caused by current flow.

In 1919 Hunter-Brown obtained two curves of electrical brush wear versus current density which indicated that the negative brush wore at a greater rate than the positive brush, and that the wear rates were approximately proportional to the current density. Hunter-Brown suggested that the wear of the collector is due to three causes: mechanical abrasion, a kind of electrolytic action, and burning away of the metal. The rate of wear of the collector is dependent upon the material it is made of, the quality of the brush, the current density, and the intimacy of contact between the brush and the collector. Hunter-Brown also suggested that material might be removed from the brush face by abrasion, combustion, or by disintegration. The very low rates of wear at zero current show that ordinarily abrasion does not account for more than a small proportion of the total wear. Apparently the flow of current across the contact produced a disintegration of the brush surface. This disintegration might be caused by thermal expansion resulting from the high current density at the discrete points of contact between the brush and ring.

Like Hunter-Brown, Baker (1931) found out that the rate of wear of the positive carbon brush was considerably less than that of the negative brush. He also found that the rate of wear of metallic brushes was much greater than that of carbon brushes, under the conditions of these tests. Baker (1934) suggested that the main effect of the current was to increase the amount of graphite transferred to the copper and to displace the wear behaviour of the brush towards the severe wear regime. The increase in graphite transfer suggests that the passage of current supplements mechanical breakdown of the oxide film, either by puncturing causes by high voltage gradient or as a result of local heating and softening of the copper which causes an increase in the deformation beneath the oxide film.

In 1935 Hessler assumed that if a brush carrying current were operated on the same ring simultaneously with a brush not carrying current, both might lose material at the same rate as a result of abrasion, but the current carrying brush would lose additional material as a result of the current flow. Hessler concluded that the rate of wear of positive carbon brushes sliding on copper was low, and independent of the current density below a critical value which carries with different brush materials. The rate of wear on negative brushes was greater and proportional to current density below a certain value; above this value there was a decrease in the rate of wear with increasing current density, followed usually by a sudden increase in the rate of wear as the current density became excessive.

Soper (1946, 1947, and 1949) suggested that an increase of current creates an increase of the wear due to rising of temperature. He assumed the existence of metallic bridges and suggested that the metallic bridges were responsible for the severe wear on the cathodic brush. Soper also offered an explanation as to why the wear and voltage drop under the negative brush was greater than that under the positive brush. He suggested that because the ring was the centre of electron emission, the motion creates greater disturbances in the electric field at the "points" of the ring surface than occurs when the brush emits the electron.

Holm (1958) suggested that the increase of wear that was observed when a brush-ring contact carries current was not directly effected by the current but probably was produced in the following way. The direct effect of the current (without sparking) was the fritting through the film and electrolysis. With the last effect, copper ions were moved away from the ring surface. Holm also suggested that though the quality of copper that was transported was probably quite small, it nevertheless seemed to be the source of formation of abrasive copper and oxide grains and of roughening of the surfaces. Both effects increase wear.

Hirst and Lancaster (1961) in their investigations of the wear process for metal combinations have pointed to the conclusions that the removal of a fragment from one of the surfaces was the final result of a succession of localized encounters.

In 1962 Lancaster studied the rate of wear of EG11 electrographitic brush sliding on copper over a wide range of loads and speeds. Lancaster suggested that at high speeds and heavy loads a continuous layer of transferred graphite is formed and the rate of wear per unit of load is relatively high. At low speeds and light loads, a surface film of cuprous oxide develops which prevents transfer of graphite and reduces the rate of wear. Lancaster concluded that current breaks down the oxide film leading to transfer of graphite, and the rate of wear increases with application of current. He suggested that the wear of the brush is a "fatigue" process resulting from a succession of repeated elastic stresses over the localized regions of true contact.

Lancaster showed curves plotting rate of wear against current for different loads and speeds. The curves showed that the rate of wear increased continuously with load increase, and decreased at low speeds. Lancaster suggested that at any one load a decrease in speed leads to an increase in the amount of oxide present in the surface film and to a corresponding decrease in the amount of transferred graphite. The increase in the electrical contact resistance obtained at low speeds of sliding suggests that the time available for oxidation between repeated contacts at a localized region on the copper is more significant in enabling a coherent oxide filmto be established than is the localized "flash" temperature rise due to frictional heating; the "flash" temperature will, of course, decrease in magnitude as the spped decreases.

In fact, the primary action of the oxide film is to impede transfer of graphite to the copper, presumably by preventing contact between the brush and the copper substrate, and the coefficient of friction between the brush and the oxide film is smaller. When this layer becomes thick enough, it might cause heavy wear, as shown in (7.1.5.).

7.2.4. Wear in Presence of Arcing.

In case of arcing or sparking, the wear rate will change. The wear/time curve (Fig.(5.2.4.), shows that the wear for positive and negative brushes was low under non-sparking conditions. When sparking occurred it caused wear in both brushes to increase rapidly with time but more so with the negative brush than with the positive.

Watts (1957) investigated the influence of sparking on brush wear and found that it could increase the wear rate by up to fifty times.

Baker (1931 and 1934), Hessler (1935), Holm (1948 and 1958) Morganite Ltd. (1961), all in their results supported the suggestion that slip ring roughening by sparking and subsequent brush abrasion constitutes an important factor of brush wear.

Mclaughlin (1951) pointed out that arcs may be produced either by the drawing out of a discharge, as occurs on opening a switch, or by the electrical breakdown of the gap separating fixed electrodes.

There is no doubt that arcs may occur if the contact interrupts a current, as happens when a bar loses contact with the brush either because it is a low bar, because of brush vibration, or because the bar moves from under the brush. The last should not occur ~~in~~ with thyristor machines because the interpole strength must be sufficient for the current through the thyristor to be brought to zero before the brush leaves the segment (Fig.1.4.), otherwise very heavy losses to either brush or ring will result.

Holm in 1948 pointed out that the arc produces disintegration of the electrodes leading to a loss of material and roughening of the surface. In 1958 he suggested that the arc affects the wear in the two respects. First, it produces evaporation form the electrodes; secondly, this leads to roughening of the surfaces which in its turn increases the mechanical wear.

Morganite Ltd. (1961) reported that the orange sparking at the brush edge was an indication that that particular brush was carrying an over load. They also suggested that excessive wear is more often electrical than mechanical in origin.

Contrary to Morganite Ltd., Thompson and Turner (1962) pointed out that in the absence of arcing, brush wear was essentially a mechanical process, so that the increase of brush wear with current was due to roughening of the slip ring rather than to direct electrical erosion.

Lancaster (1962) pointed out that two forms of wear can occur, mechanical and electrical, but there was then little evidence available to support the existence of the latter, except when visible arcing was present beneath a brush. Lancaster suggested that mechanical wear was usually attributed to abrasion, either by losses, graphitic debris trapped between the surfaces or by oxides and other corrosion products present on the surface of the copper.

In 1963 he studied the relative importance of erosion and mechanical wear specifically under arcing conditions. Using an EG11 electrographitic brush and a copper slip ring, he found that the arcing increased the roughness of th slip ring and the resultant additional mechanical brush wear was of comparable magnitude to the direct loss of carbon by erosion. The erosion was almost independent of the load on the brush, but the additonal mechanical wear due to arcing increased with decreasing load, particularly at high speeds of sliding. Both the erosion and mechanical wear were greater for the negative brush. Lancaster attributed the larger negative brush erosion to greater localized surface temperature due to positive ion bombardment, which led to a higher rate of oxidation of the binder material.

As indicated in the previous discussion, arcing represents the greatest enemy of electrical sliding contact and causes heavy damage to both brush and ring. This fact was verified by the author's own experiments, see (4.6.)

7.2.5. Wear and Humidity

The absorption of water vapour by solid surfaces appears to be much heavier than we should expect. Many workers have found that water vapour reduces friction and wear rates.

Baker (1931) in his investigations with hydrogen found that a well designed commutator machine will operate satisfactorily and give good brush life in hydrogen, and if a brush must spark in hydrogen, the brush life may be increased many times by maintaining the relative humidity below 10 percent. Baker also concluded that the contact drop between a carbon or graphite brush and a brass slip ring, was ten times as high when the ring was running in air as when it was running in hydrogen.

Van-Brunt and Savage (1944) suggested that water vapour reduces friction and wear rate in proportion to pressure up to the range from 3 - 5 mm Hg, by a process of reversible adsorption. For higher pressures, the surfaces become covered, and no further reduction is observed. They also show that if a graphite brush was run against steel in a vacuum rather than in air, there was a fivefold increase in friction and a considerable increase in wear. Van Brunt and Savage concluded that the low friction and wear of graphite under normal conditions was due not to any lubricant quality inherent in the graphite itself but to adsorption upon its surfaces of substances derived from the ordinary atmospheric environment.

The main effect of water vapour may be to act as a lubricating film, preventing adhesion between the rubbing surfaces. But this same film might be a contributing factor in the formation of cuprous oxide film, which will cause an increase of the wear rate.

It is to be concluded that, in general, both brush and ring wear can be decreased by reducing ring temperature, increasing humidity, and decreasing current.

8. CONCLUSIONS

8.1. Summary of the Results.

The results of the tests described in the above sections may be summarised as follows:-

1. Both EG11S and EG16 brush grades, investigated with half sine wave current and square wave current, can be run for 100 hours with brush pressure of 2 lbs/sq.in. with 400 Amps/sq.in. without any significant damage occurring to the ring but there is however excessive brush wear.

2. Brushes of the CM3H grade, investigated with half sine wave current and square wave current can be run for 50 hours with brush pressure of 2 lbs/sq.in. with 400 Amps/sq.in. without any damage to the brush or slip ring.

3. There is no ~~measurable~~ significant time lag between the application of voltage and the passage of current with half sine wave current or square wave current

However, a delay of the order of 100 microseconds was observed with rough surfaces.

and occur due to the high contact heat and sparking.

5. The wear of the brush with half sine wave

current or with pulsed current is much smaller than that with direct current for either polarity with the three types of brushes investigated.

6. The wear of the ~~EG11S~~ EG11S brush grade is smaller than that of the ~~EG16~~ CM3H grade and greater than that of the ~~CM3H~~ EG16 grade for the same duration and current density.

7. The wear of the EG11S, EG16 and CM3H brushes investigated is greater when the brush is running with current than without current, and in general, the wear of the brush increases as the current density increases. It is greater on the negative brush than on the positive brush with electrographitic brushes and the reverse is the case with metallic brushes.

8. Heavy erosion and burning due to sparking is caused to the brush and segment when a brush is turned on before it is fully on a segment.

9. An increase of mechanical wear may well occur to the brush due to the length of the gap between segments.

8.2. Suggestions for Further Work.

In thyristor machines, the commutator peripheral speed can be high as 16000 ft./min. The experiments described in (4) and (5) were at one speed 4000 ft./min. (1500 r.p.m.).

It is suggested that several tests be made at higher speeds to investigate the possibility of time lags appearing due to ~~a slow build up of current and~~ the time required for a contact to be established.

Since a time lag was observed with rough surfaces, experiments could be usefully carried out to show the minimum smoothness required for which no time lag is to be observed under various conditions of brush pressure. The effect of the thickness of the carbon deposit on the ring on establishment of current needs further investigation.*(see page 94)

The process of establishment of a surface film is itself of interest when pulsed currents are used. The question of how the film is transferred round the ring - is it deposited mainly when current flows, and then dragged across the non-current portions and how fast does the distribution advance - is worthy of further consideration. This is an important matter in thyristor commutators where the ring consists of alternate active segments and inactive segments. Uneven deposits of carbon may have a deterimental effect on brush wear characteristics.

The tests carried out with the split ring and early thyristor firing were made when the brush was sitting half on an active segment and half on an inactive segment. Further -studies are needed for variation of brush position to determine the allowable distance at which a brush may turn on early without any erosion.

Probably the most important factor which will decide the practical application of thyristor machines is the behaviour of the commutation segment in respect of relative wear between the active and inactive segments. The experiment showed no damage with EG11S or EG16 brush grades on brass ring, but they were used only for 100 hours of running. It is necessary to make detailed measurements of the brush and ring wear for longer periods.

The choice of materials for the commutator also depends on the relative wear. Since the author's studies have been confined to EG11S, EG16 and CM3H brushes and brass slip ring, it would be desirable to repeat many of the experiments using other brush grades and slip ring materials. In this context, the use of insulating material for the inactive bars could be investigated.

The length of the air gap between the commutator segments has an important bearing on the wear characteristics of the brush and investigations currently proceeding elsewhere should provide useful information on commutator air gap and insulator design.

The parallel line of research mentioned in the above chapters, when completed will show the real behaviour which in fact occurs under a brush in a thyristor-assisted commutator. Correlation of other work with the above results, may make possible improvements in thyristor-assisted commutation machines and which may perhaps prove their advantages and their reliability in a number of motor and generator applications.

*

Care must be taken to distinguish between the time required to establish a contact and any time lag due to circuit inductance.

9. APPENDICES

9.1. The Parallel-Capacitor Commutated D.C. Switch.

The thyristor can be simply connected in series with the load and provision made for triggering using a circuit connected to the gate of the thyristor.

To turn the thyristor off by static means in a d.c. system requires external commutating means. Fig.(9.1.1.) illustrates the fundamental method of thyristor switching employed, using a capacitor and a second thyristor to turn off the load-carrying thyristor.

When thyristor (1) is triggered into conduction, voltage E is applied to the load R_1. With thyristor (2) in the off state, capacitor C is connected across the load through R_2 and charges to the supply voltage with positive polarity on its left-hand plate. When thyristor (2) is triggered, the right-hand, or negative, plate of C is connected to the positive d.c. supply line while its positive plate is still connected to the cathode of thyristor (1). This momentary reverse voltage on thyristor (1) turns it off, while thyristor (2) continues to apply the supply voltage to its load R_2. Capacitor C now reverses its charge to positive polarity on its right-hand plate. If thyristor (1) is triggered at this time, the circuit reverts to its original state. Fig.(9.1.2.) illustrates the voltage wave forms across thyristor (1) and the load R_1 during a typical sequence of triggering.

For satisfactory turn-off of thyristor (1) time t_c indicated on this wave form must be longer than the maximum required turn-off time of thyristor (1). Otherwise, thyristor (1) will fail to turn off, and both thyristor (1) and thyristor (2) will conduct simultaneously.

The required size of commutating capacitor C for resistive loads can be determined by analyzing the switching intervals just after thyristor (2) is triggered. As in other calculations of this type, the thyristors are assumed to be perfect switches; that is they are assumed to have infinite resistance in the off-state and zero resistance in the on-state. Aslo, it is assumed that reverse recovery is instantaneous, that is, that no reverse recovery current flows.

Just before thyristor (2) is triggered, capacitor C is charged to E. If thyristor (2) is triggered at time $t = 0$, and we then consider the discharge current i through C and load R_1 -

$$E = \frac{1}{C} \int_{o}^{t} idt + iR_1$$

The laplace transform of the loop equation is

$$\frac{E}{S} = I\ (5)\ R_1 + \frac{I\ (S)}{C_S} - \frac{E}{S}$$

solving for i, we have

$$i = \frac{2E}{R_1} \exp - (t/R\ C.)$$

The voltage V_c across capacitor C, which is also the voltage across thyristor (1) when thyristor (2) is conducting, is

$$V_c = -E + \frac{1}{C} \int_{o}^{t} i\ d\ t$$

$$= -E + \frac{1}{C} \int_{o}^{t} \frac{2E}{R_1} \exp\ (-\ t/R_1\ C)\ dt,$$

so $V_c = E\left[1 - 2 \exp\ (-t/R_1\ C)\right]$

Turn off t_c is the interval between $t = 0$ and the instant when $V_c = 0$

or $0 = E\left[1 - 2 \exp\ (-t_c/R_1C)\right]$

solving for t_c we get

$$t_c = 0.69\ R_1\ C.$$

The capacitor C was varied between 100 and 400 μ.farad to give minimum pulse rise time and to maintain the same rise time with all current densities in the range 55 - 380 Amps./sq.in. This rise time was approximately 80 μ.sec.

9.2. Firing Requirements of Thyristors.

The thyristor is a four layer P-N-P-N device, shown diagrammatically in Fig. (9.2.1.)

In order to ensure proper firing of all the thyristors irrespective of their individual firing characteristics, pulse-firing rather than d.c. firing is employed. When thyristors are fired with short pulses it is possible to inject a peak power into the gate in excess of the maximum average gate power rating. The two thyristors must be fired separately at the appropriate time.

Shortly after the initiation of conduction by the firing of one thyristor, the pulses to the other thyristor must be discontinued; thus only one thyristor must normally be fired at a time, otherwise, both thyristors will conduct simultaneously.

The basic firing system for this application consists of two parts:

1 - Pulse-train oscillator.

2 - Gates for regulating the pulses.

1. Pulse-train Oscillator.

Provision should be made even at this early stage so that the application of the firing pulses while the thyristors are negatively biased has no damaging effect. Pulses of short duration avoid this danger when the thyristors are reverse biased.

Since thyristors turn on within 5 to 10 μ-secs, pulse lengths of the order of 25 μ.secs are adequate.

The mark-space ratio of the pulse-train should be about 1:3 that the duty cycle is 25% or slightly less. A fairly short rise time is preferable.

A suitable pulse-train oscillator is shown by Fig.(9.2.2.). This includes the basic "square wave" oscillator and pulse-amplifier. One further stage of amplification is necessitated by the design of the gates used to regulate the pulses to the thyristors. It is essential that the oscillator should be free-running immediately on switching on. Fig. (9.2.4.) shows the voltage wave form of the thyristor gate firing pulse.

2. Gates.

Each thyristor is provided with a gate circuit so that the firing pulses may be held off when not required.

Simple "Nand" gates of the type shown by Fig. (9.2.3.) are suitable. One input to this one-transistor Nand gate is driven by the pulse-train oscillator.

One oscillator of the type shown in Fig.(9.2.2.) is adequate for the two gating circuits.

The transformer ratio is selected after due consideration of the gate characteristics of the thyristor. A certain minimum voltage required to fire all thyristors of a given type under all conditions. This voltage is usually about 3V.

The maximum permissible gate voltage decides the lowest primary to secondary ratio.

It has been found preferable to use pulses of fairly high amplitude to fire the thyristors. A transformer ratio of 9:1 was actually employed in the circuit Fig. (9.2.3.) used in conjunction with Mullard BTY99(500R) thyristor.

9.3. Measurements of Brush Temperature by Thermocouple.

Heat is generated near the interface of electrical contact both by the friction itself and by the flow of electric current. The frictional heat is evolved at the surface of the contacting members, but the Joule electrical heating occurs wherever the current flows.

This series of measurements was made in order to give an idea of the temperature of a brush in sliding contact passing half sine wave current. EG16 and CM3H brush grades were used with the current densities of

55 and 110 Amps./sq.in. and also without current at a brush pressure of 2 lbs./sq.in. The slip ring peripheral speed was 4000ft/min. and the tests were carried out at a duration of one hour each. The brush had a contact area of 0.375 sq.in.

A simple arrangement using copper constantan thermocouples as shown in Fig.(9.3.1.) was employed. The thermocouple was close to the interface but not touching it. The voltmeter had an accuracy of ± 10 μ volts. Fig.(9.3.2.) shows the calibration curve of temperature/volts. The results of the temperature measurements over one hour of duration are shown in Fig. (9.3.3.).

As the thermocouple could not be located actually on the brush surface, the results of the temperature measurements are comparative. The higher thermal conductivity of the copper impregnated brush enables heat to be conducted away more readily and the running temperature is thus lower than for the graphitic brush. The effect of current increase on temperature is greater for the graphitic brush because of the construction difference. In studies of brush wear it is clearly important to determine the effects of brush temperature and it is shown that for the same contact area and circuit, different types of brush will run at temperature differences of the order of 10° to 20°C.

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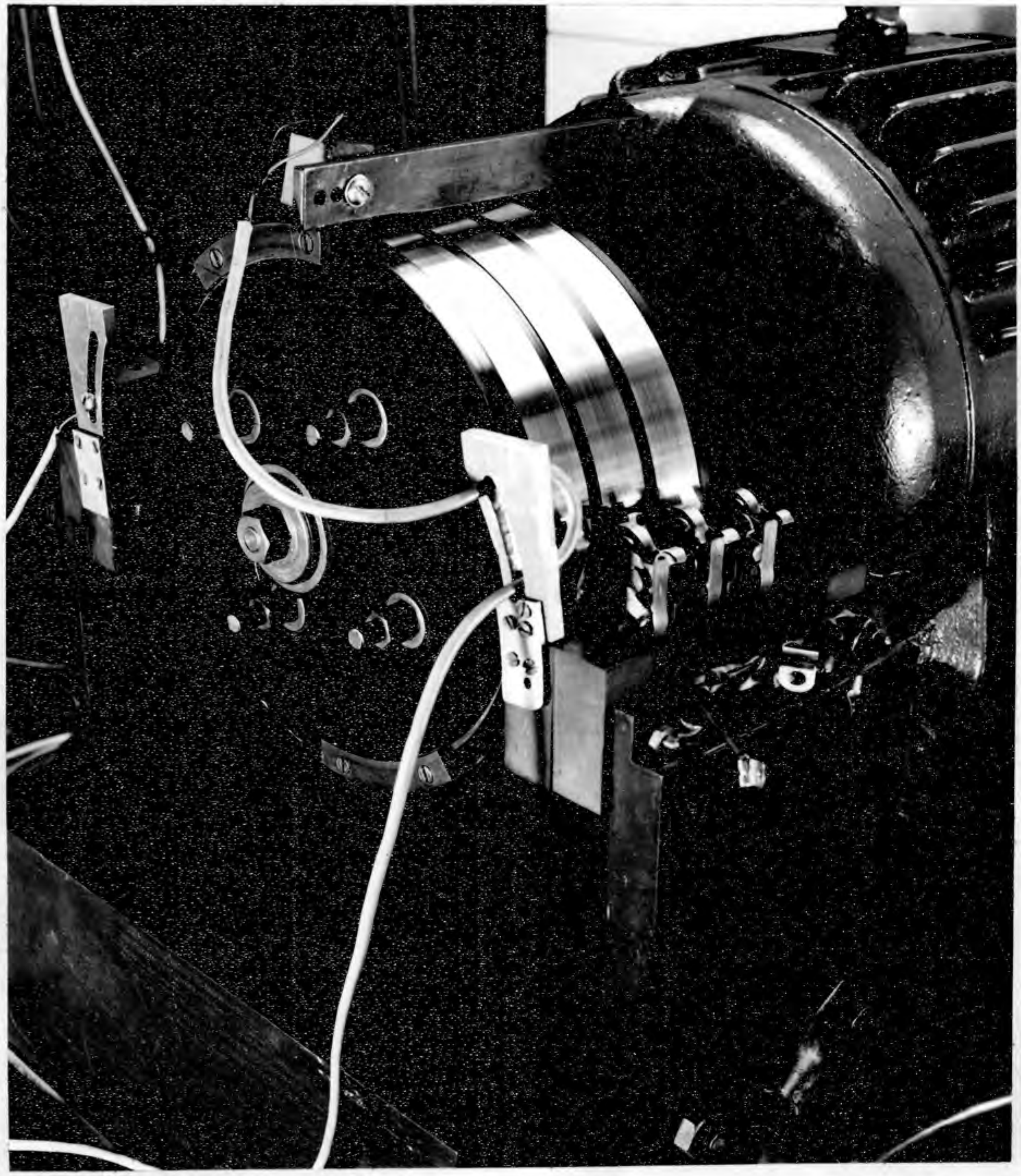
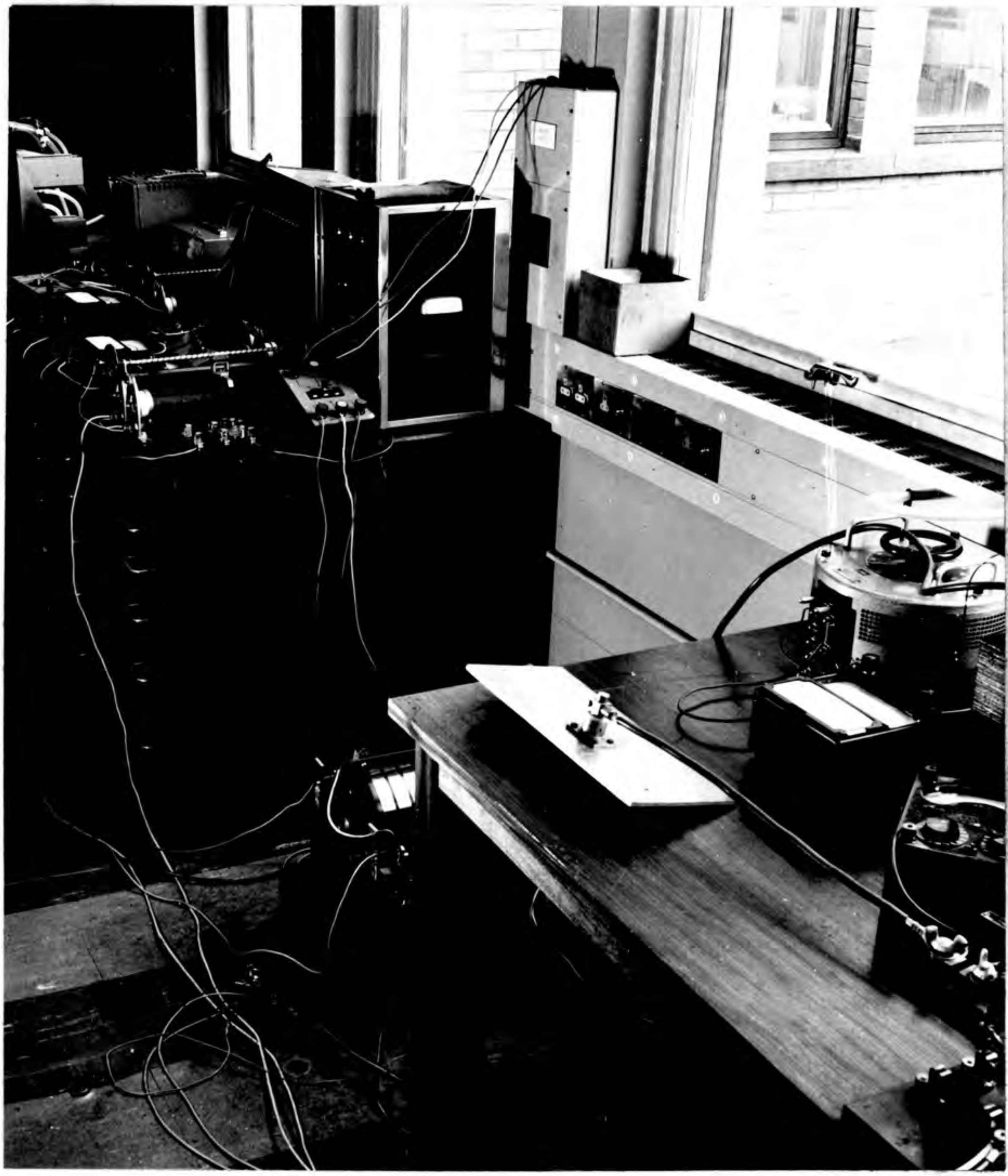
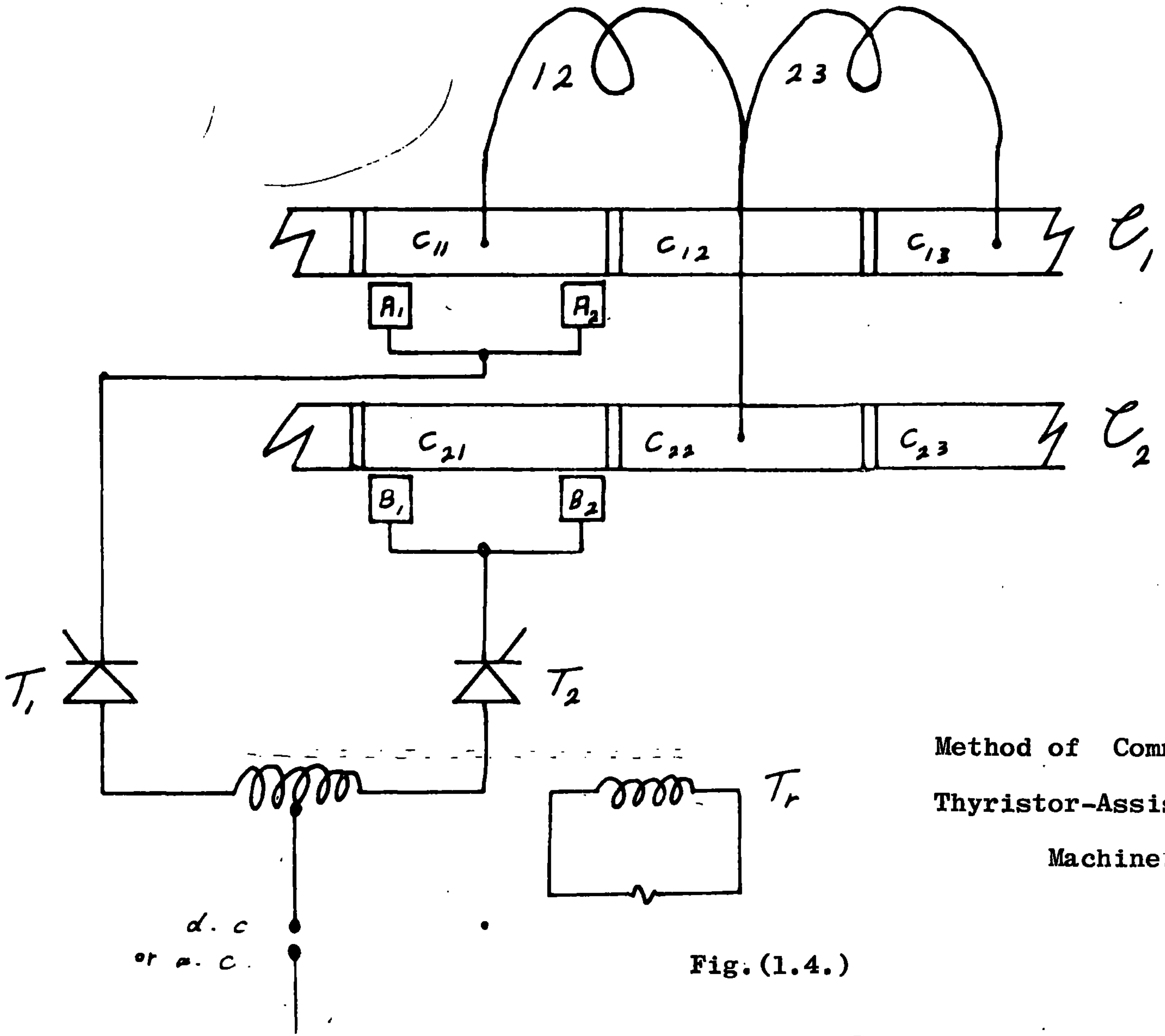


THE BRUSH-RING ASSEMBLY

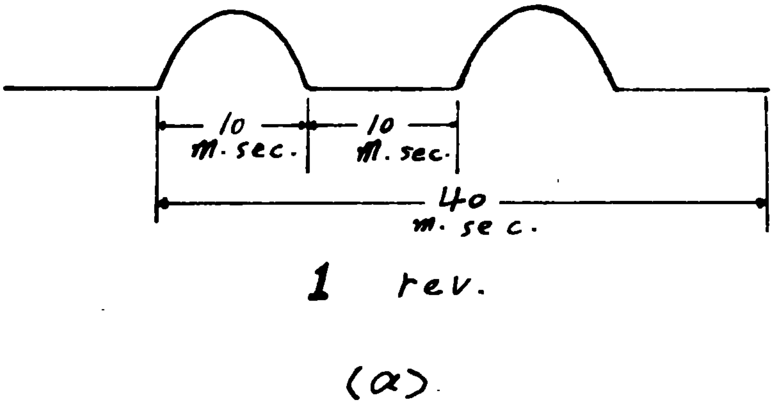


THE EQUIPMENT



Method of Commutation in a Thyristor-Assisted Commutation Machine.

Fig. (1.4.)

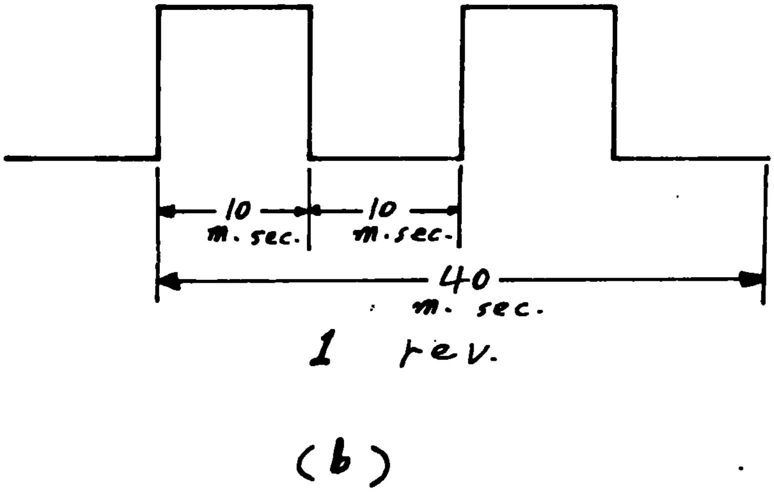


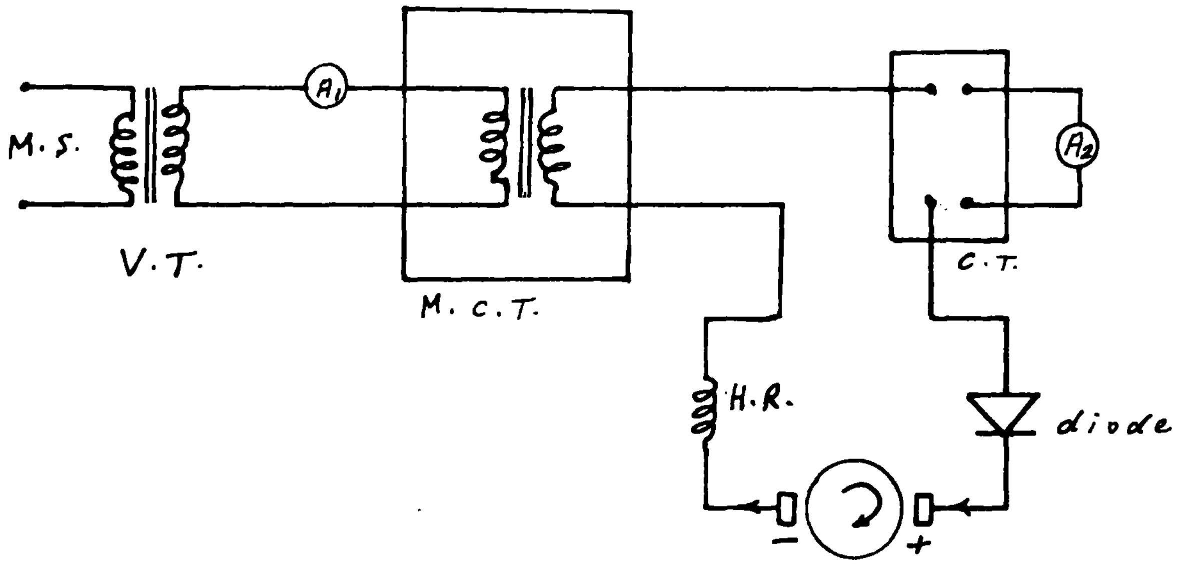
The Wave Form of the

(a) half sine wave current.

(b) square wave current.

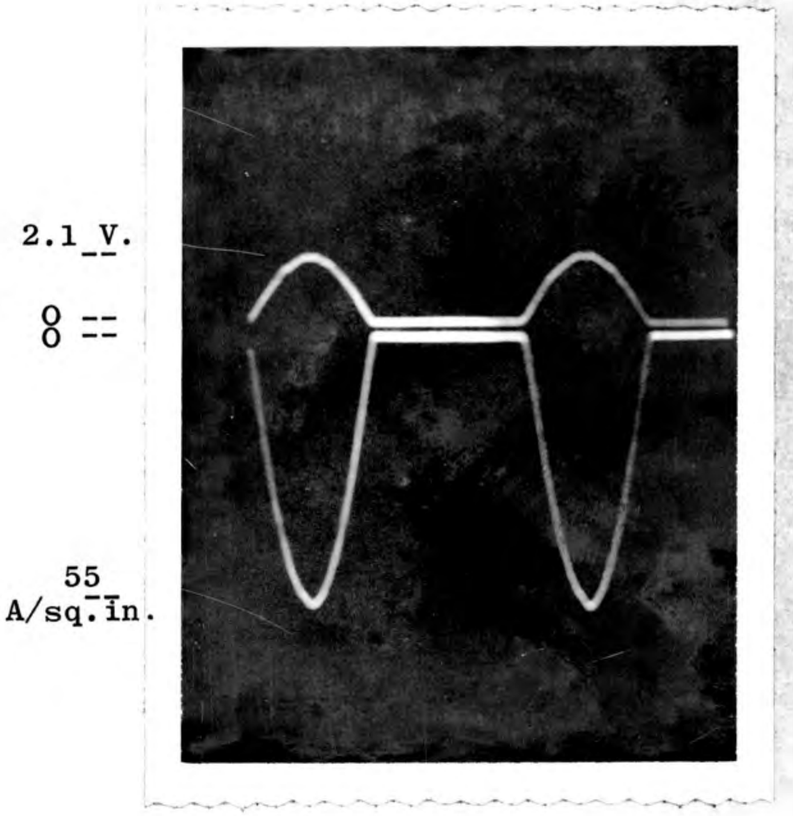
Fig.(2.1)





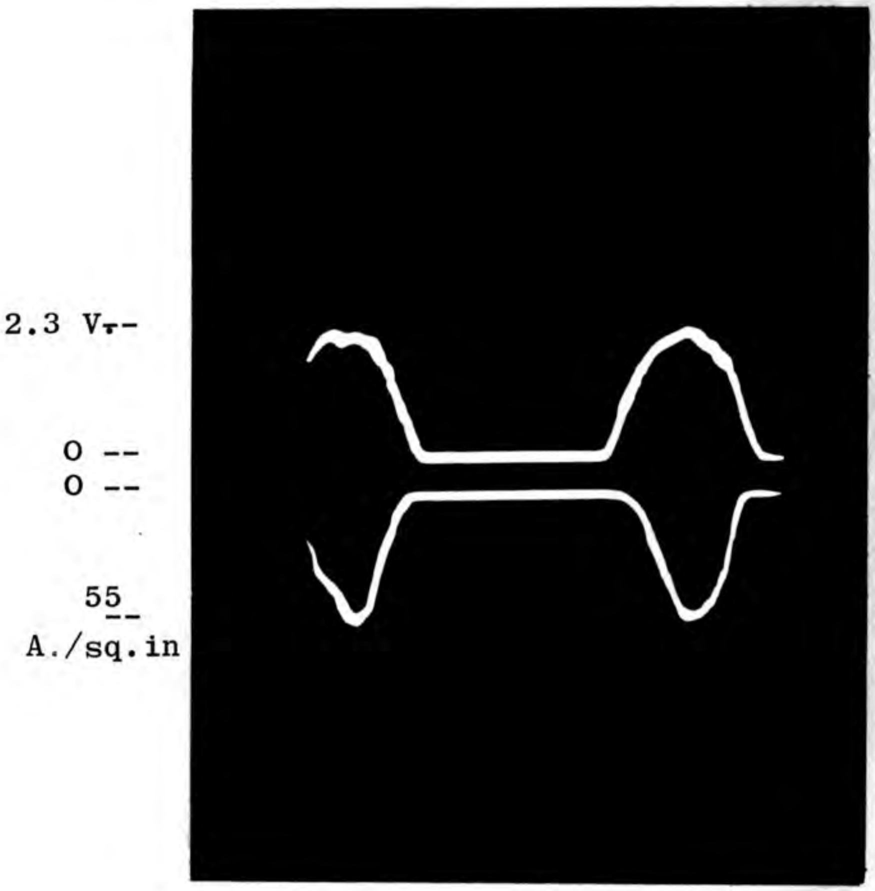
Circuit for half sine wave current tests.

Fig. (3.1.1.)



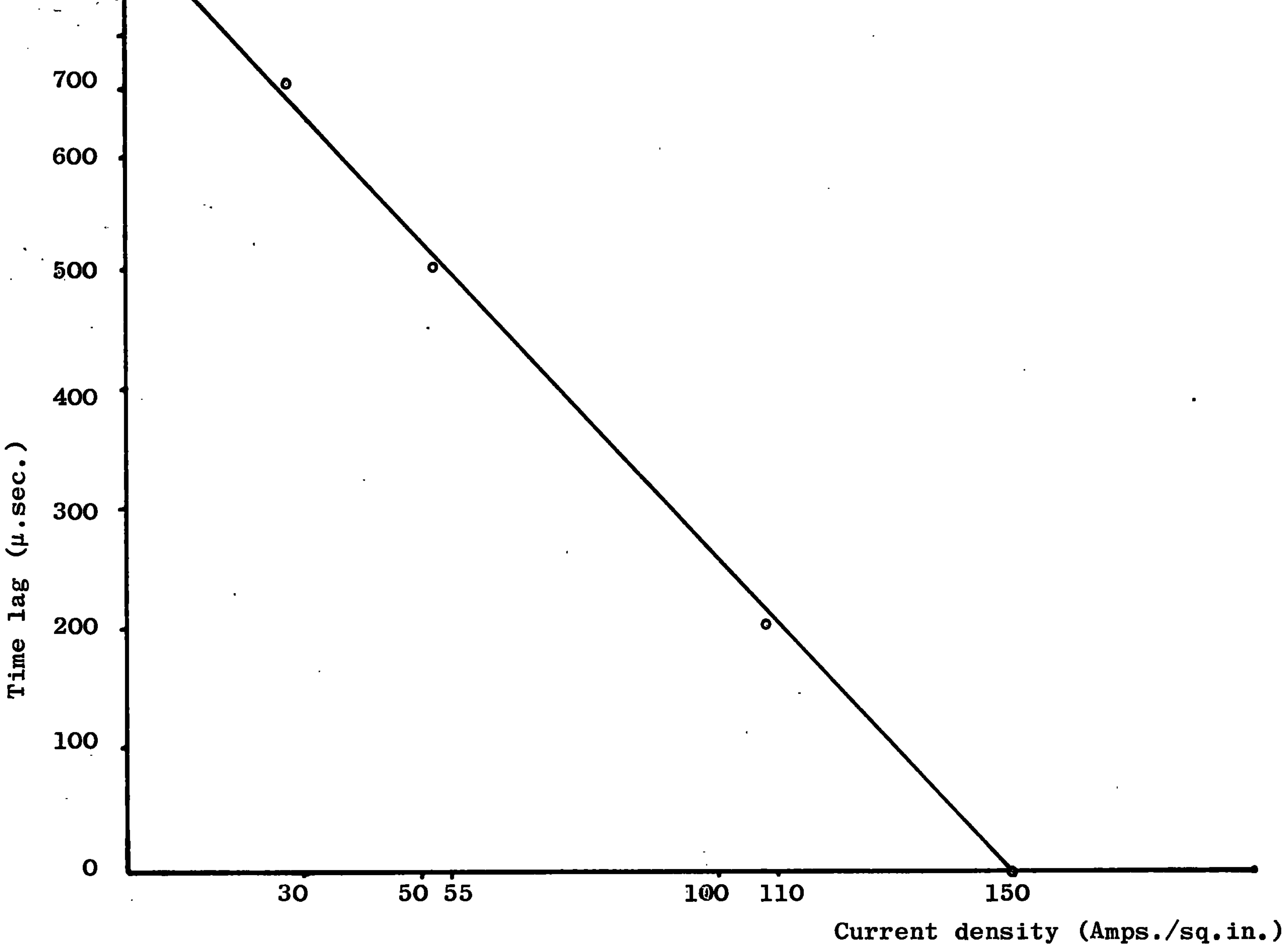
The wave form of current and contact voltage drop with EG11S brush grade, at the beginning of the test.

Fig. (4.4.1.)



The Wave Form of Current and Contact Voltage Drop with EG11S Brush Grade, and Rough Ring Surface, Where Time Lag was Observed.

Fig. (4.4.2.a.)



Time lag against current density with rough ring surface.

Fig. (4.4.2b)

Contact voltage drop against time with EG11S brush grade and half sine wave current.

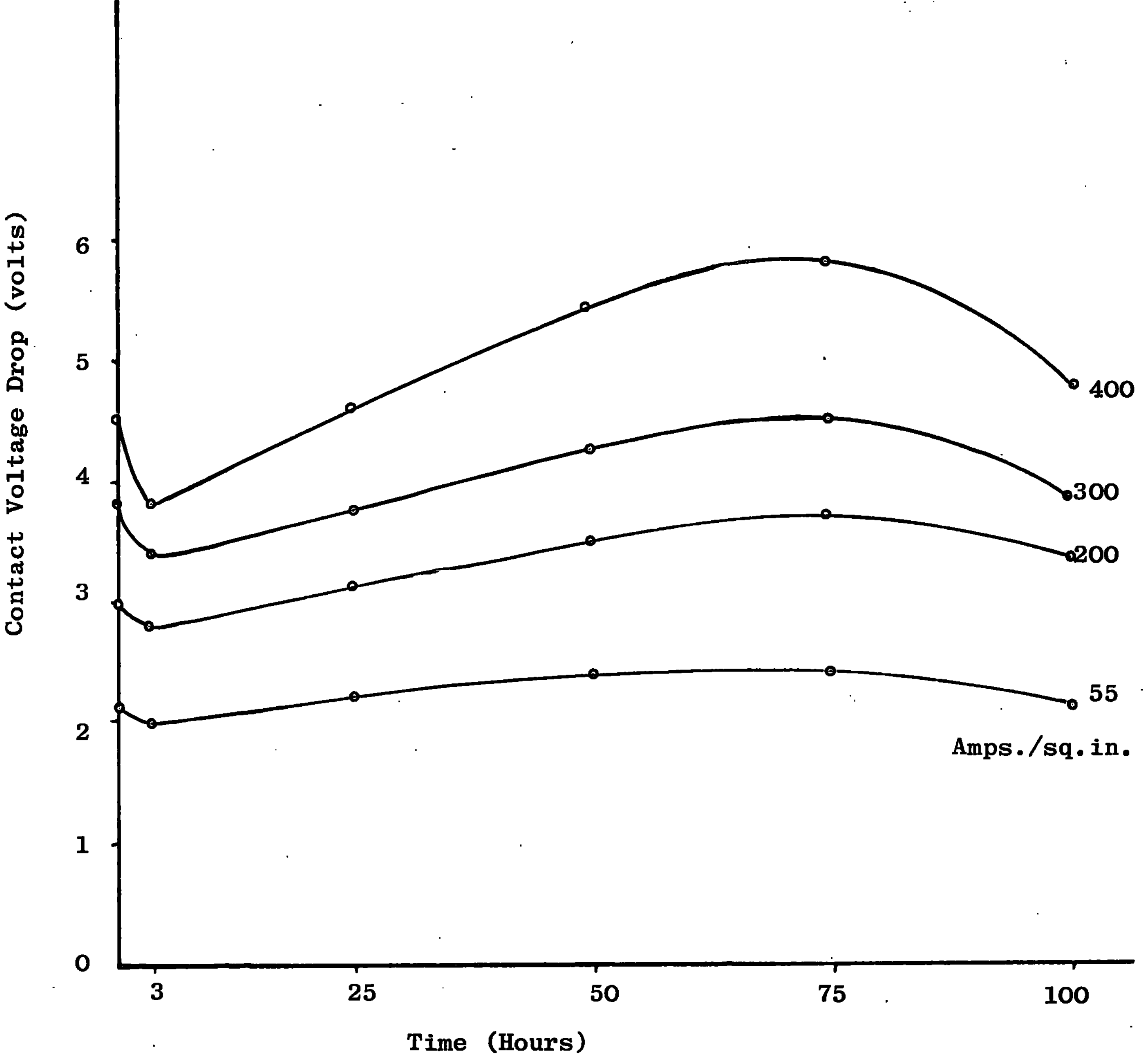


Fig.(4.4.3.)

Contact voltage drop against current density with half sine wave current.

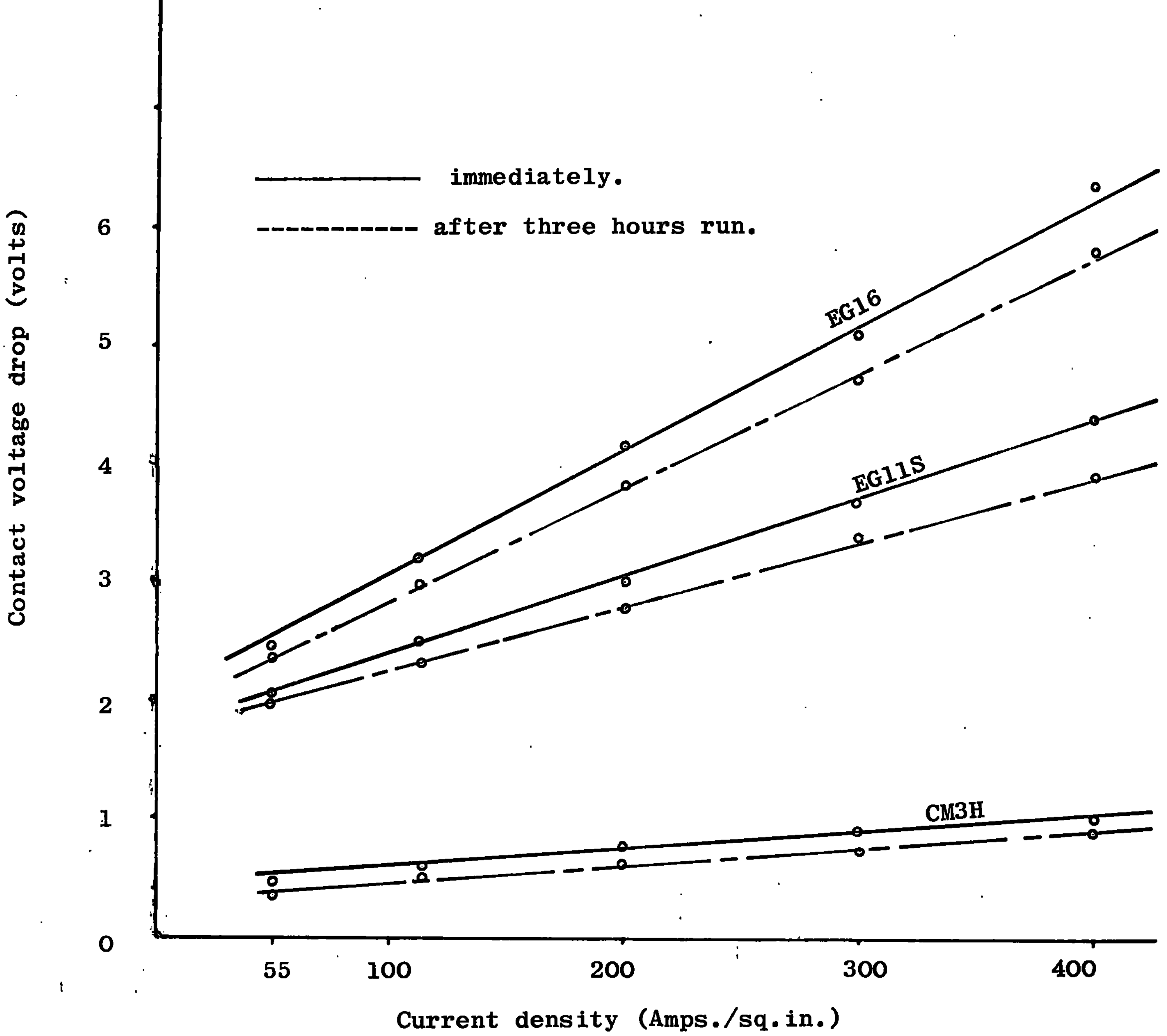
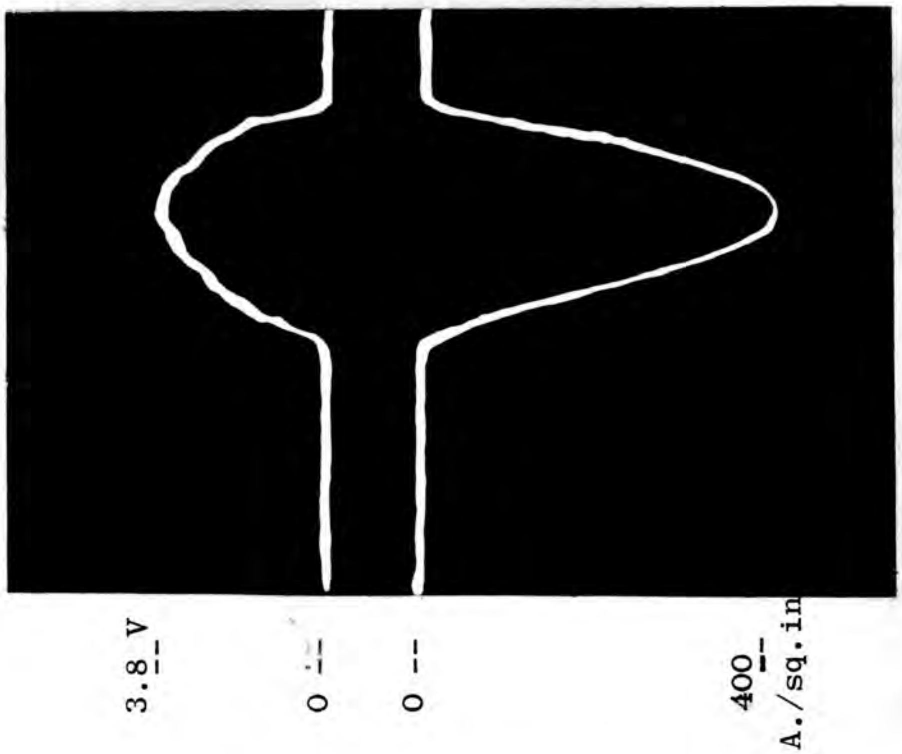


Fig.(4.4.4.)

(a)



The Wave Form of Current and Contact Voltage Drop with EG11S Brush Grade,

a) at the beginning of the test.

b) after 100 hours run.

(b)

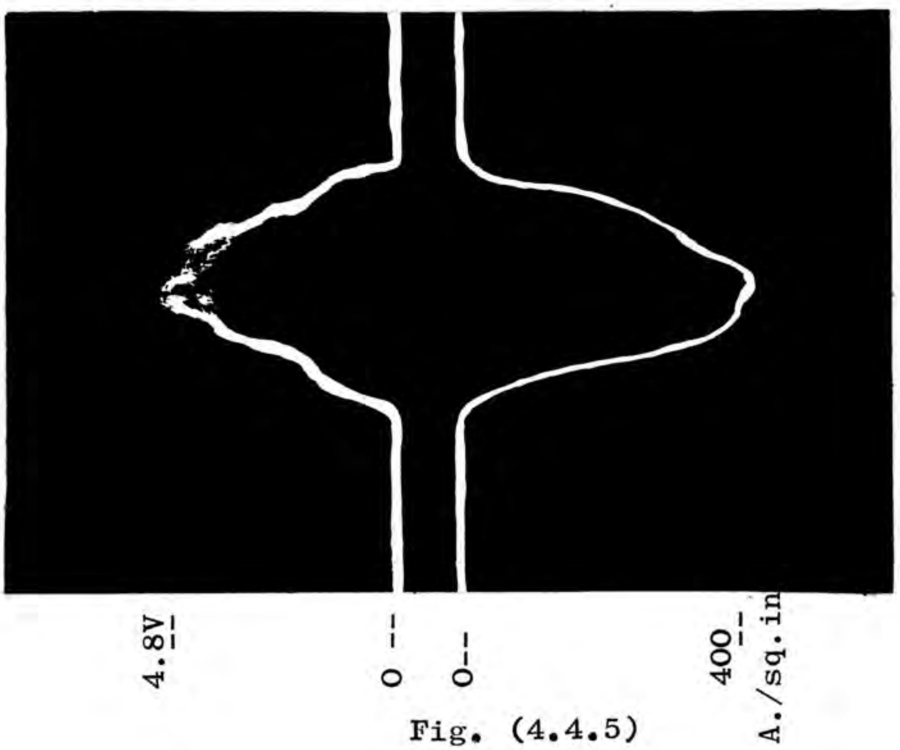


Fig. (4.4.5)

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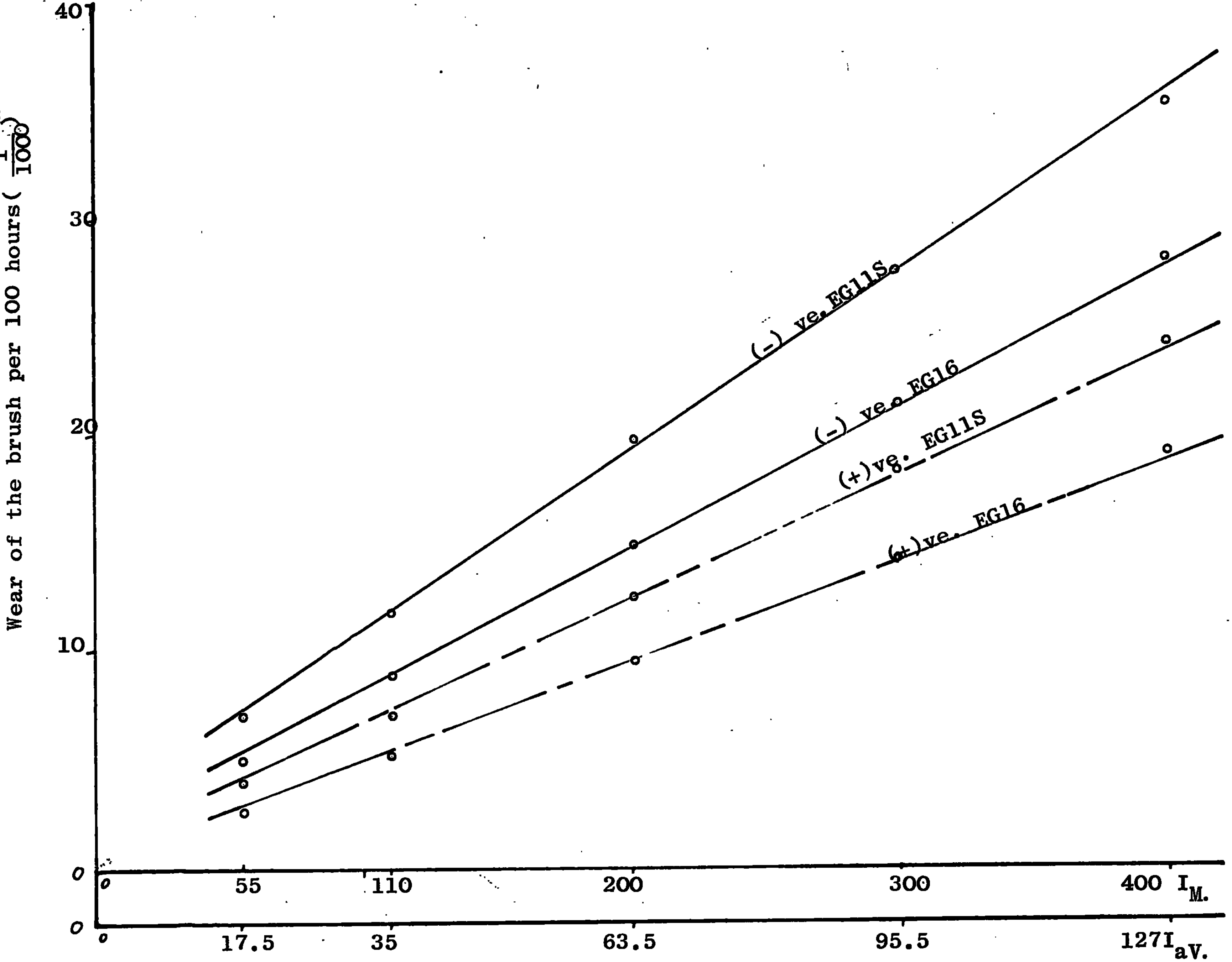


Fig. (4.4.6.)

Brush
Wear
against
time
with
half
sine
wave
current.

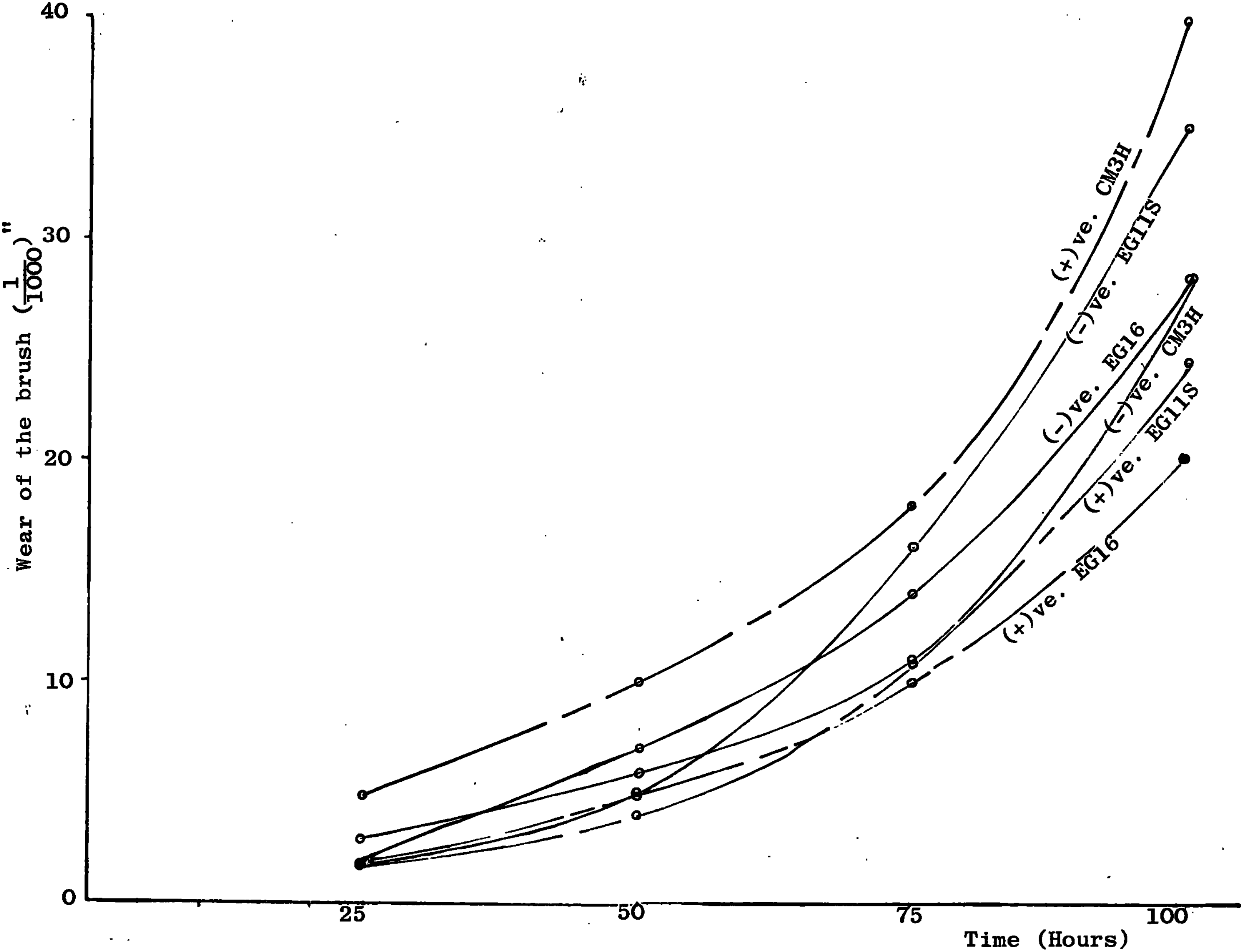


Fig. (4.4.7.)

Fig. (4.4.8.)

Brush Track of EG11S after 168 Hours Run with 110 Amps./sq.in. Half Sine Wave Current at the End of an Active Current Wave.

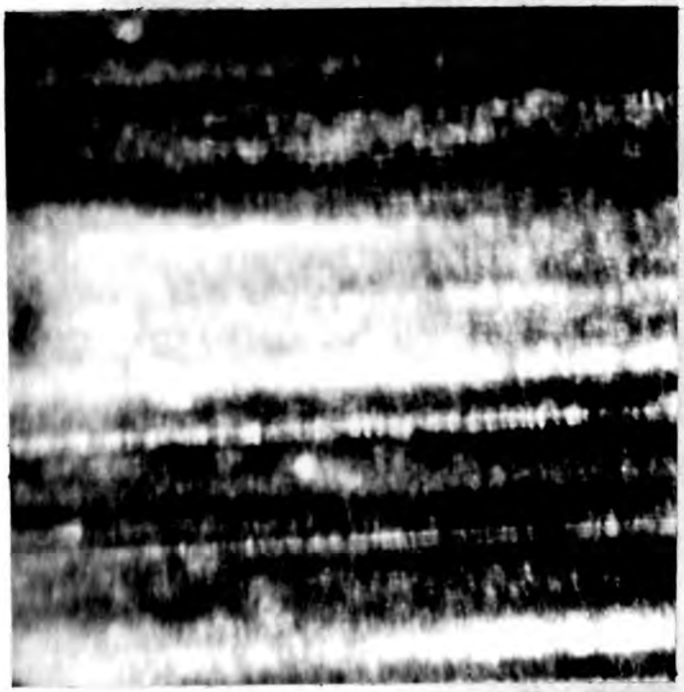


Fig.(4.4.9)

Brush Track of EG11S after 168 Hours Run with 110 Amps./Sq. in. Half Sine Wave Current, at the Beginning of an Active Current Wave.

Fig. (4.4.10)
Brush Track of EG11S after 168 Hours Run with 110 Amps./sq.in. Half Sine Wave Current, at the Middle of an Active Current Wave.

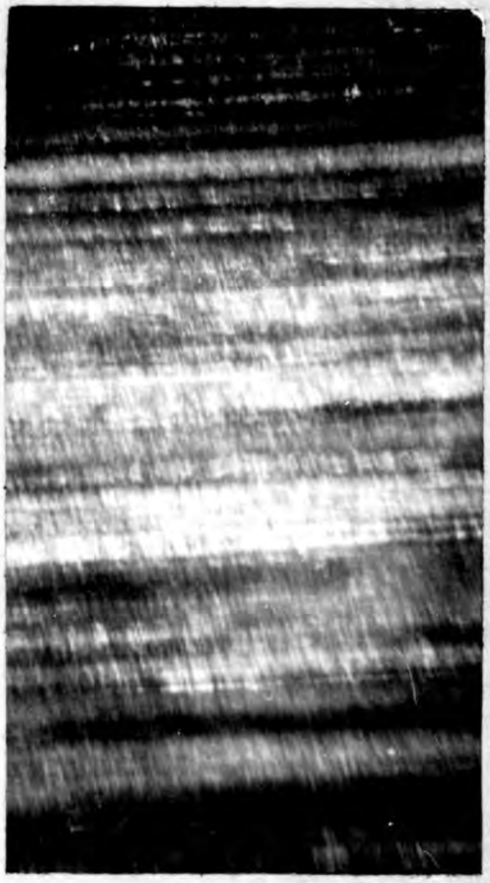


Fig. (4.4.11.)
Brush Track of EG11S after 168 Hours Run with 110 Amps./sq.in. Half Sine Wave Current, at the Middle of an Inactive Current Wave.

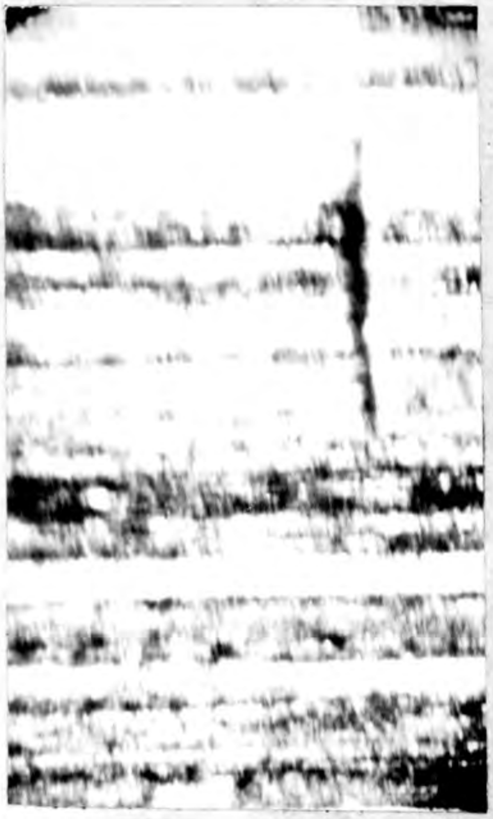


Fig. (4.4.12)

Brush Track of EG11S after 100 Hours Run with 400 Amps/sq.in. Half Sine Wave Current, at the Middle of an Active Current Wave.

Fig. (4.4.13)

Brush Track of EG11S after 168 Hours Run with 80 Amps/sq.in. Direct Current.

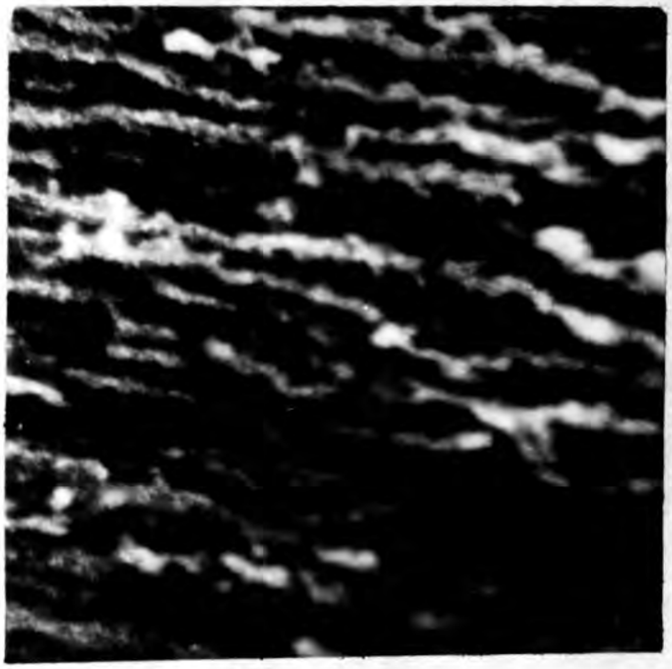
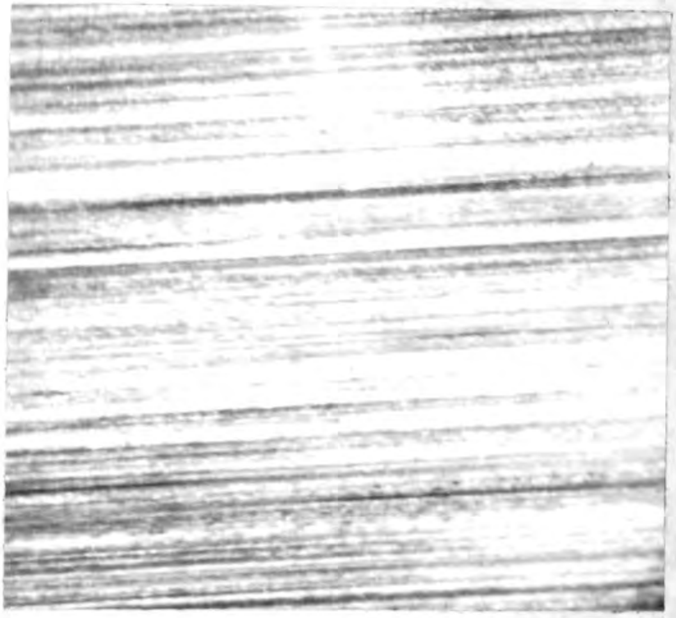


Fig.(4.4.14)
Brush Track of
EG11S after 100
Hours Run Without
Current.



Contact voltage drop with EG16 brush grade and half sine wave current.

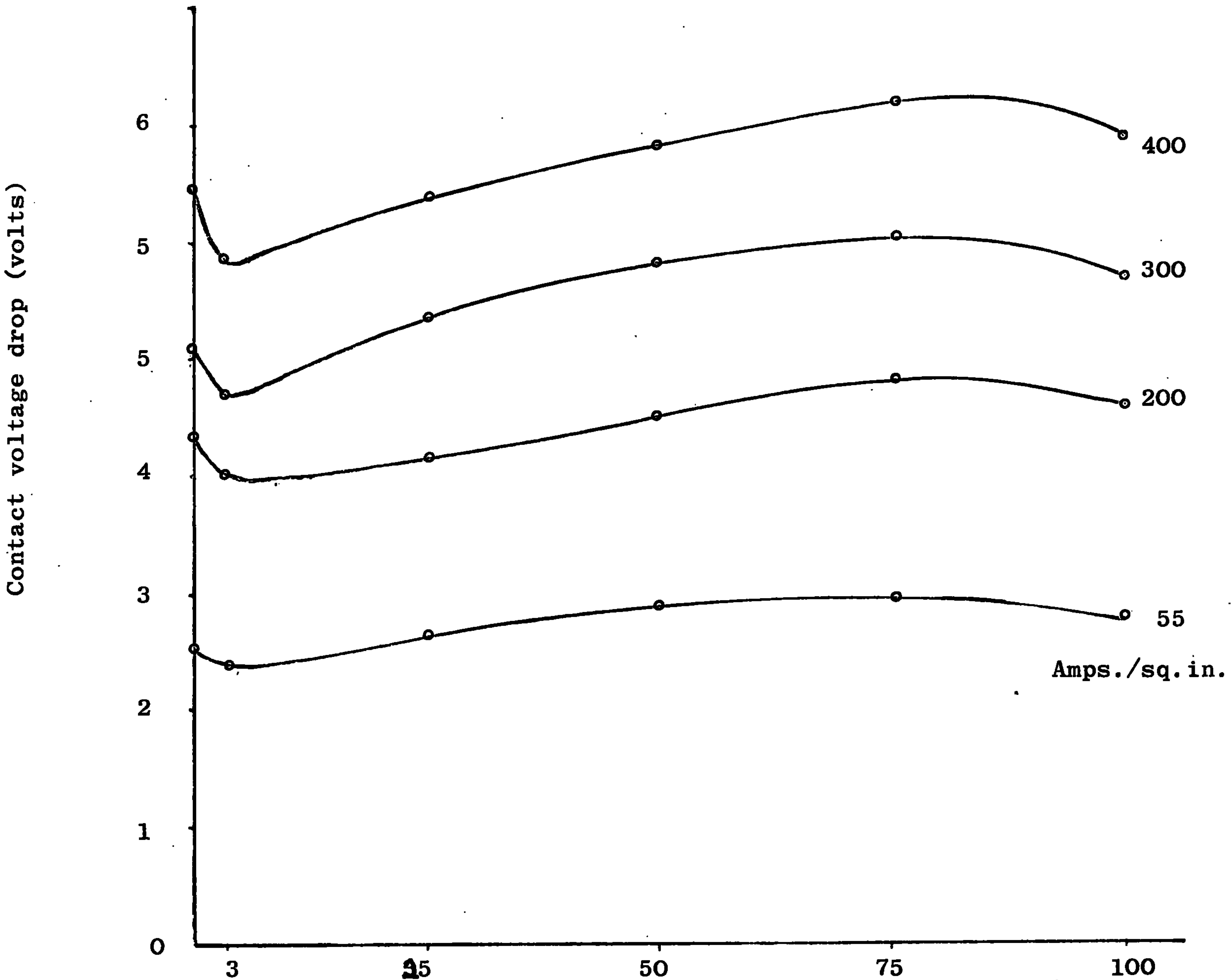
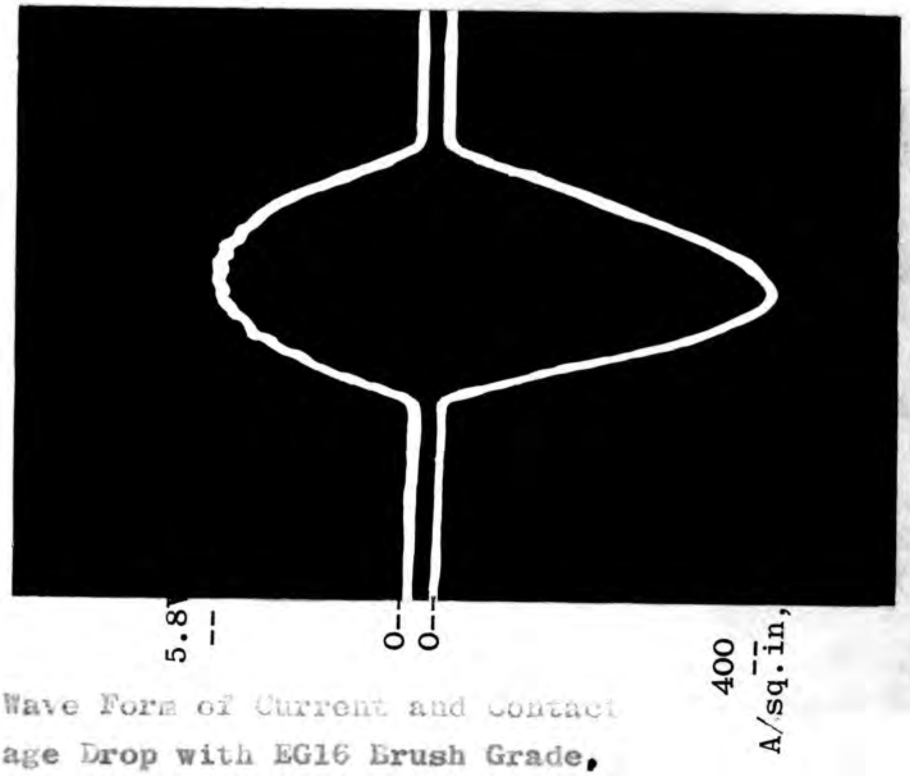


Fig. (4.4.15)

Fig. (4.4.16)

(a)



The Wave Form of Current and Contact Voltage Drop with EG16 Brush Grade,
a. at the Beginning of the Test.
b. after 100 Hours Run

(b)

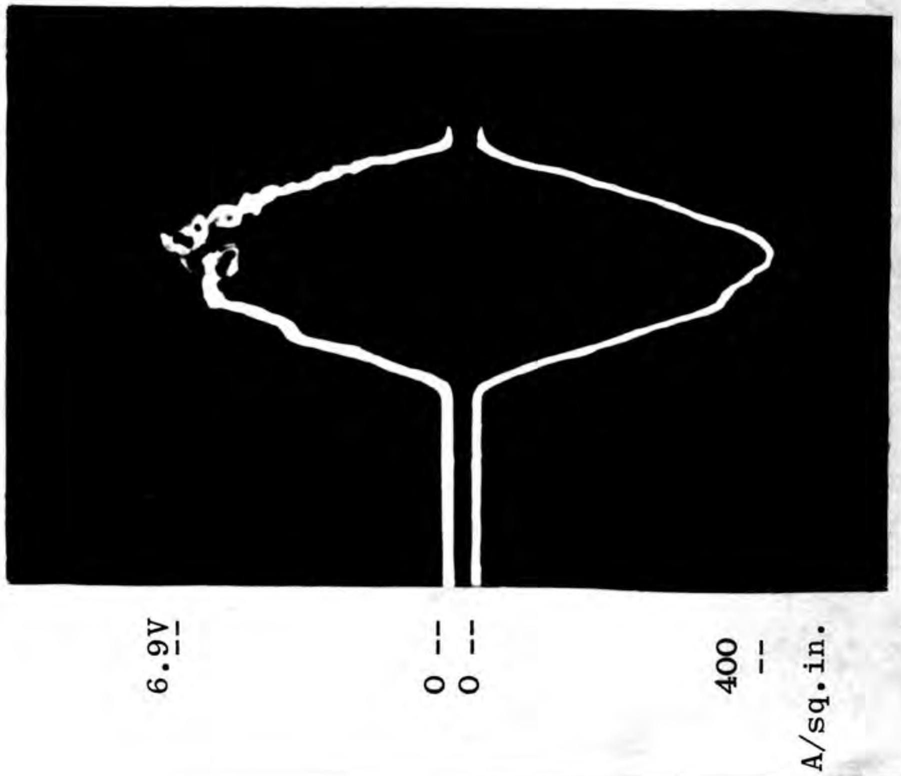
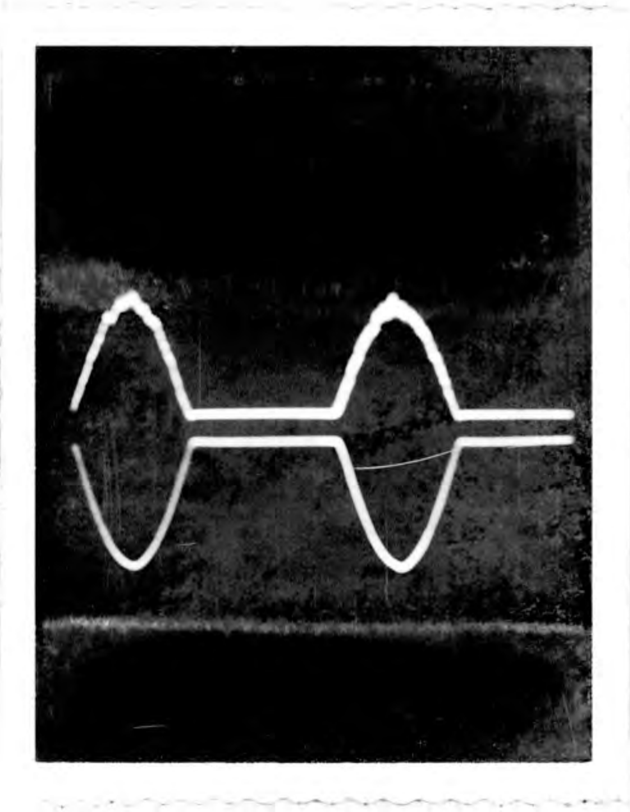


Fig. (4.4.17)



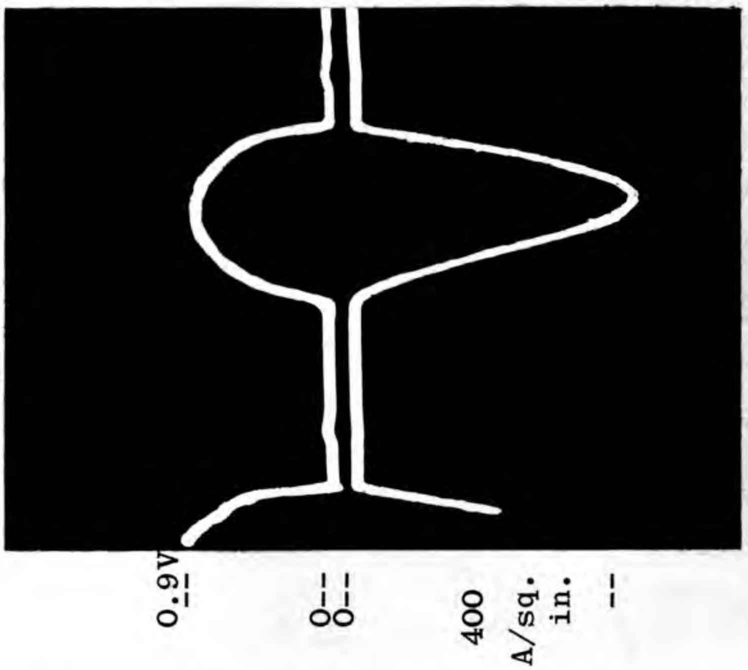
The Wave Form of Current and Contact Voltage Drop With CM3H Brush Grade.

Brush Track of CM3H
After 100 Hours Run
with 400 Amps/sq.in.
Half Sine Wave Current,
at the Middle of an
Active Current Wave.

Fig.(4.4.18)

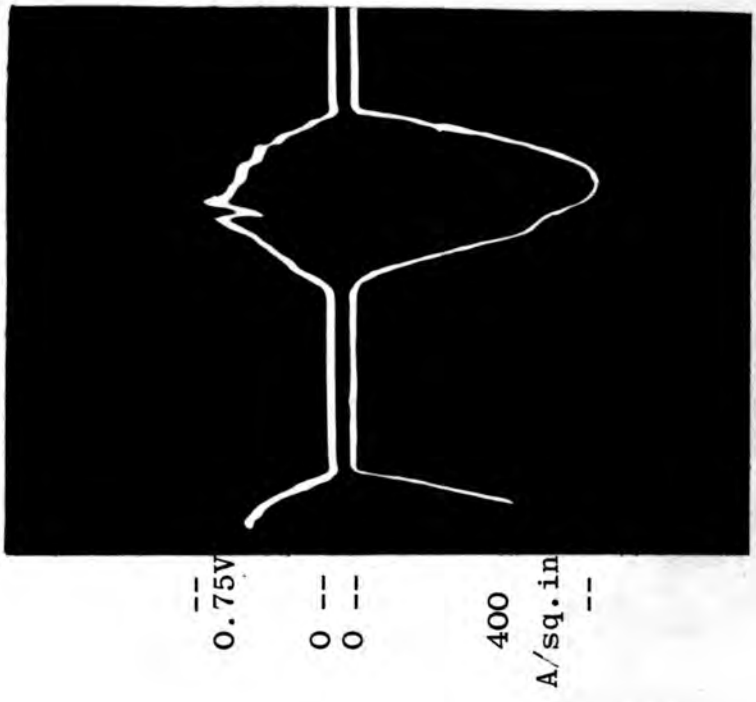
Fig. (4.4.19)

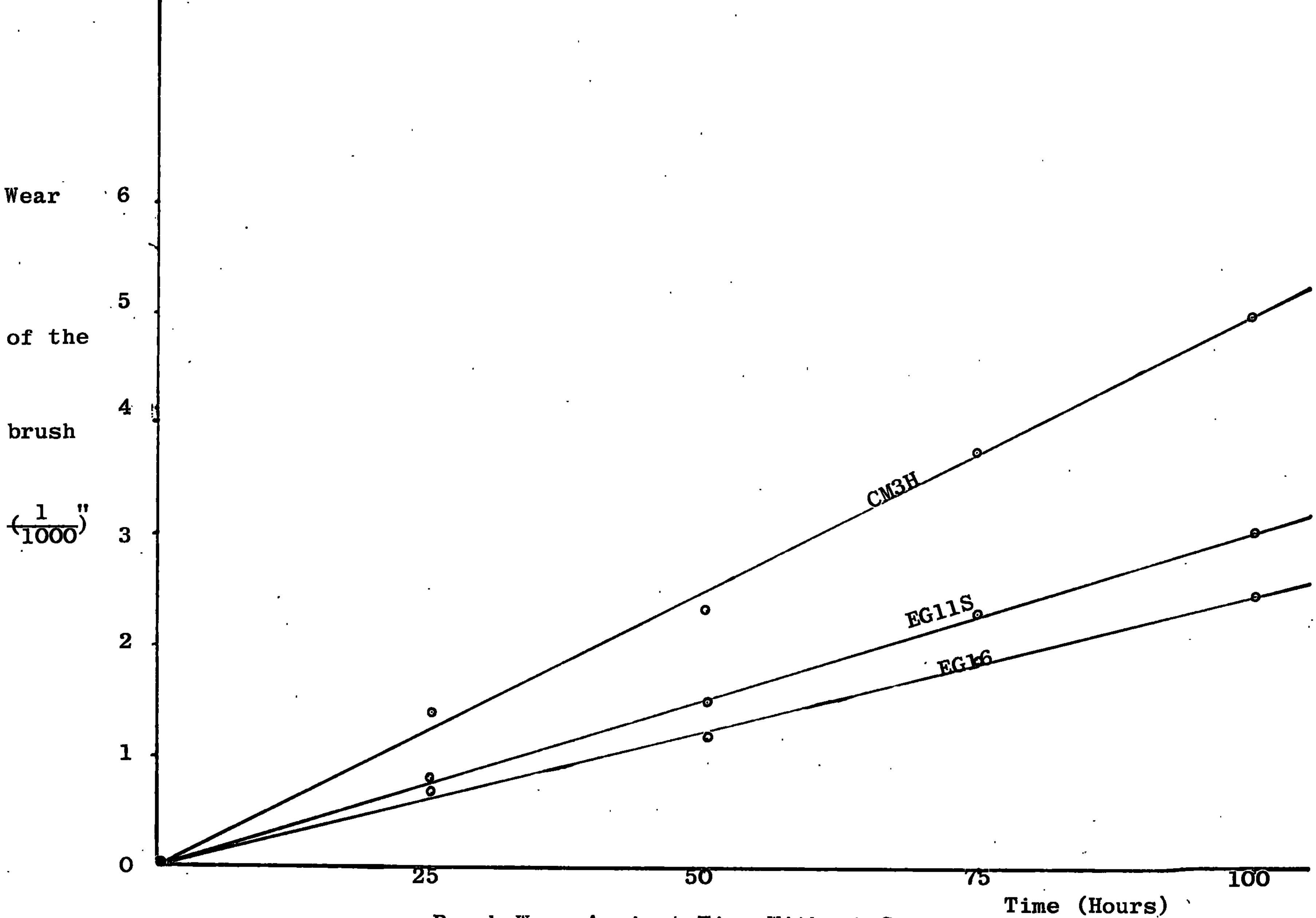
(a)



The Wave Form of Current and Contace Voltage Drop with CM3H Brush Grade,
a. at the Beginning of the Test.
b. after 100 Hours Run.

(b)





Brush Wear Against Time Without Current.

Fig. (4.6.20)

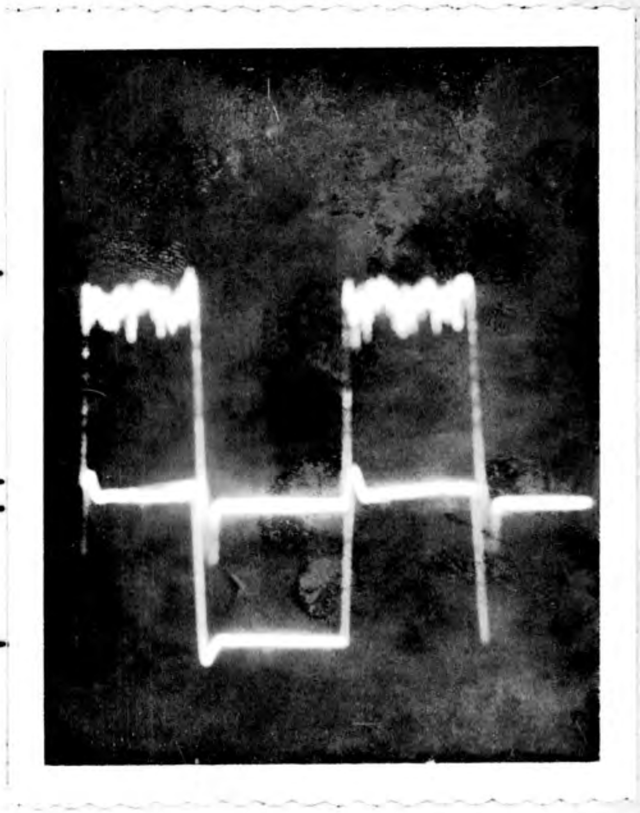


Fig. (5.2.1.)

The Wave Form of Current and Contact Voltage Drop with EG11S Brush Grade.

Brush
wear
against
current
density
with
square
wave
current.

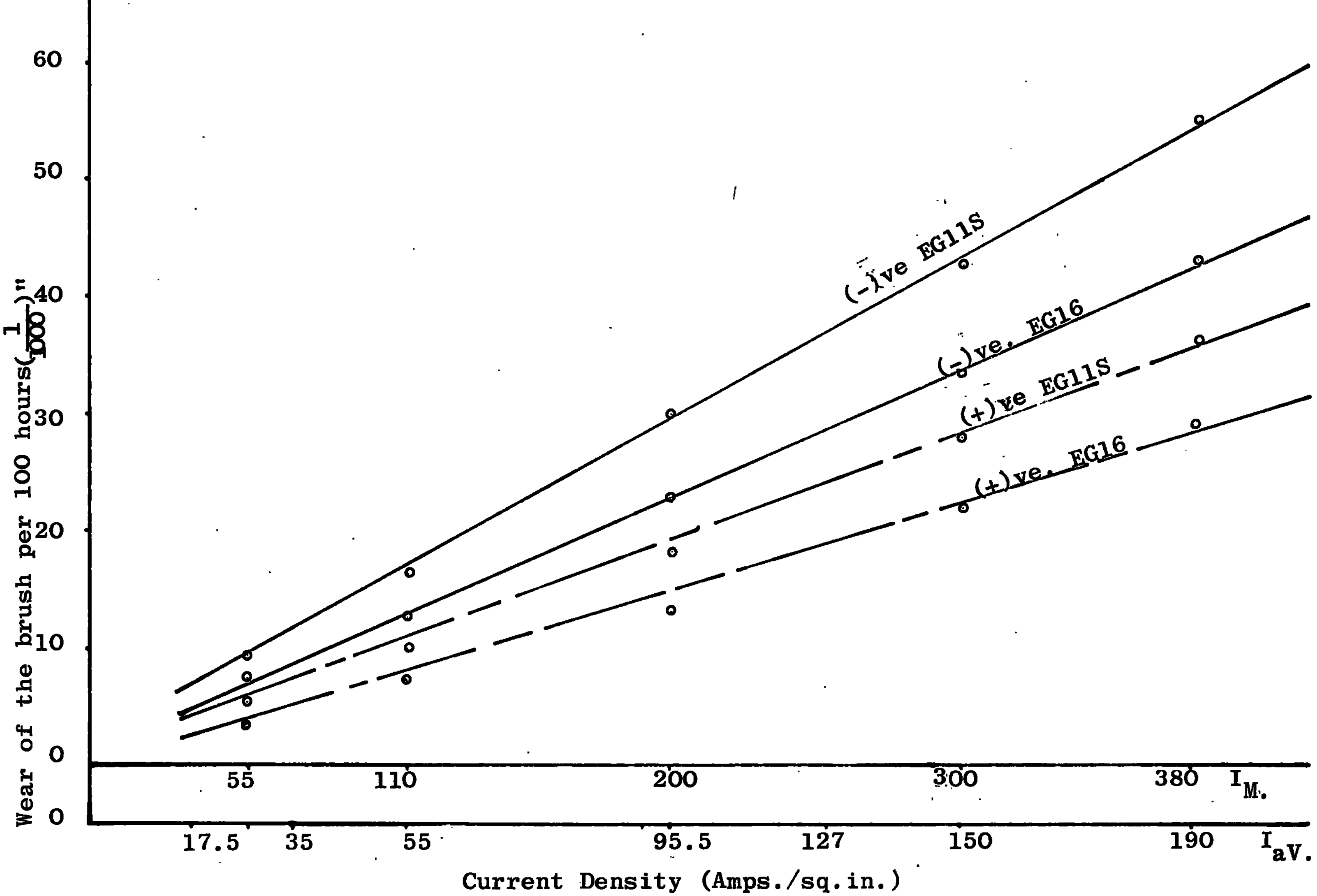
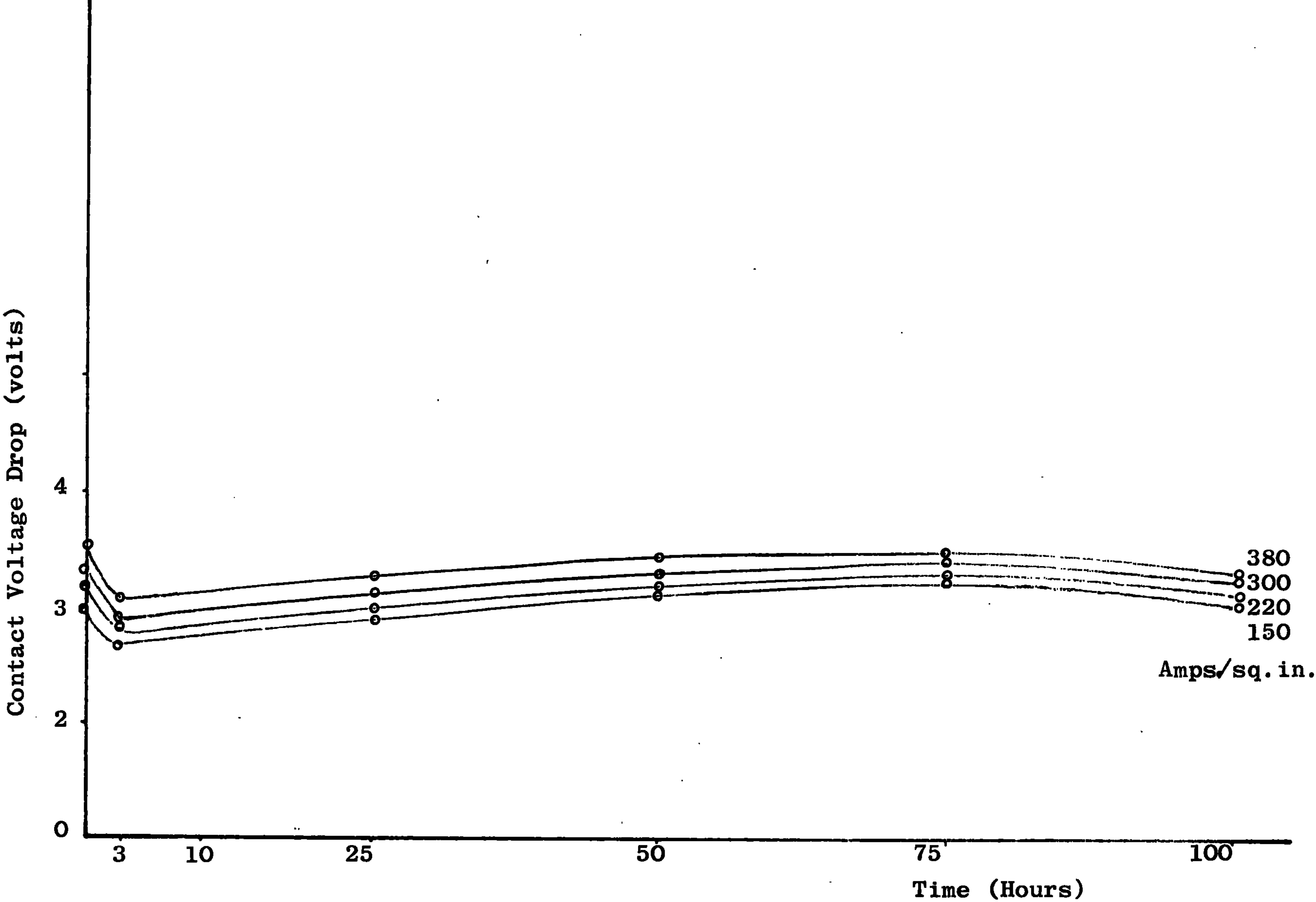


Fig. (5.2.2.)



Contact Voltage Drop Against Time with EG11S Brush Grade and Square Wave Current.

Fig. (5.2.3.)

Contact voltage drop against current density with square wave current.

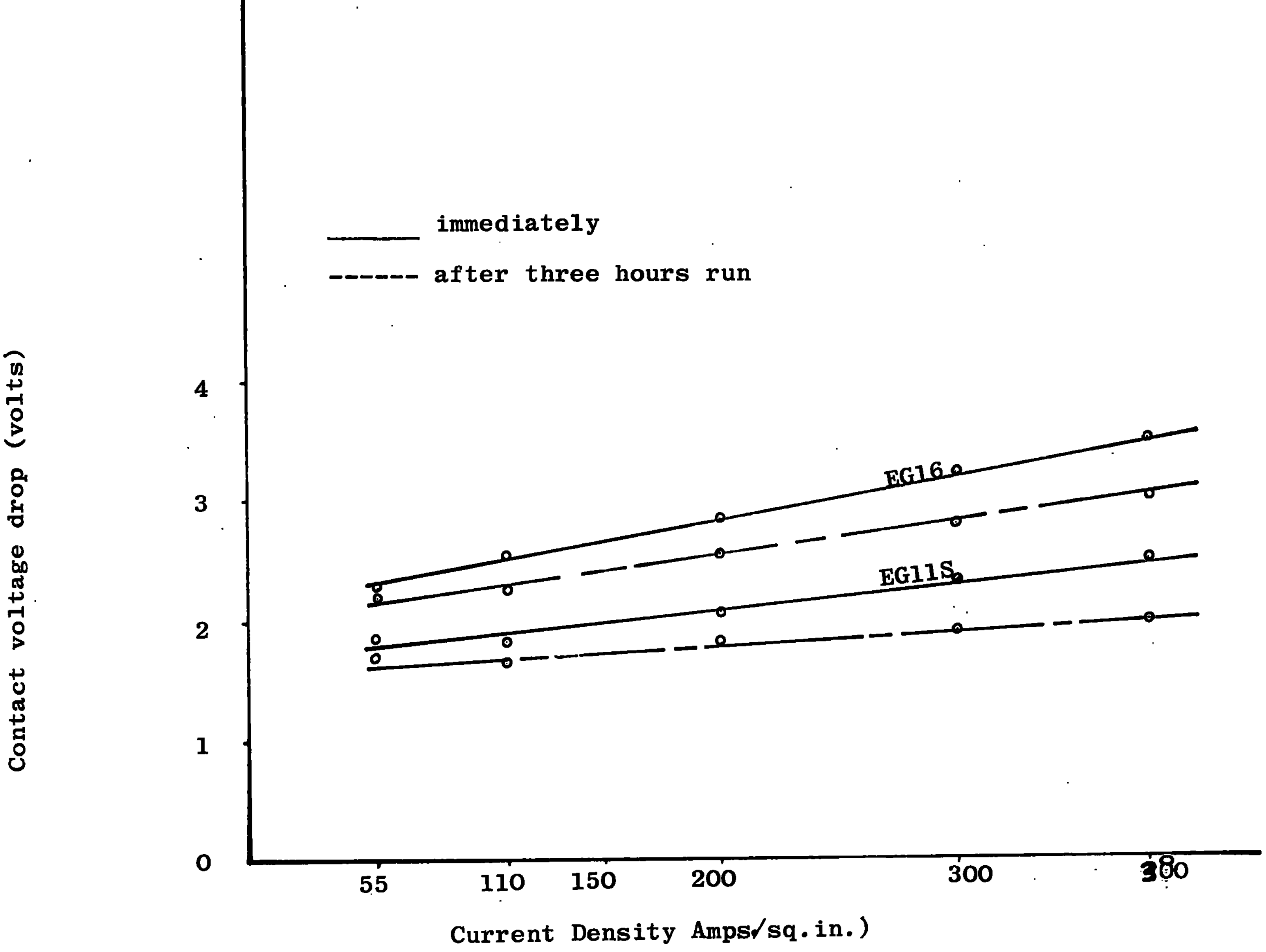
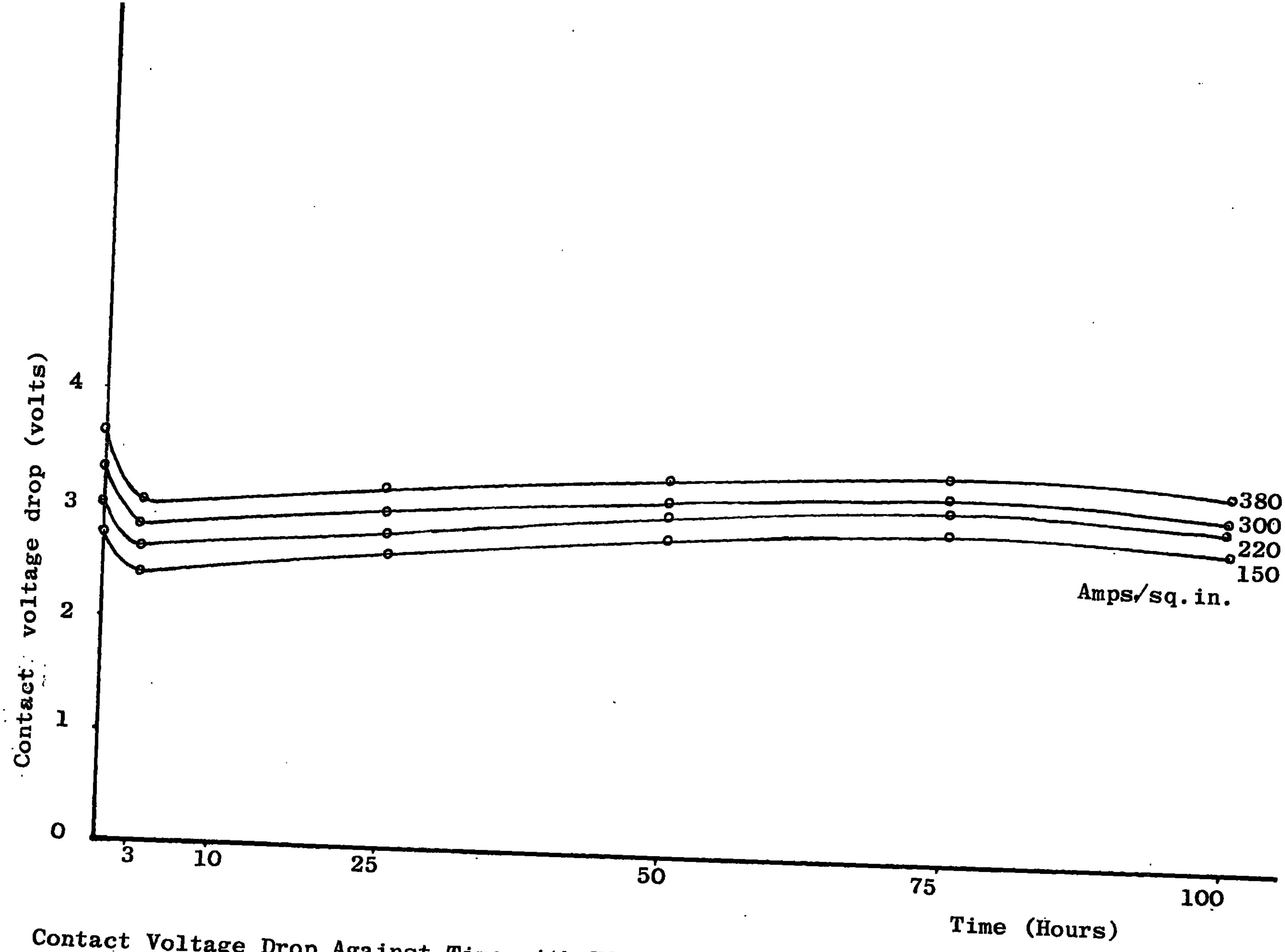


Fig. (5.2.4.)



Contact Voltage Drop Against Time with EG16 Brush Grade and Square Wave Current.

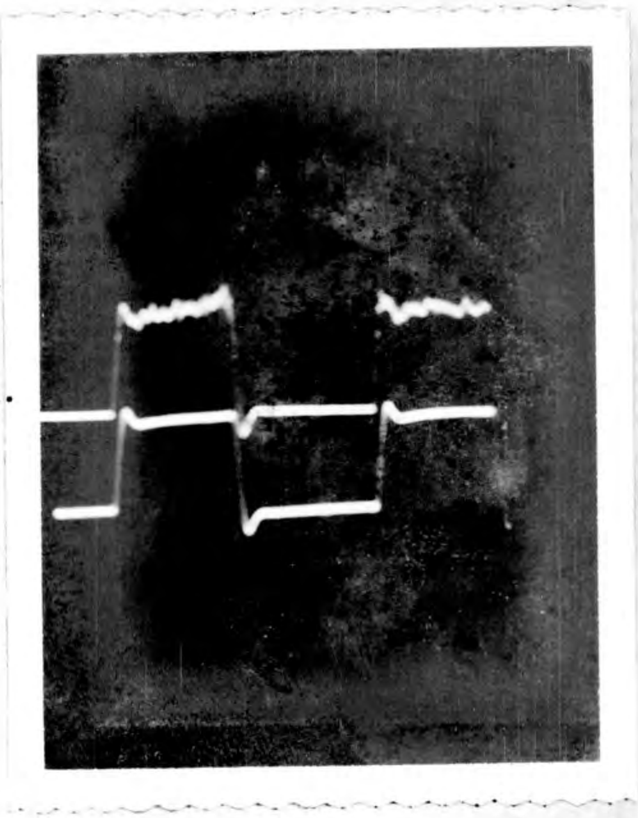
Fig. (5.2.5.)

Fig. (5.2.6.)

Brush Track of EG16 after 100 Hours Run with 380 Amps./sq.in. Square Wave Current, at the Middle of an Active Current Wave.

Fig. (5.2.7.)

The Wave Form of Current and Contact Voltage Drop with CM3H Brush Grade.



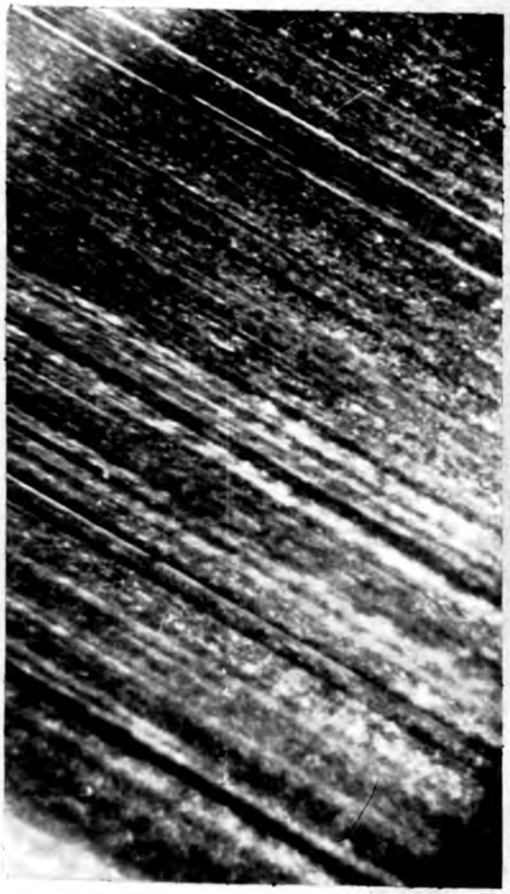
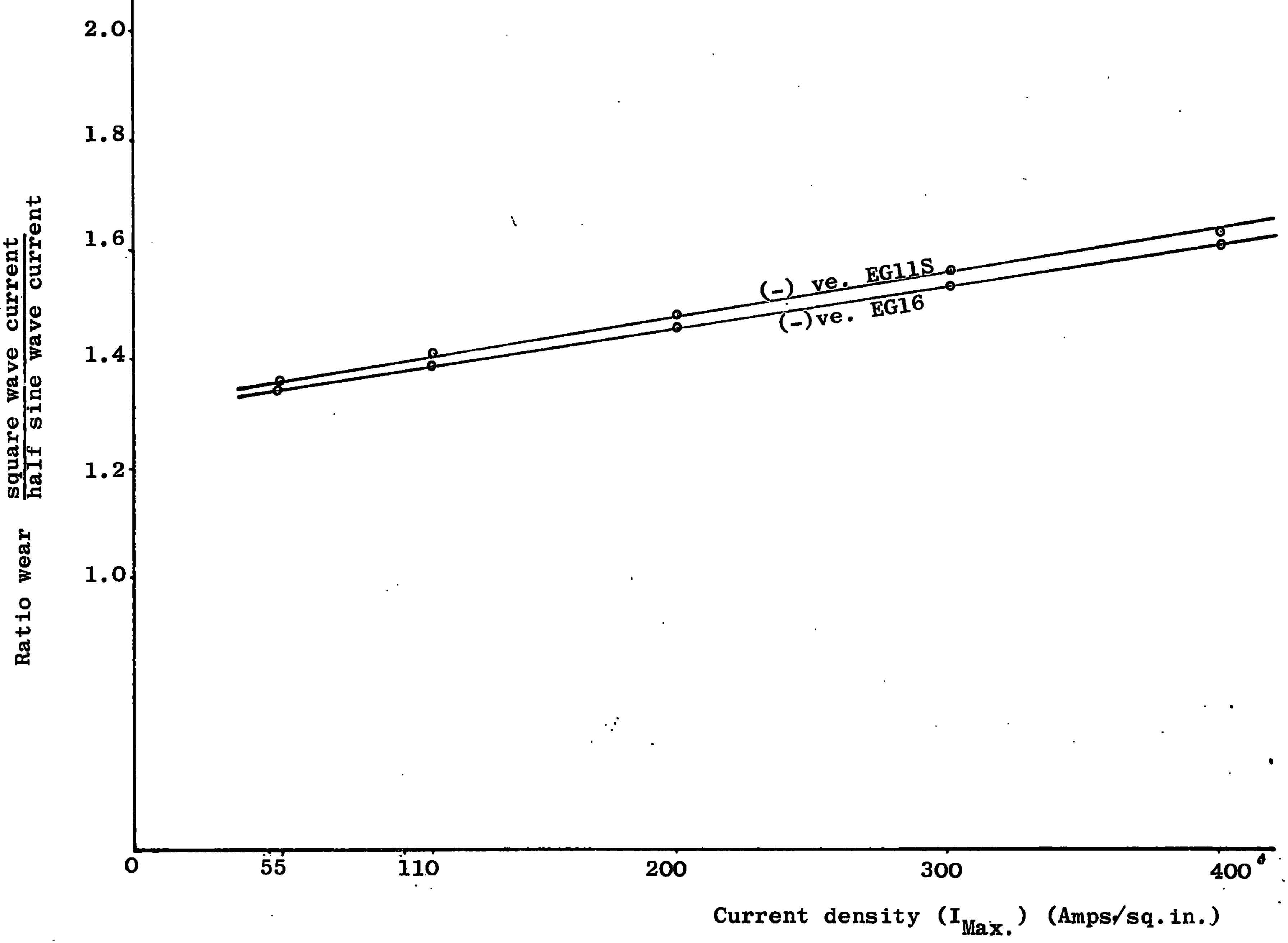


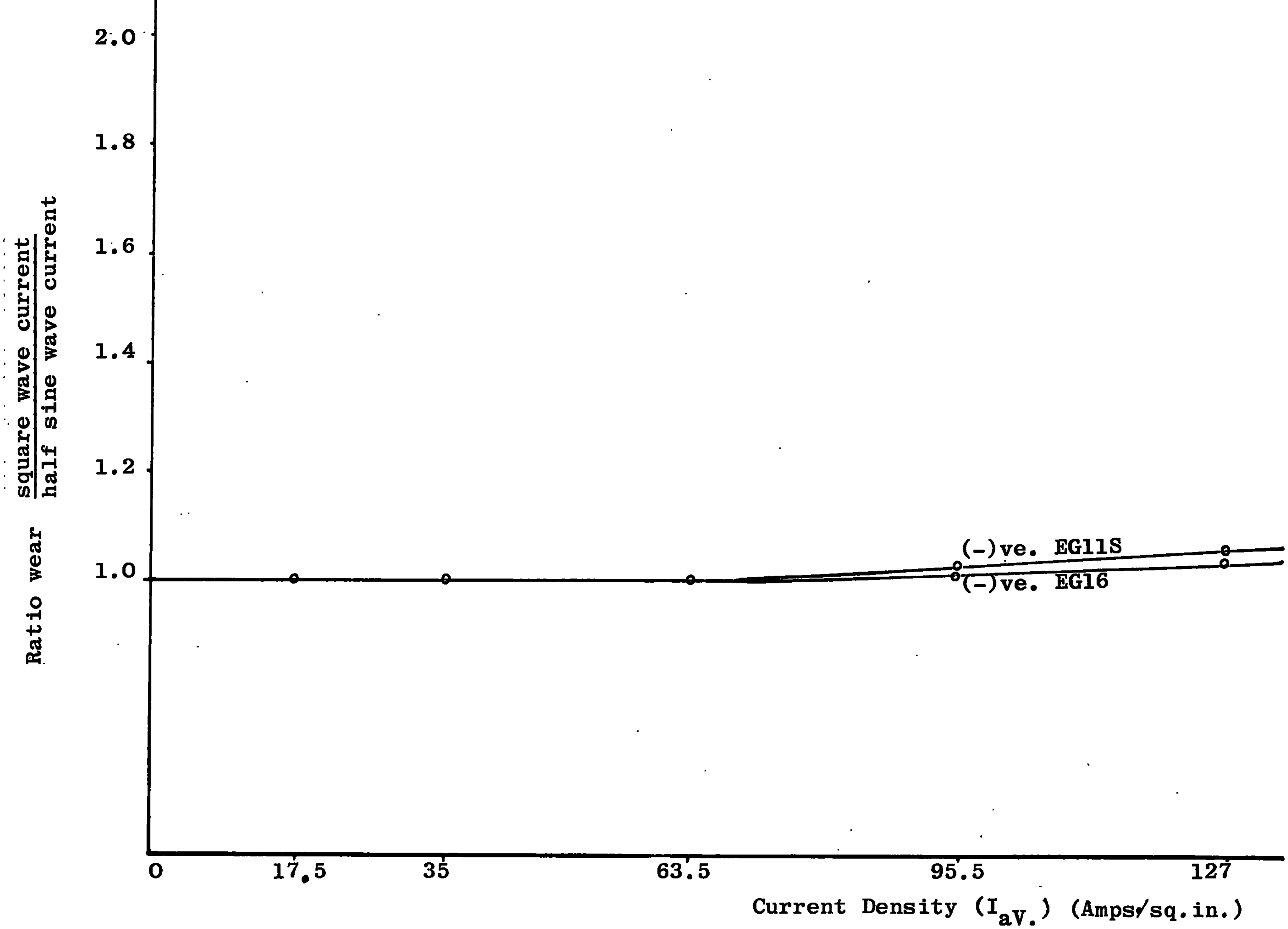
Fig. (5.2.8.)

Brush Track of CM3H after 100 Hours Run with 380 Amps/sq.in. Square Wave Current, at the Middle of an Active Current Wave.



Ratio Wear Against Peak Current Density.

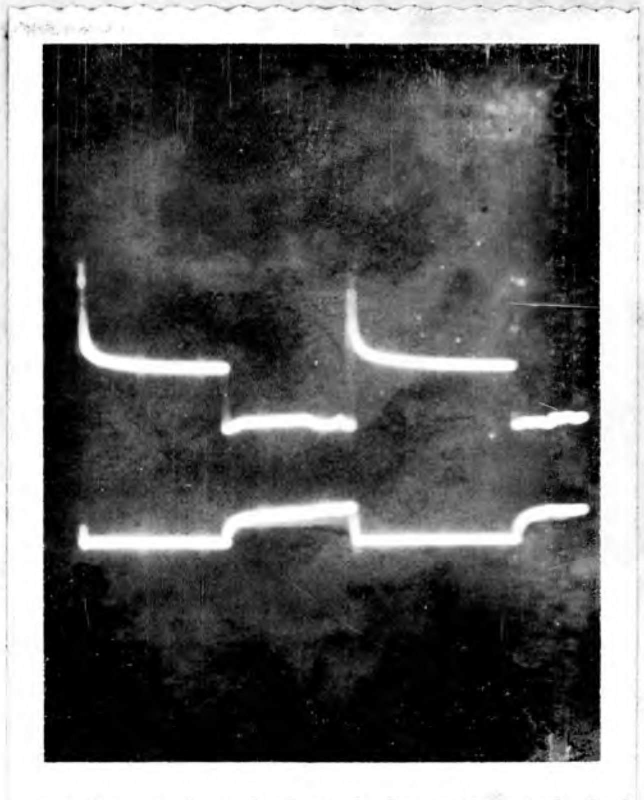
Fig. (5.4.1.)

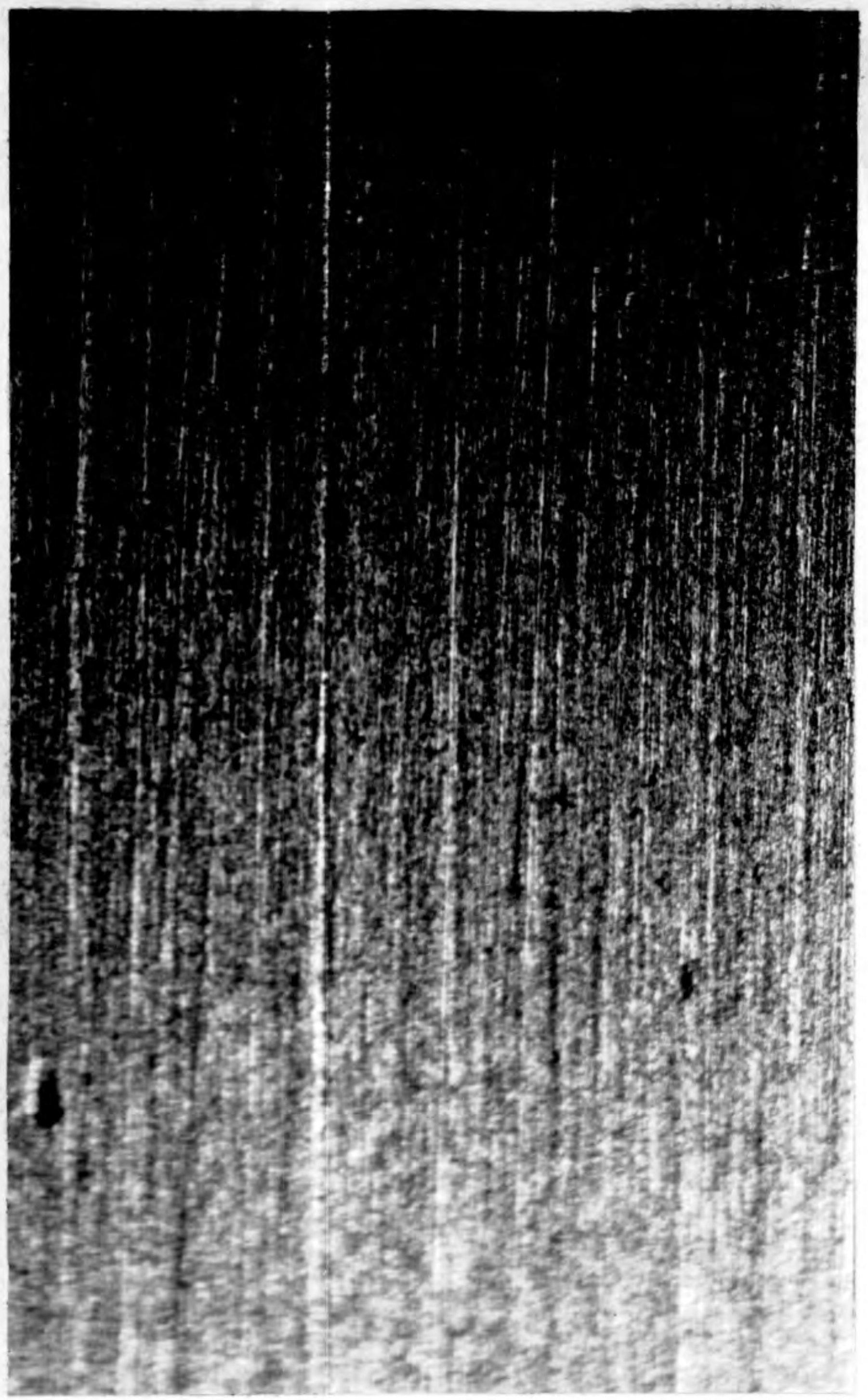


Ratio Wear Against Average Current Density.

Fig. (5.4.2.)

Fig.(6.2.1.)
The Wave Form of Current and Contact Voltage Drop with EG16 Brush Grade and Segmented Ring.





Uneroded Segment

Fig. (6.5.1.)

Erosion of an Active Segment in Segmented Ring.(Compare Opposite)

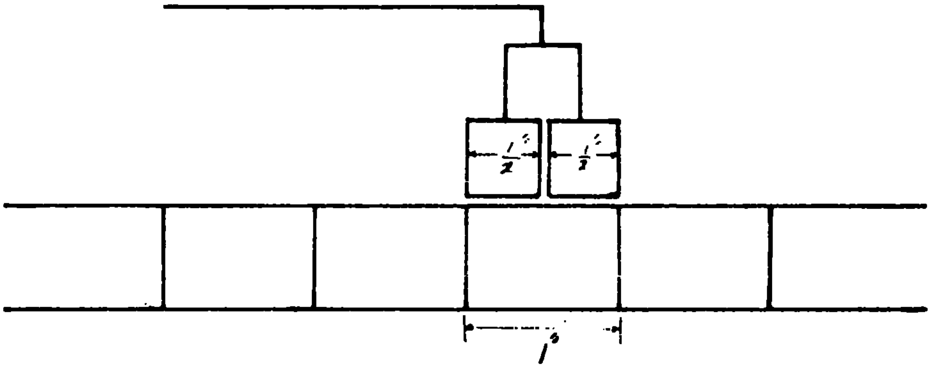


Fig. (6.1.1.)

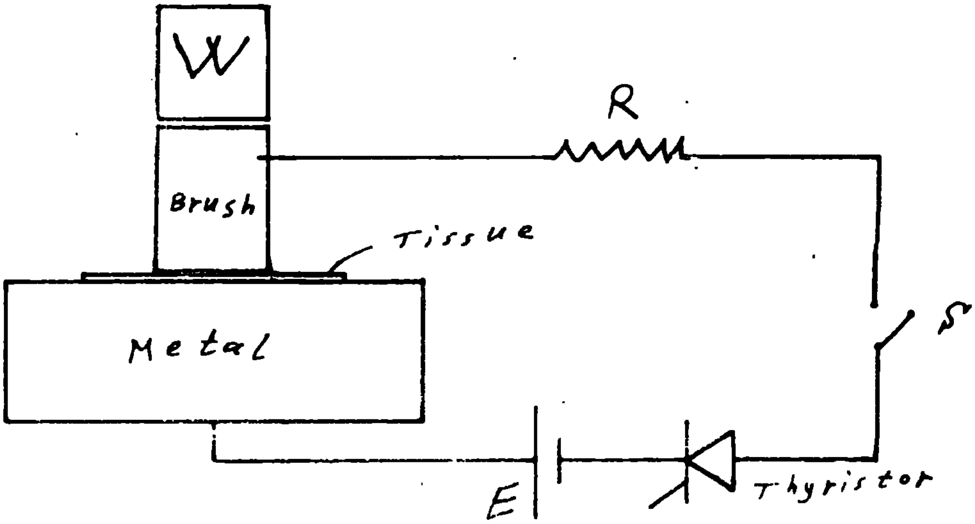


Fig.(6.5.2.)

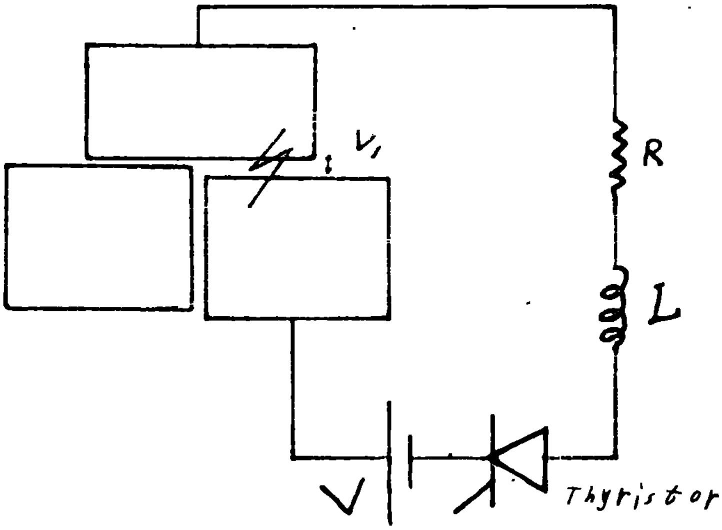
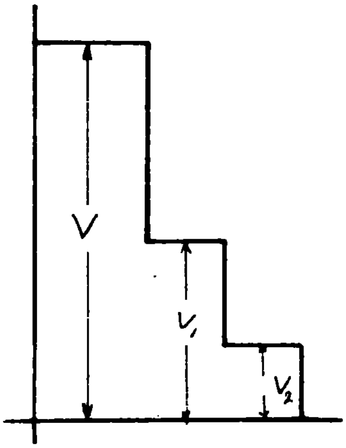


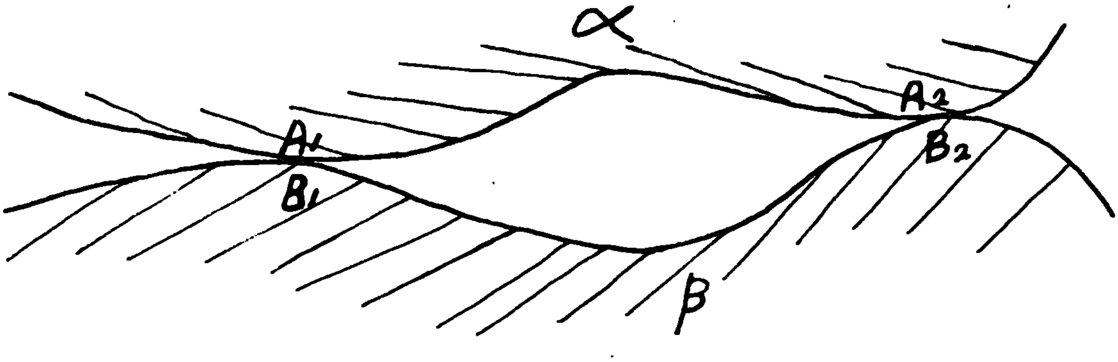
Fig. (6.5.3.)



V = supply volts

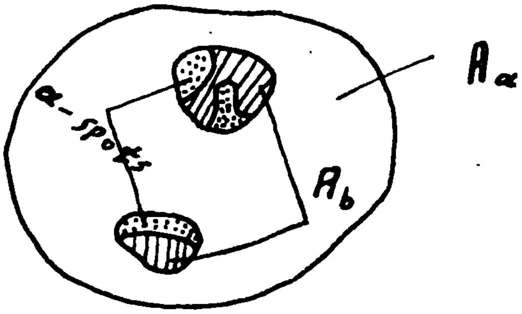
V_1= arc volts

V_2= brush drop



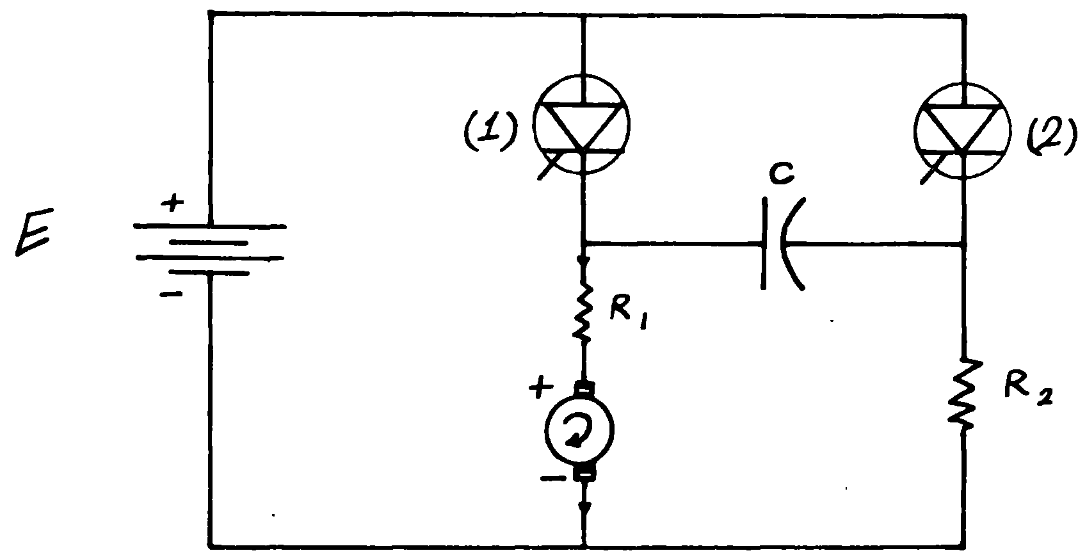
The conditions of contact as suggested by Bowden and Rider.

Fig. (7.1.1.)



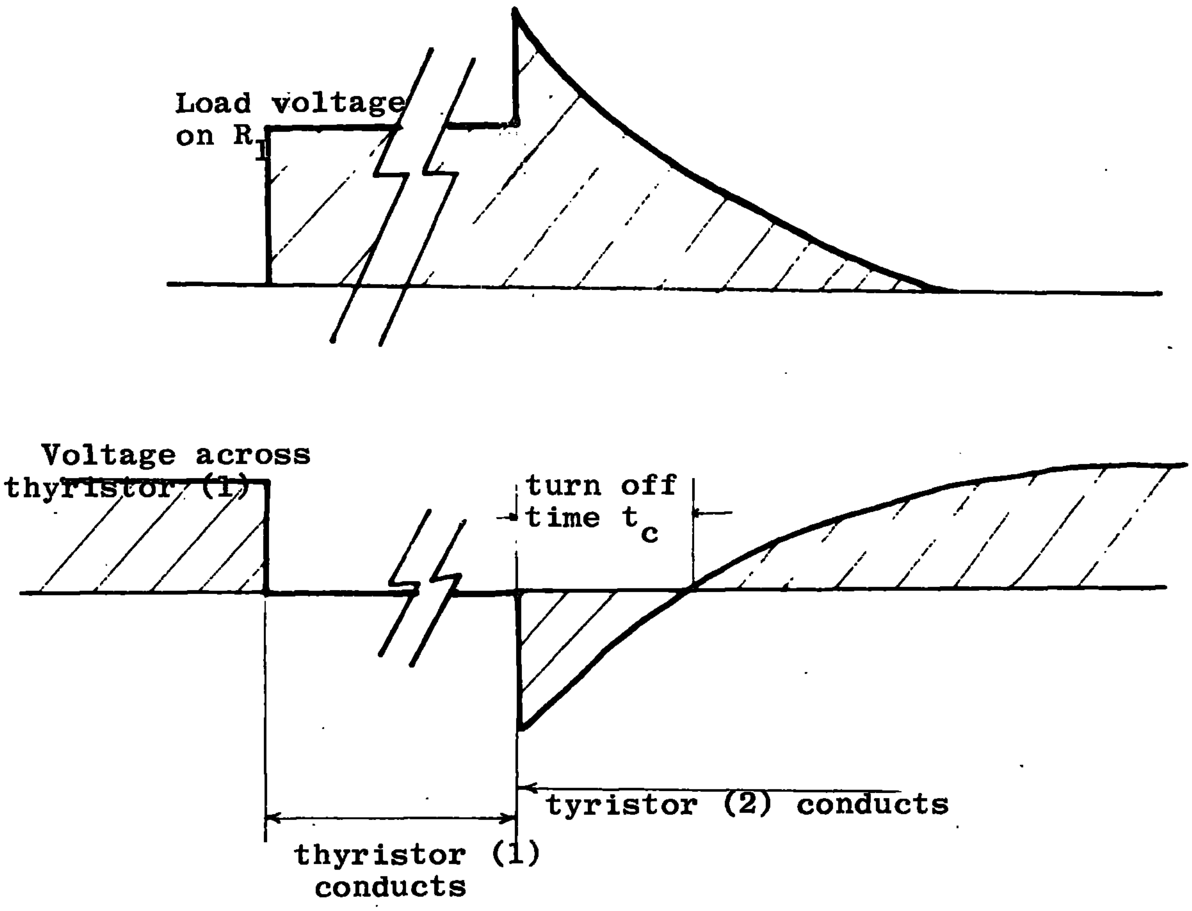
Apparent contact area, A_a, load bearing contact area, A_b, containing insulating spots, shaded and conducting a-spots, dotted.

Fig. (7.1.2.)



Parallel capacitor commutated d.c. switch.

Fig. (9.1.1.)



The voltage wave form across thyristor (1) and the load R_1.

Fig. (9.1.2.)

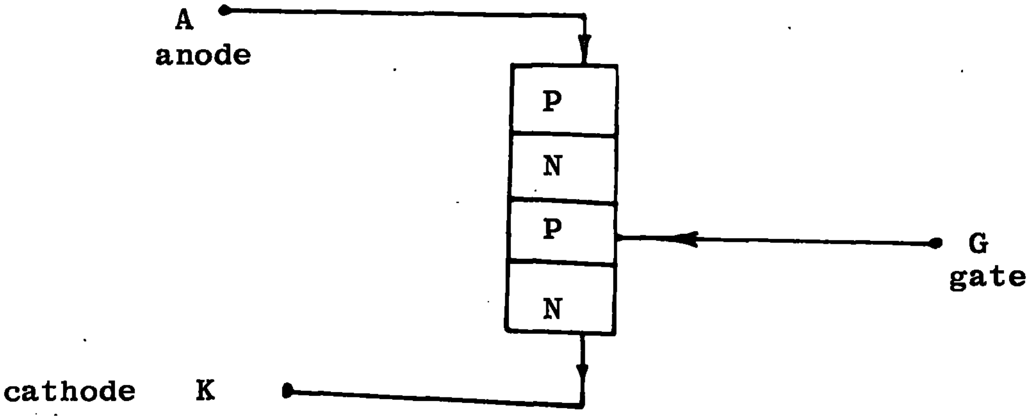


Diagram of the thyristor.

Fig. (9.2.1.)

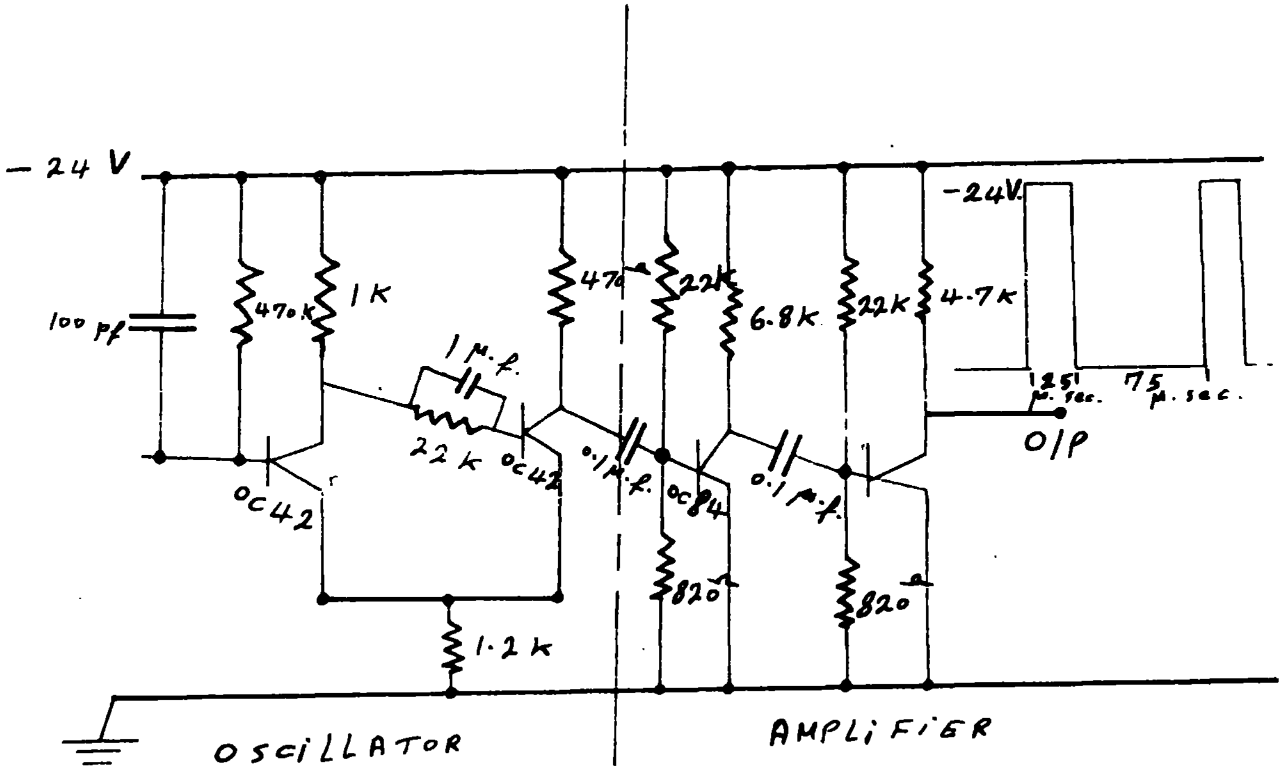
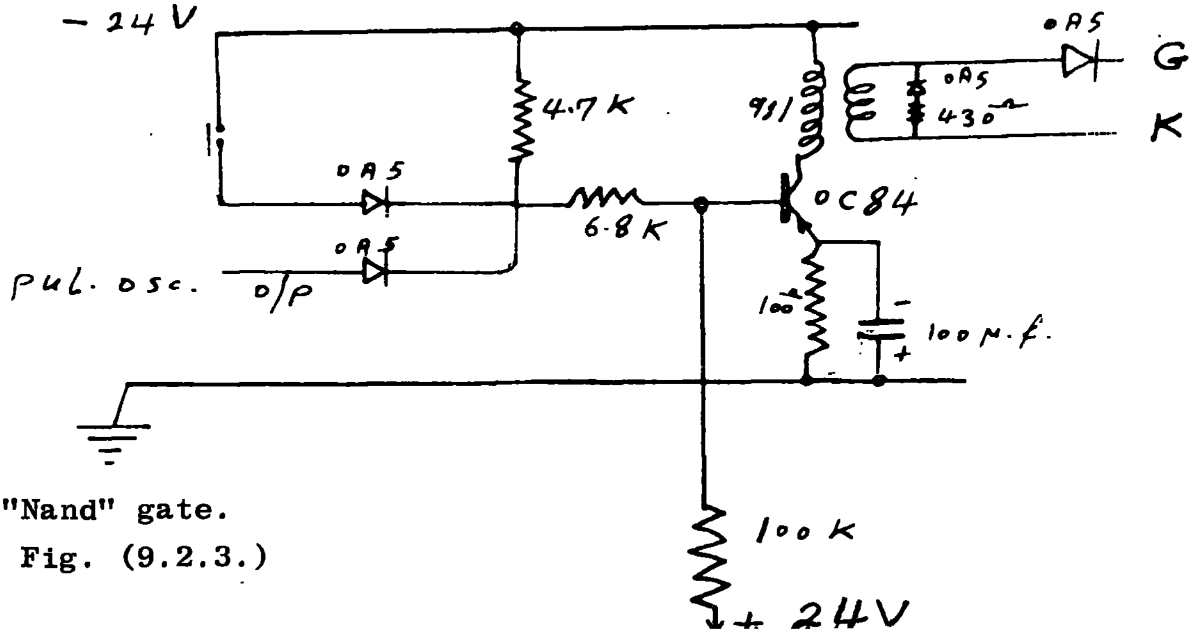


Fig. (9.2.2.)



"Nand" gate.
Fig. (9.2.3.)

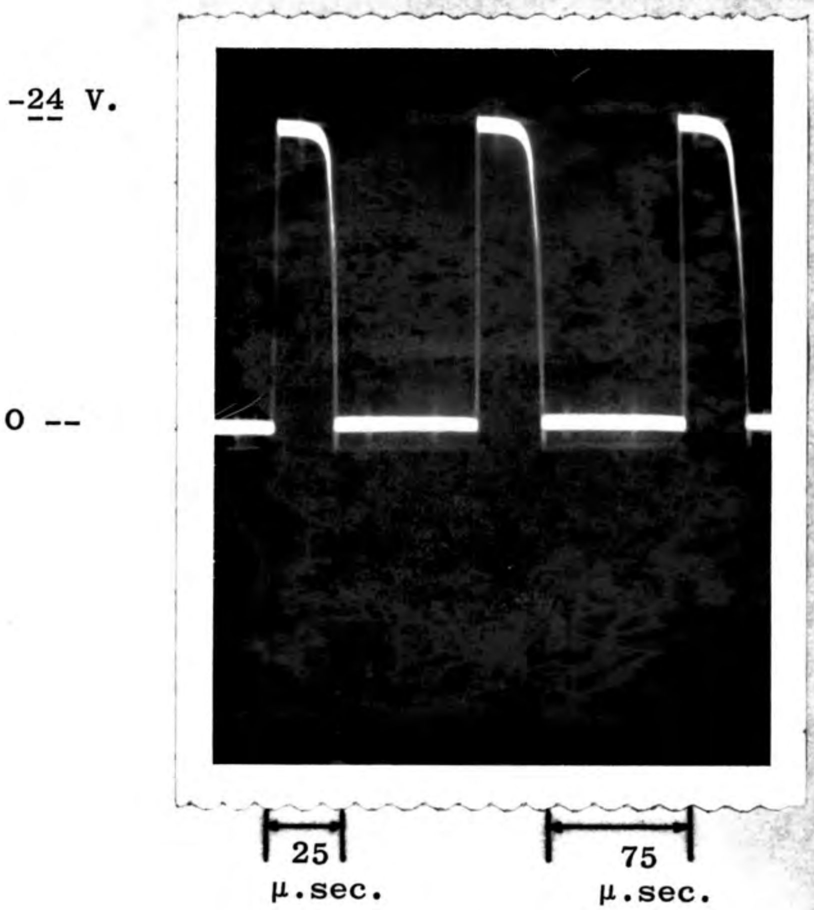
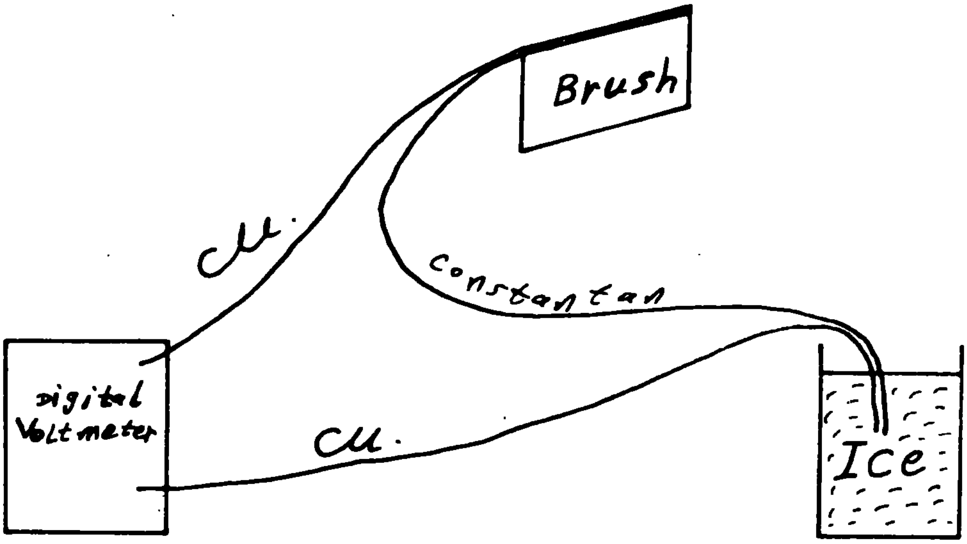


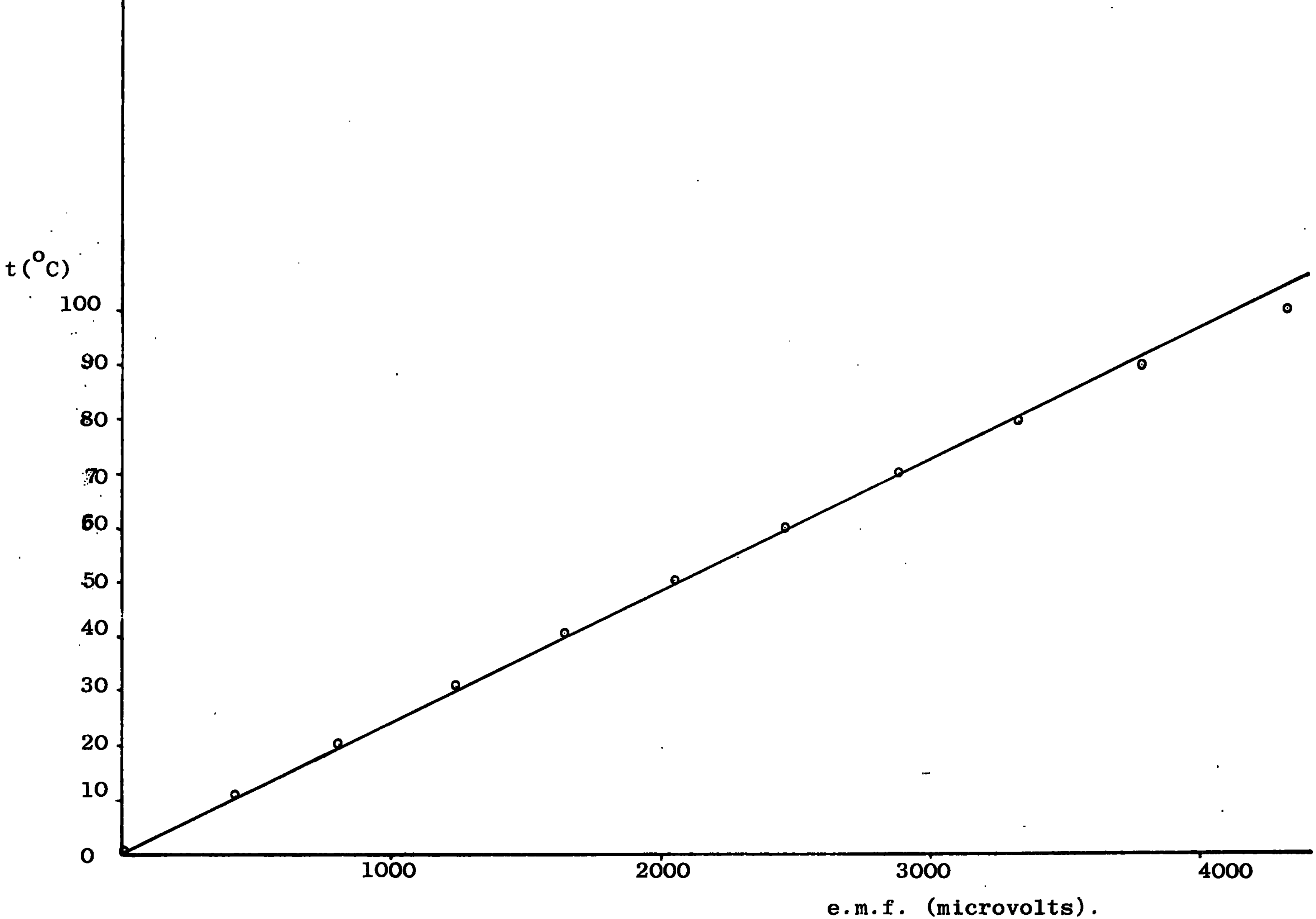
Fig. (9.2.4.)

The Voltage Wave Form of the Thyristor Gate Firing Pulses.



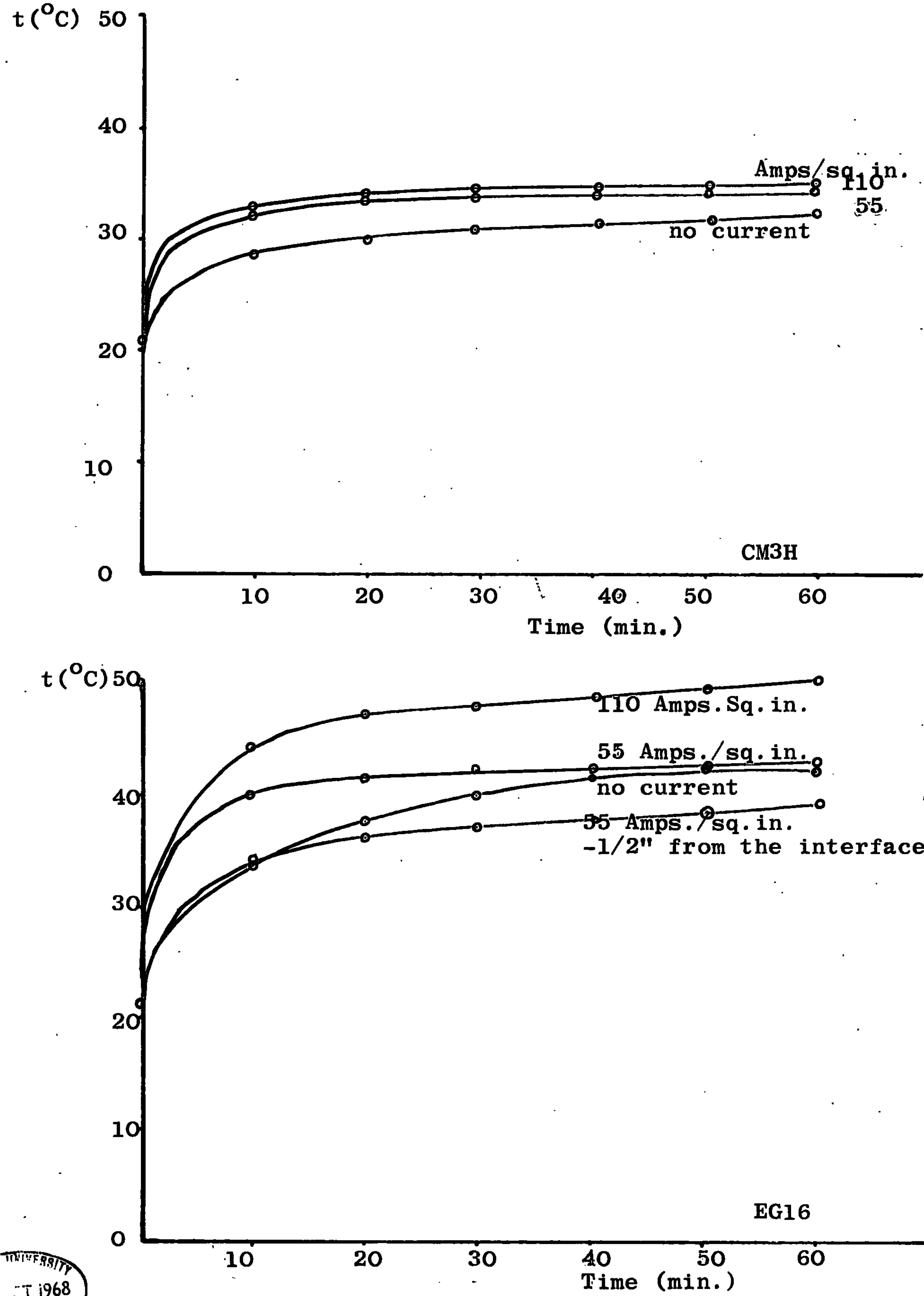
Measurements of brush temperature .

Fig. (9.3.1.)



The Calibration Curve of Temperature/Volts.

Fig. (9.3.2.)



Temperature Against Time for One Hour
with Half Sine Wave Current. *Fig. (9.3.3.)*