

is not within the scope of this paper to deal with these in detail. It may not be out of place, however, to emphasize the importance of close attention to what may appear trivial mechanical details, for experience shows that it is not as generally recognized as it should be how much the life of both brushes and collector may be increased and the general performance improved in this way. Undoubtedly it does pay to give a new set of brushes a good send-off, to see that the clearance is sufficient without being excessive, to adjust the pressure accurately by an intelligent use of a spring balance, and to bed the brushes thoroughly. The collectors should be made to run as truly as possible, and vibration due to loose bearings or want of balance should be reduced to a minimum.

Commutator surface speeds frequently reach 6,000 feet a minute and sometimes as much as 9,000 feet a minute, and the trend of design is in the direction of still higher peripheral speeds. Commutators are never mathematically circular and a very small mechanical defect is sufficient to cause a momentary separation between the brush and the collector. It is of vital importance, therefore, that the brush should be free to follow up any slight irregularities, and since a slight accumulation of dust is liable to cause a brush to stick, the question of clearance should be carefully watched, not only when the brushes are first mounted, but at regular frequent intervals.

A slight amount of dust is formed by mere abrasion; more is formed by the action of the current, especially if contact between brush and collector is poor. If this dust is allowed to accumulate in the holders the brushes will become sluggish, even if they do not actually stick. Sparking then occurs under the brush, accompanied by a transmigration of metallic particles from the "low" portion of the collector surface to the brushes, and what was merely a very slightly "low" place on the collector may rapidly develop into a flat. Thus close attention to the condition of the brushes and brush gear leads not only to a saving in time but also to a marked reduction in maintenance costs.

A large turbo dynamo equipped with over 100 brushes had been running perfectly for weeks. Suddenly it began to vibrate badly and spark violently. It was shut down at once and close examination revealed that the cause was solely due to one brush becoming stuck in its holder. As soon as this was freed the machine ran perfectly as before.

STANDARDIZATION.

From time to time this question, which is beset with difficulties, has been discussed in this country in an

informal way, and at the present time definite recommendations are under consideration with regard to standard sizes of brushes for shipboard machines. In America greater efforts have been made in this direction. The Electric Power Club, after investigating the matter for many months, have recommended for general adoption certain standards. According to these recommendations there are five permissible standard lengths between the limits of $1\frac{1}{2}$ inches and $2\frac{1}{2}$ inches inclusive (to be reduced where possible to three). There are five permissible standard widths between the limits of 1 inch and $1\frac{1}{2}$ inches inclusive (to be reduced where possible to three), and there are 10 permissible standard thicknesses between the limits of $\frac{5}{16}$ inch and 1 inch inclusive (to be reduced where possible to eight). Thus, even within comparatively narrow limits, there are 250 permissible standard sizes (to be reduced where possible to 72). This would appear to suggest that designers in America are of the opinion that very considerable latitude must be left to them in the selection of brush dimensions. The dimensions of the actual block, however, are only the beginning of the problem. There is the question of fittings to be considered. If brushes are really to be standardized as regards their mechanical design a certain degree of uniformity in the design of holders becomes necessary, so as to permit uniformity in the length and position of flexible and also in the type and size of terminal. When it comes to a question of quality this would appear to defy all efforts at standardization; except possibly on exceedingly broad lines. Even standardization of machine design would not completely eliminate the difficulties here, since the differences in brush properties are so subtle and yet so pronounced in their influence on the behaviour of a machine that it seems fundamentally impossible to harness them in a specification.

A certain measure of standardization is possible within prescribed limits. Any recommendations that could be applicable to all types of machines, however, must necessarily be on such very broad lines that they could scarcely be described as standardization. It is therefore wise to proceed by stages, including at first only the mechanical design of the brush and applicable only to machines intended for a certain class of work, such as motors and generators (excluding turbo dynamos) for shipboard use. This is the sphere in which the benefits of standardization would naturally make themselves most felt, and by proceeding cautiously in this way it may in time prove practicable to introduce recommendations of a more comprehensive character.

DISCUSSION BEFORE THE INSTITUTION, 19 DECEMBER, 1918.

The President: A Sub-Committee of the British Engineering Standards Association has at present in hand the question of the standardization of brushes. They are making a small beginning, as mentioned in the paper, in the direction of standardizing the sizes of brushes for use on board ship, but it is hoped eventually to go very much further than that and some

day to prepare a specification which will enable brushes to be specified accurately instead of allowing them to be purchased in the very haphazard way by trial and error that exists very often at present. The author is a member of that Sub-Committee and we hope that with his assistance something will be done in the not very distant future.

Mr. A. D. Constable: The paper brings home to us how little we know about the apparently simple problem of collecting current from a moving surface. Most engineers think they know all about carbon brushes, but the knowledge of the carbon-brush expert is not always transferred to the drawing office of the manufacturer of the machines. Some of the peculiar results observed with carbon brushes appear to transcend the ordinary physical laws. I think there is one explanation for nearly all these occurrences, and it is mentioned in the last part of the paper, namely, that it is impossible to make a mathematically true commutator. One can easily see that with commutators running at a surface speed of about a mile a minute any small departure from accuracy will cause the brush to leave the surface, or at any rate will vary the pressure between the brush and the commutator very greatly. That explains the rapid drop of the coefficient of friction with increase of speed. I think that the idea of a film of air between the brush and the commutator is untenable, but that we get an intermittent contact so that there is friction at one instant and practically none at another. The increase of contact drop at high speed is also explained by this intermittent contact. We have a certain resistance at the time the brush is in contact; on passing the high parts this will naturally increase when there is less pressure, and much more so in the case of separation between the brush and the commutator. We also find that the increase in friction loss may go up very greatly if the pressure on the brush is slightly increased. I think the explanation of this effect is probably that the increase in pressure at a given speed may be just sufficient to prevent the loss of contact between the brush and the commutator, therefore we get continuous friction instead of intermittent friction. One difficulty I have is in understanding the nature of the contact drop to which the author calls attention. He regards part of it as still remaining when the voltage is reduced to a point below which no current will pass. I have found in some experiments with ordinary carbon brushes, making contact with a stationary copper plate, that current will pass at any voltage so long as that voltage is high enough to overcome the very slight thermo-electric effect due to contact between the brush and the commutator. That does not seem to explain, however, all the figures that the author gives, and I should like to have some further information on that point. One would think that a brush which is actually making contact with a metal surface must always pass current when there is any potential difference at all. It would be very interesting to take some oscillograph records between the brush and the commutator at various speeds. It would tell us very much more clearly what is actually happening whilst the collection of the current is going on. The author has referred to a suction effect between the brush and the commutator. I quite believe there may be such an effect very similar to that between very highly finished metal surfaces. If the surfaces are sufficiently highly finished, no air can enter between them if they are pressed together. It is quite possible that when a brush gets thoroughly well bedded down on to the commutator this effect is obtained, and at

the extreme limit we might get a pressure of 15 lb. per square inch tending to prevent loss of contact between the brush and the commutator. With regard to the question of size, large brushes are necessarily used for large currents, but they are unsatisfactory. It is practically impossible to get a very large brush bedded down well on to the commutator, and on the other hand if we multiply the number of parts we get trouble with complication. It seems to me it would be advisable to make experiments with divided brushes for large currents, the divisions being made circumferentially. Each brush would be smaller and lighter, each would have its own tail and slide, and we might in that way get very much better results. As is well known, Professor Miles Walker uses a split brush on some of his machines, but for a different purpose. One point about the use of carbon brushes is the margin they allow for inexactitude of calculation and imperfection of material. One does get a very big margin to work on by using different grades of brush, but that unfortunately means one has to have many qualities. One can standardize sizes fairly well, and our President has done a very great deal in that respect. In the Navy we do not use very many sizes of brushes, but unfortunately we have to use several qualities. I suggest that it might be an advantage to make a greater distinction between the different qualities of brushes to avoid the danger of taking a wrong quality of brush from stock and mixing it with brushes that are not of the same quality. That leads to hopeless results. I therefore suggest that the ends of the brushes might be marked with grooves formed in moulding them. One kind of brush might have a plain top, another with grooves made parallel to the sides, and another again with diagonal grooves, so that the brushes could be easily distinguished and mistakes avoided. Such simple markings used alone and in combination would serve to distinguish six qualities. The author has referred to the question of recessing the mica in the commutator. I thought we had almost got to the position where it was accepted as necessary to recess the mica on all commutators, but recently we have found it very desirable in some large motors in the Navy to go back to smooth mica because of the trouble experienced with oil and dirt collecting in the grooves. I think that the commutators if they had been in a clean situation would have run better with recessed mica, but difficulty was certainly caused by the grooves in this case. With any commutator, success is only obtainable if the air surrounding it is free from dust, dirt, and oil. If more attention were paid to this point, better results would be obtained with many machines which now give trouble. There is one little point I should like to mention with regard to the bedding down of the brushes. The ordinary method is to take a strip of carborundum cloth and pull it to and fro under the brush. One gets a curve approximating to the commutator curve, but it is obvious that that curve is not correct since it has a radius equal to the commutator radius plus the thickness of the cloth. It is necessary to run on an average for two or three hours before the brushes come into proper contact with the commutator. The question of copper "pick-

ing" is rather difficult. I do not think we ought to call the action electrolytic, because, if so, where is the electrolyte? It seems to me it is purely the carrying over of particles of copper from the commutator by the minute sparks formed when the brush jumps from the commutator. This appears to explain its occurrence only under the negative brushes. It always seems to me a pity to use carbon brushes with a plain collector ring, but at the same time one does get fairly good results, and one probably would not get such good results easily by using metal brushes without lubrication. If too little surface is used, with high pressure as in a controller, efficient lubrication is impossible and the wear becomes excessive. If we lubricate the brush properly, the brush is separated by the lubricant from the surface from which the current is collected, and that defeats the end in view unless the lubricant is conductive. It seems to me wrong to use a high-resistance brush with a plain ring, except when unavoidable. There are four main points to observe in the design of brush-gear. First, we must have as nearly as possible a mathematically true collecting surface when running; secondly, all the brushes and parts attached to them that move must be light; thirdly, good lubrication must be provided, so that, fourthly, as heavy pressure as possible may be used in order to prevent the tendency of the brush to jump from the commutator. The more closely each of these points is met the better will be the results obtained.

Professor J. T. MacGregor-Morris: The paper gives us a number of facts connected with carbon brushes on which I think we can rely to a large extent. There are certain points upon which I should like the author to give more information, the first being with regard to the contact drop, a matter to which Mr. Constable has already alluded. How has the contact drop been measured? Has it been measured by an ammeter and a voltmeter, putting the ammeter in series and the voltmeter in parallel? The next point I wish to refer to is testing. The author refers in a general way to the contact drop of collector rings. I should like to know whether the curve in Fig. 1 is determined for a collector ring or for a commutator having no armature attached to it, or for a commutator with an armature but with the field winding not excited, or for a complete machine which is working under load. I believe that the results obtained in each case would be different. Mr. Constable has already alluded to the question of the contact not carrying current below a critical value. I do not know how low that value is, but I have measured contact drops on machines with commutators in as perfect a condition as possible, with the brushes very carefully bedded, and I have been unable to detect a point at which no current will pass. When the author speaks of sparkless commutation or no visible sparking, does he imply that there is absolutely no sparking at all underneath the brush when it is running? If that is so, then the theory may be different from that in connection with the potential difference across an arc. I should like to illustrate some comparative results obtained for the contact drop on a 2-kw. machine. The machine was driven by a separate motor, its fields were not excited,

and a current was sent through the armature from a separate source, and the voltage across the machine and the current flowing were measured (see Fig. A). The curve is very much like the author's curve, but my experiments showed that beyond the curved piece, the curve becomes straight. It is true that the current density did not exceed about 12 amperes per square inch, and I believe that when we get to much higher values another effect is introduced, a grosser kind of sparking, which suggests a possible reason for this curve turning off as shown in the paper. If we take a microphone, which has a large number of contacts.

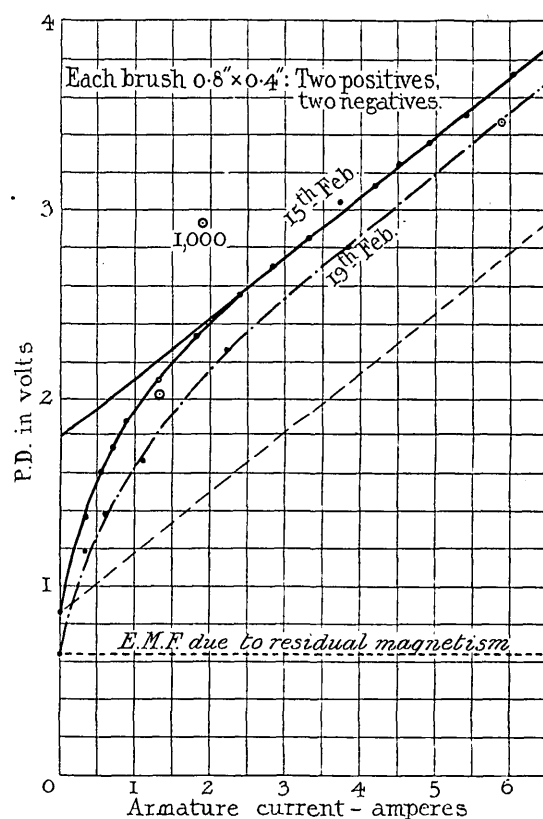


FIG. A.

Speed constant of 110-volt motor at 500 r.p.m.
Only residual field acting; no current in shunt winding.
Driven by another motor, various currents were passed through the armature and the drop at the brushes was measured.

in parallel as well as in series, the volt-ampere curve would be like Fig. B, which resembles the previous curve. I suggest that the theory underlying the microphone contact may be the same as that which underlies the single contact used in the motor. There is perhaps another method of measuring the contact drop. I have suggested that if it be measured when the machine is working on full load, it would be different from the contact drop at no load. [The Author: My curve was taken on a short-circuited commutator.] For practical work one wants to know the contact drop when the machine is on load, and that is much more difficult to obtain. I have attempted to obtain it in the way shown in Fig. C, but have so far failed. Three machines like an ordinary booster set are used. Two

of the machines are identical, and the other is a small booster. Those two machines were for 240 volts and were connected as in the Hopkinson test, whilst the small machine kept the set running, so that it supplied the friction, windage, hysteresis, and eddy-current losses. The voltmeter reading gives correctly the

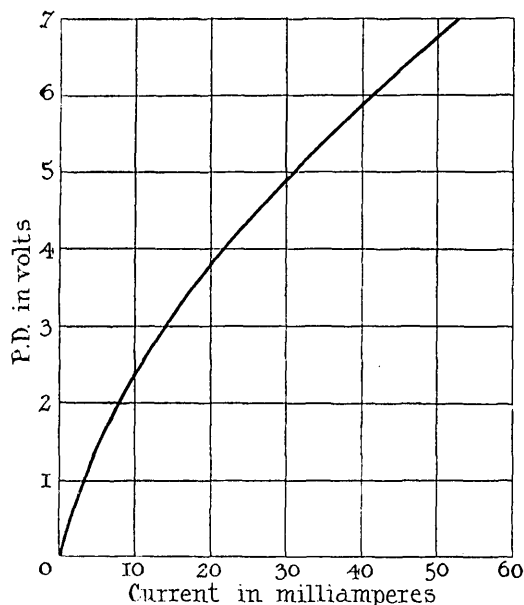


FIG. B.—Volt-ampere characteristic for a standard form of microphone.

contact drop at very small loads when the armature copper drops have been deducted. But unfortunately on load one machine works as a motor and the other as a dynamo, so that one field is distorted forwards and the other backwards when loaded, and a back electromotive force is therefore introduced into the

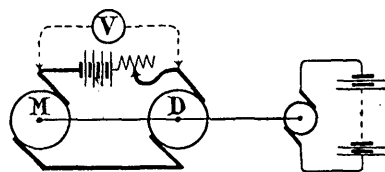


FIG. C.—Diagram of connections.

circuit, which upsets the measurement. In order to correct for that we should have to shift one pair of brushes backwards and the other forwards, or determine experimentally the magnitude of this correction. I do not know whether anything practical can be made of this suggestion, but I do feel that it is important to obtain measurements with the machine on load.

Mr. R. Orsettich : I should like first of all to refer to the universal brush which the author appears to have dismissed as an impossibility. I would point out that when dealing with this problem we have to consider different classes of machines. Large generators are always ordered and kept supplied with a reasonable amount of spares, and these are available in the correct quality and quantity when required.

The same remark applies to large users of motors, who can afford to keep an engineering staff to look after them. The user of small motors, however, who owns only one or two machines, generally has no spares. Whenever his brushes are worn out, this is usually indicated by excessive sparking, and he has to obtain a set of brushes from stock from an ordinary dealer. It is absolutely impossible for such dealers to have available all qualities and makes of brushes, and usually the nearest best brush is taken and the motor run with it. It seems to me, therefore, it is essential that in making these machines and selecting the brushes, we should take care of that fact. I believe a universal brush has been produced by the firm with which the author is connected, and I believe it has proved very satisfactory indeed for average conditions. I can say from experience ranging over six or seven years that this brush has proved perfectly satisfactory for machines of between 300 and 460 volts. It is not a purely graphitic one; it has a fair amount of abrasiveness, and on the whole it works exceedingly well on ordinary motors. It seems to me that, if this brush could be further developed, we should not be so far from the condition which the author seems to think is very far ahead. Dealing with the question of leads and connections, it seems to me one point should be mentioned, viz. that the leads should always be twisted and not braided. I have had a great deal of trouble with braided leads in the past, and I now always specify only twisted leads. I believe the majority of engineers are adopting the same view, because twisted leads, when they do heat, can be untwisted and a larger cooling area provided with practically no other alteration. The question of the connections has already been raised. There are some brushes which have the flexible lead fixed by means of a short tube, riveted at both ends of a hole drilled through the body of the carbon. I have recently had to replace a large number of brushes made in this way which, for some non-apparent reason, broke right across. I explained the trouble through difference in expansion of the carbon brush itself and the copper or metal tube which was used for making the connection. In regard to the operating conditions of brushes, I missed from the paper a discussion of the oscillating gear as supplied to slip-rings and commutators of rotary converters. This is often specified, although there is no clear reason why it should be used on these machines more than on others where similar conditions obtain. Probably this is due to a kind of fashion, which started originally from the necessity of assisting the brushes in cleaning the surface of the commutator or rings, some artificial glutinous substance being applied to help in the lubrication. As machines are made to-day there should be no reason to provide such gear, which, without doing any good, causes the serious trouble of producing a convex surface on the brush and a concave path on the rings or commutator. The best way in which one could comply with the condition, if it be specified, would be by making the travel of the commutator as small as possible. Another point which has not been raised in the paper, is the artificial lubrication of rings. For some reason, makers of brushes appear not to have

been able to produce a brush which is sufficiently metallic to collect current at very high current densities and at the same time sufficiently self-lubricating to reduce the wear on the slip-rings, and the habit has been introduced of using brushes which have a very high co-efficient of friction and adding a wooden brush, or one made of some other fibrous material, dipping in a container filled with oil. This has been recently adopted in several stations, and it seems to me to be desirable that makers of brushes should eliminate such a makeshift arrangement and produce a brush which is sufficiently self-lubricating to avoid the necessity of artificial lubrication. Another point I should like to mention is the use of a curve indicating the voltage drop across the brush to show the distribution of current in the contact surface. This curve is nowadays practically standardized by all makers, and it is the only criterion we have for the purpose of adjusting the strength of the commutating poles, unless one should test the machine at full load. In view of the importance of this curve and of the information which it gives, I think it should be considered and criticized further. I should also like to know if the author has endeavoured to determine the maximum voltage which can be short-circuited under the very worst conditions between the extreme tips of the brush (this is the "apparent" short-circuit E.M.F. of the brush). Mr. Lamme read a paper at San Francisco some three or four years ago in which he discussed this matter at some considerable length. He then stated that under the very worst conditions he would never consider a higher pressure than 30 volts between the tips of the brush. I believe that most of the designers in this country were astounded by that figure, and that most brush manufacturers would also object very much to guarantee a brush which would work under such conditions, especially as Mr. Lamme showed in that paper that the adjustment of the commutating poles must be improved at the same rate as the voltage is increased, so that a brush which has 30 volts across it must have commutating poles adjusted within 90 per cent of the correct value when working under the conditions represented by this voltage. In connection with the standardizing of new brushes, the fact that the Electric Power Club has contemplated as many as 250 different sizes seems to me worthy of consideration. The point which must not be lost sight of is that there will always be a very large number of old-type brushes required as spares for machines now running, and that a good many of the sizes of these brushes could be retained for new standards. The standardization will have already achieved a great deal if we should not require to increase the number of brushes for the future. We must not, however, make the new standards too few or with too great gaps amongst them, to avoid either handicapping progress in machine design or compelling makers to go outside the standards for new designs. Further, standards should not be concerned with the quality of the carbons, but only with their dimensions; they also should not consider anything but the simplest forms of connectors and their fixing, and should always keep in view the possibility of having to shorten or

narrow the body of a brush in order to adapt it for some other dimensions for which no other brushes are available. For this reason, copper covering of brushes should not be admitted as a standard feature. As approximate standard sizes I should like to suggest the following:—

- (1) Length: 1 in., $1\frac{1}{4}$ in., $1\frac{1}{2}$ in.
- (2) Thickness: $\frac{1}{4}$ in., $\frac{3}{8}$ in., $\frac{1}{2}$ in., $\frac{5}{8}$ in., $\frac{3}{4}$ in., $\frac{7}{8}$ in., and 1 in.
- (3) Width: $\frac{5}{8}$ in., $\frac{3}{4}$ in., $\frac{7}{8}$ in., 1 in., $1\frac{1}{8}$ in., $1\frac{1}{4}$ in., and $1\frac{1}{2}$ in.

These, after eliminating some combinations which do not answer practical cases, would give about 120 sizes and should fill most requirements, even for special machines.

Mr. J. McI. Cater: There is one thing I should like to say with regard to standardization. I have examined the lists of brushes which many well-known machine manufacturers require my firm to hold in stock for them, and I find that the number in one of them is 76, in another 53, and in a third 42, whilst the average of a considerable number of lists is something like 30. Standardization, therefore, it seems to me must first come from the machine builders and then the brush makers will be only too pleased to follow suit. One speaker has referred to the use of what he describes as practically a universal brush. I am pleased to think he has found something which so nearly approaches his ideal, but I venture to think as the representative of a concern in rivalry with that to which the author of the paper belongs that there will still be room for both of us in the manufacture of brushes for a very long time to come.

(Communicated): Abrasion is very frequently referred to in the paper, but in the experience of my firm it is quite exceptional for constructors using mica with a normal degree of hardness to specify that the brushes they require should have special abrasive qualities. It seems necessary, on the contrary, to emphasize the fact that an average high-grade carbon brush with or without graphite (excluding soft graphite brushes used on high-speed machines) will operate perfectly satisfactorily for years on machines with flush mica without any appearance of mica trouble, and this is well known to British constructors of electrical machines, as the result of their experience extending over 20 to 25 years. Innumerable instances could be cited of brushes containing no abrasive material producing splendid commutators without mica trouble and with a wear of the commutators so small after years as scarcely to be measured. It is almost a truism to say that a brush maker must never think of abrasives and that his products must be such as to be essentially non-abrasive. Some people have the mistaken idea that abrasive brushes are the best remedy for the prevention of blackening. Blackening is the result of unsatisfactory commutation, and may sometimes be cured by a non-abrasive brush having a higher contact resistance. As stated above, it is quite exceptional for inquiry to be made for brushes with special cleaning properties either with or without graphite, and such few cases as occur certainly do not exceed, say, 5 per

cent. These relate for the most part to brushes required for train-lighting dynamos, regenerative control, or similar purposes. I do not, of course, deny that for any particular machine suffering from proud mica the application of abrasive brushes is at times a remedy, but the case is an isolated one. On page 202, col. 2, the author says: "When the mica is well recessed a high-grade non-abrasive graphitic brush may be used, and the wear of both commutator and brush is reduced to a minimum." I do not agree with this statement. On the contrary, I maintain that experience shows that in most cases soft brushes are detrimental to commutators. Their use may result in a machine being enabled to operate satisfactorily, which is the main consideration, but this is at the expense of the commutator, and the latter frequently assumes a wavy appearance. I am obliged in fact to confess as a brush manufacturer that although in the case of high-speed machines with recessed mica soft graphite brushes supposed to be essentially non-abrasive and containing in fact no kind of grinding or polishing element in their composition should operate without commutator wear, the general rule is that the wear is incomparably more accentuated than with hard or medium hard brushes. This wear is so considerable that to prevent grooves and waves oscillators are frequently provided. On the other hand, when electro-graphitic brushes are substituted for the soft graphitic ones oscillators are unnecessary. To what is this wear due? The phenomenon is difficult to explain, but is possibly due to ionization occurring as the result of eddy currents under brushes which make very intimate contact with the commutator and follow it more closely than would be the case with harder brushes bearing on relatively fewer points of the collector. That the phenomenon may be of a purely mechanical nature is very difficult to say. As regards slip-rings, what I have just mentioned also applies, the wear with pure graphitic brushes being far greater than with the electro-graphitic. I believe that most textbooks and previous literature on this subject refer to the + or positive brush in the dynamo sense, i.e. collector to carbon, and the other brush as the negative one. This may be mere convention, but as the author uses the term positive brush in the motor sense it may be a point worth mentioning. One speaker in the discussion raised the question whether the curve in Fig. 1 should pass through zero. A test made in our laboratory has shown that it does so. The high thermal conductivity of a graphite brush does not satisfactorily explain why the flexible conductors on graphite brushes are liable to burn out, and I should like to add a few words on this subject. As has been stated in the paper, soft graphite brushes have a contact drop which is practically constant over a certain range of current, even with heavy loads. Now on a perfectly good commutating machine it may be admitted that, owing to some very subtle causes, an unequal distribution of current takes place. This, when started, rapidly accentuates itself, as the heating of the brushes which suddenly happen to be more heavily loaded than the others reduces their specific contact resistance and aggravates the instability under these conditions to

such an extent that it gets out of control, and one particular brush probably grabs some hundreds of amperes, causing the flexible to fuse although the brush does not glow. The remedy for this trouble should be sought in the selection of brushes whose contact drop is not too greatly influenced by temperature rise. It may be of interest to mention here that, as a rule, brushes taking current from the collector show with a rising temperature a considerably smaller decrease in their contact resistance than those giving current to the collector, the figures being about 25 per cent from 30° to 60° C. in the former case, and about 50 to 60 per cent from 30° to 60° C. in the latter. This explains why, in unfavourable cases, with heavy loads, and heating of commutator the negative brushes of a generator are the first to spark. Before leaving this subject, I should like to say that I believe a reason for the grabbing of heavy currents by soft brushes, without glowing may be found not only in the high thermal conductivity but also in the softness itself, combined with the innumerable points in contact with the commutator. On the question of size of brush, much more might be said. To a very great extent the limit of size is controlled by the current to be carried, and relatively more current can be carried by a small brush than by a large one. Observations have been taken on a very large number of machines, and the results plotted for the purpose of showing the proportional decrease of admissible current densities. The following table shows the kind of results obtained:—

Grade	Permissible Current per Brush having a Contact Area of		
	$\frac{1}{2}$ sq. in.	1 sq. in.	2 sq. in.
Carbon	16	26	47
Electro-graphitic..	24	42	68
"	33	54	83
Graphitic	36	58	92
Copper-graphite ..	47	90	140
Bronze-graphite ..	67	130	210

This table shows that if on an alternating-current machine with 10 copper-graphite brushes on each ring, each brush having a contact area of 1 square inch and a load of 90 amperes per square inch, one brush were for any reason to stick in the holder, the remaining nine would be overloaded by 11 per cent, whereas if the number were increased to 20, and the contact area of each halved, the overloading would be diminished to about 4 per cent. This, of course, is an exaggerated case, but serves to illustrate my point, which I venture to think is of considerable importance in view of the very large slip-ring brushes that have been fitted by some constructors during the last year or two. I should like to suggest that the maximum current per brush should be standardized, and for the sake of discussion I propose, say, 60 to 70 amperes per brush for direct-current and 100 or 125 amperes per brush.

for alternating-current machines. When brushes are to have fittings added, it is distinctly advisable that the carbons should be coppered. The reduction in the resistance between a brush and its fitting is in the ratio of 10 to 1 for coppered and uncoppered brushes respectively, and this fact alone shows the advisability of coppering carbons under the fittings. The spring pressure on a brush should be reduced to a minimum, and it is probable that even in exceptional cases the 6 lb. per square inch mentioned by the author for traction brushes is excessive. American experience shows that on good commutating traction motors a light spring pressure, particularly with electro-graphitic brushes, is most desirable. It should undoubtedly be the aim of every engineer so to maintain his gear as to avoid excessive spring pressure. The author mentions that Admiralty gunmetal (88 per cent copper, 2 per cent zinc, 10 per cent tin) has been found excellent. Another mixture for slip-rings which has given very satisfactory results contains 90 per cent copper, 8 per cent tin, 2 per cent phosphuret of copper. It seems difficult to admit the possibility of electrolytic action in the case of a.c. slip-rings on account of the continuous change in the direction of the current. Copper picking usually occurs when working conditions are unfavourable, and particularly when heavy currents have to be dealt with. Heating then takes place, and as the contact between the brush and the collector may be described as being made at a large number of points, copper is deposited round that zone where the contact is most intimate; dust is next caused by the brush eating into the ring, and an accumulation of copper results. The same difficulty may also occur with copper and graphite brushes when very heavily loaded, the sequence being (1) heat, (2) volatilization of copper, and (3) quick wear of the roughened surface. The author states that when a few graphitic brushes are mounted on the same slip-ring with metallic brushes, the former having a contact drop so much higher than that of the latter will carry no current whatever, and that incidentally there is no need to fit them with flexibles. I do not agree. Measurements just made to determine this point have shown that on a 1,500 kw. rotary converter fitted with a mixture of bronze-graphite and graphitic brushes the former carried 125 and the latter from 4 to 5 amperes per brush. The author's statement would only be correct if there were a minimum contact drop below which no current would pass; but as this is not the case, all contact curves passing through zero, the graphite brushes necessarily follow the law $I = E/R$ (E being the volts between the ring and stud and R the total of the resistances, including the contact resistance). It is probable that the ionization of plumbago is a material aid to the lubrication of the ring, and that even if the current be so small as 1 ampere it has a beneficial effect. In these circumstances it is manifestly advisable to assist the lubricating effect as far as possible by fitting the graphite brushes with flexibles.

Mr. H. Brazil: The cutting away of the mica between commutator segments is now recognized to be the best practice in almost every case, but it is very necessary to be careful not to cut too deep. In a case

I had under observation, where a dynamo was directly coupled to a Diesel engine, the vaporized fuel-oil deposited between the segments became carbonized, causing arcing between segments, and this arcing burnt away the mica to a considerable depth, necessitating re-making of the commutator. I was very interested to hear what the author had to say about the partial vacuum formed between the brush and commutator increasing the coefficient of friction, and while quite agreeing that tests taken in the laboratory would be of value, I think that one cannot apply any quantitative measurements obtained there to actual practice where it is impossible to eliminate dust. A point that interests me very much is the addition of a small quantity of abrasive material to the brush, and the effect this has upon the running of the machine. We had a rotary converter, the commutator of which was working at 4,700 ft. per minute peripheral speed, and the brushes at 33 amperes per square inch. The brushes contained a certain quantity of abrasive material, and the machine ran very satisfactorily, except that the amount of copper dust due to the abrasive action was rather larger than was expected. To get over this, a set of brushes having, I believe, about 4 per cent less abrasive material in them was tried. The commutator was ground up perfectly true to start with, but after eight days the brushes were sparking so badly that the machine had to be shut down. The commutator was re-ground and another trial was made, with precisely the same bad result. The commutator was ground once more and the old brushes put back, with the result that except for the amount of copper dust, the machine has run quite satisfactorily ever since. This case emphasizes the importance of small details and of keeping the commutator clean by adding a suitable amount of abrasive material to the brush. With regard to brush holders, the sliding type with flexibles embedded directly in the brush appears to be recognized as the best practice, and I am glad the author emphasizes the importance of making the brush holders very solid. I had some experience of a rotary converter with brush holders made up of sheet brass, with springs pressing the brush against the side of the box. Various springs were tried and adjustments made, but the running was very unsatisfactory due to the tendency of the brush, after running for some time and forming a good surface, to get tilted and start forming an entirely different bevel. These brush holders were replaced by the solid cast type with a very small clearance between the brush and box, and this type has proved to be excellent. On the question of flexibles, I think that as large a section as possible should be provided, having due regard to the free movement of the brush in its holder, and to obtain this result it is better to use four small flexibles than two large ones. An arrangement I have used and found very satisfactory, as it does away with all sweating of thimbles, is to fix two flexibles so that they come out at one end of the brush and re-enter at the other, thus forming a loop. The centre of the loop is twisted round the screw in the brush holder, and the whole arrangement is the equivalent of four flexibles with thimbles on each. With regard to slip-rings, it seems impossible owing to the

presence of dust, and to the slight variations of hardness in the brush and the ring, entirely to prevent grooving, but as long as the groove and the brush fit one another no appreciable heating results. The obvious cure for this is the armature end-play arrangement mentioned by Mr. Orsettich; but I am entirely in agreement with him that it is not satisfactory. We have tried it and given it up, as it introduces trouble on the commutator end.

Mr. H. F. Joel, jun.: Some years ago I attempted to prepare a paper on this subject. I had through my hands something like 100 different kinds of brushes and 30 different kinds of mica, but I had to stop, owing to the war. I find, however, that the majority of my data is confirmed by the present paper. One of the great difficulties I found was that the mica varied so much in hardness, that with abrasive material in the carbon it was impossible to keep the mica in its place. By cutting the mica into the sizes required, separating them with little sheets of nickel, bolting several complete sets between iron plates and making them red hot, I found that even a soft brush would keep the mica in its place. The mica under these conditions was not injured from an insulation point of view. This is good practice with pure mica, when we can see what grade we are using, but with built-up mica, when any old scrap can be and is used, it is of the utmost importance if we wish to avoid flats and trouble. The cement should have a very low carbon factor and probably gum tragacanth and water is useful. I suggested to a carbon maker that he might make some brushes in which the abrasive material was mica, which I find is perfectly satisfactory and cuts away the mica in the commutator without touching the copper. There is no difficulty in designing a machine to suit any carbons, and at most three grades should cover all requirements. (1) "S" type, "Le Carbone" with mica abrasive for high-voltage machines. (2) Electro-graphitic with mica abrasive for low-voltage machines. (3) Electro-graphitic with copper for slip-rings. Unfortunately, many machines are designed and the brushes are experimentally fitted on the test bed. The commutator is skimmed in axial length, and to keep the current density of carbon within reasonable limits makers have to use a wide (circumferential) brush. This gives rise to large circulating currents within the brush, great heat, and a multitude of quantities of carbons, which is not conducive to intensive production or economy. I agree with Mr. Orsettich that all small motors up to 10 kw. should be run with any brush. As a maker of small machines I find that when the machines are sold the customer seldom asks the maker for a brush, but goes to the nearest brush factor, and it is essential that they should run well with any ordinary brush. The under-cutting of commutators is an evil to overcome, an evil caused by the hard mica. If one can keep the mica in its place, undercutting is quite unnecessary. My experience with slip-rings is that in the majority of cases the brushes used are copper carbon, and the rings are copper. I suggest that if copper rings are used, we should use iron in the brushes, or, better still, cast malleable iron or steel rings and copper-carbon collectors, as copper

or brass slip-rings are only a conservative convention and unnecessary, and it is well known that dissimilar metals work better together as bearings than similar metals.

Mr. P. R. Friedlaender: I wish to refer to the difference that the author mentioned between negative and positive brushes. I recently made some experiments on some very small series motors, running at about 10,000 to 15,000 r.p.m., which were normally quite sparkless, but whenever the mechanical balance of the armature was faulty these machines showed a very peculiar sparking effect, the sparking being practically confined to the negative brush. There is only a single brush on each side, so that mechanical vibration at these very high speeds is liable to break the circuit by throwing the brush right off. The sparking is quite characteristic. The positive brushes show a slight red sparking, whilst the negative brushes show a long blue spark, perhaps $\frac{1}{4}$ inch long, drawn out round the commutator in the direction of rotation. If the polarity of the supply is reversed the sparking is transferred from one brush to the other. The effect seems to be due to some commutator copper being vaporized where the current passes from copper to carbon through a bad contact. It is also clear that the current is intermittent, from the fact that an appreciable shock can be felt across the field winding, although the normal drop there is only 3 or 4 volts. This is purely a mechanical effect, because the same machine with a copper-leaf brush or with greatly increased brush pressure will not spark at all. It is a question of arranging a brush so that only one part lifts at a time. Neither of those remedies, however, is satisfactory, because of increased wear. The mechanical balance must be put right. Very many of the troubles mentioned by the author would be got over by something like a flexible carbon brush. It is not a practical proposition at present, but I have made experiments—and I expect that many other people have done the same—with the object of getting something which will have the qualities of a carbon brush as regards conductivity and contact resistance, but otherwise resembling a piece of asbestos. It is not obtainable at present, I know, but over 30 years ago Mr. F. H. Varley took out a patent for a flexible carbon for use on an arc lamp. I have tried material made to that specification, but it is not workable as a brush, as it is not tough enough. It seems to me, however, that it is not an impossible proposition. Such a brush would resemble a copper gauze brush, in being able to raise itself in parts without leaving the commutator completely, in spite of a certain unavoidable amount of mechanical irregularity.

Mr. H. K. Whitehorn: Since carbon brushes are used far more on commutators than on slip-rings, if the results given were more directly applicable to commutators than to slip-rings they would have been more valuable, but it is difficult to get reliable results of contact drop from anything but slip-rings. The difficulties of making measurements on a commutator, particularly with the field excited, are due to the circulating currents in the short-circuited coil, which interfere with the results obtained. There are four

important points in relation to the use of brushes on commutating machines: (1) grade; (2) spacing, which is overlooked in the paper, although the author mentions some mechanical points; (3) the fit of the carbons in the holders; (4) bedding. It is impossible to exaggerate the importance of making the mechanical conditions as perfect as possible. I am convinced that a great many troubles that are now thought to be due to the carbon will be found to be due to incorrect spacing of the carbons round the commutator. A good plan is to wrap paper tightly round the commutator, and then cut a mark on it with a flat blade pressed against the side of the holder. The measured distance between the marks must be adjusted to be equal within $\frac{1}{2}$ per cent. If lowering of micas be done at all, it ought to be done thoroughly to get success. Dealing with machines up to about 100 h.p., narrow brushes will be found, from several points of view, to give extremely good results. It is difficult in discussing a paper on carbon brushes to eliminate questions affecting the design of the machine. The following are figures of a 25-h.p., 4-pole, 110-volt, 1,000-r.p.m. machine, with a 9-in. diameter commutator. A soft graphitic brush (type B), four bars, three carbons per bar, 1 inch by $\frac{7}{16}$ inch, giving a current density of 70 amperes per square inch (the makers recommend 60) gave in three hours an armature temperature rise of 50 degrees C. and a commutator rise of 89 degrees C. Using the same number of brushes, 1 inch \times $\frac{5}{16}$ inch, still called by the makers a soft graphitic brush (but type H.M. 6), gave a current density of 98 amperes per square inch, and after $5\frac{1}{2}$ hours the armature temperature-rise was only 35 degrees C. and the commutator rise 30 degrees C. with sparkless commutation. The micas were lowered in each case. It is an instance showing that brush selection is very important. The machine is on full load six days a week.

Mr. A. B. Eason: I want to ask two questions. If the curves which the author has given are plotted on log paper it will be found that the contact voltage-drop takes the form of a law:—

$$\text{Contact drop} = \text{Constant (Current density)}^n.$$

I worked out some of the figures and they show that no matter how far the density is reduced, current still flows, and that the figure 0.74 given by the author really does not exist. I should like to ask him if he could give the values of the constant and of n as found from all the tests connecting contact drop with density. I next want to refer to undercutting the mica. The author suggests that it is useful when the commutator runs at high speeds. Would it be useful at low speeds? If not, where would he draw the line between high and low speeds; at 2,000 or 3,000 or 4,000 ft. per minute? Two papers dealing with brushes might be referred to. The *Revue Générale d'Electricité* (1918, vol. 4, p. 115) has a paper dealing with the standardization of carbon brushes in France. One standard adopted is of the type—objected to by one speaker—which has metal plates riveted to the brush. Martindale (*Proceedings of the American Institute of Electrical Engineers*, 1915, vol. 34, p. 973) deals with the general use of brushes on commutators in practice.

Mr. L. B. Atkinson: It is some years since I have had the opportunity of studying in any great detail the question of brushes; but in the earlier days of the dynamo, when sparking was a much more difficult question than it is now—at all events in smaller machines—it was a subject to which I gave a very great deal of attention. The first patent I ever took out was for a brush that prevented all sparking, and that brush had in it the principle that lies at the root of carbon brushes, namely, a transverse resistance, a resistance between the point and the heel. These brushes were made of copper layers with resistances between each layer, and enabled machines that ran very badly with certain currents to carry two or three times those currents, so far as sparking was concerned, without any difficulty. This type of brush was discussed before the Institution not very many years ago by Mr. Mordey, who gave some very interesting results of his own experiments on a similar type. Two things, however, happened. First of all, dynamos were very much improved, so that the question of commutation was less important. Then came the invention of the carbon brush, and from that time onwards we have moved forward. But still I feel that it is difficult to say whether the carbon brush has been more of a blessing or a curse to the industry. It tided us over a point so that we were able to do a great many things at a time when otherwise they could not have been done. That particularly relates to the tramway and the locomotive motor. It seems to me there are two ways in which we may look at the carbon brush. To begin with, everybody will admit that to try to collect current from a solid commutator by means of a solid brush, fitted as well as it may be, is mechanically and electrically the worst possible way of doing it if it can be done in any other way. But first in the case of small motors that will be in inexperienced hands and where the commutation is not difficult to deal with, it is a great convenience to have a brush that does not alter its shape. Once fixed in position it stays until it is worn out, but that does not necessarily involve a carbon brush at all—it might really be a solid metal brush. We naturally use carbon because it keeps its shape, but it is purely an alternative. Then we have the use of carbon brushes to adjust the commutation when we have not succeeded in producing a true electro-dynamic commutation. But what are we doing? We are at once lowering the efficiency of the machine. It would perhaps have sparked so badly that we could not use it, so we fit a carbon brush and the energy which was going before in the spark is now being wasted in the brush. That is where the carbon brush has been, I think, perhaps a curse to the industry, because it has enabled us to use machines of inefficient design which we should have corrected if it were not for the simplicity of this solution. The number of brushes that have to be made of different qualities shows the extent to which they are being used as correcting agents for really incorrect designs and incorrect constructions. The point at which the carbon brush became absolutely imperative in my own experience was when we came to the slotted armature. The old smooth-core armatures did not require carbon brushes,

and if we had those to-day I do not think we should need carbon brushes. I think the use of carbon brushes with slip-rings is really inexcusable, and I do not know why it should be done. I have never found anybody who could give me a proper reason for it beyond the fact that people like a brush which once inserted need not be taken out again. A previous speaker queried the use of flexible carbon for brushes. I have used brushes having metallic layers with Varley flexible carbon in between the layers as a resistance. Used in that way we are not employing carbon to collect the current, whilst as a resistance it is very effective. We can also make brushes with metallic resistances between the layers that collect the current very well and have a very considerable commutating effect. One item in the paper which interested me very much was the question of a fixed contact drop across the brush. The curve is fairly convincing, but on the other hand Professor MacGregor-Morris has shown us that certain other conditions arise. I think it is a question that we ought to settle, because if the author's statement is correct we have an element there that does not exist in the metallic brushes that I have been speaking of, and that is not ordinarily taken into account in the discussion of the carbon brush for a commutating purpose. I should like to hear a little more about that from the author in his reply to the discussion, and it may be that further research is necessary on the point.

Mr. A. A. Pollock: I should like to call attention to what I consider to be an incorrect statement in the first column of the paper, where the author, in speaking of commutating-pole machines, says that the commutating flux is correct for one value only. I maintain—and I think all other designers of electrical machinery will also maintain—that the flux is substantially proportional to the load up to the point where saturation begins, and that point on a properly designed machine should not occur until the maximum prolonged overload is reached, i.e. about 25 per cent overload. The general impression I received on reading the paper was that the author considered the designers of electrical machinery to be very haphazard people. I think the reason is that he had had to deal with such a large number of ancient machines, and that if he had had only up-to-date machines to deal with, fitted with commutating poles and properly adjusted, many of the remarks he has made would not apply. Speaking of my own experience of machines over, say, 100-kw. capacity, it is our practice so to adjust the strength of the commutating field that there is substantially a constant voltage drop across the brush from the heel to the tip, and this makes it possible to use a low-resistance high-grade good-lubricating brush. We use practically one class of brush on all machines of the larger sizes, and I think there are only one or two cases where we have had to change the brush in order to help commutation. There are cases where changes in brushes have been found desirable, but not necessary from the commutation standpoint. With respect to ring wear, the author gives on page 197 some data regarding the rate of wear of slip-rings with pure graphite non-abrasive carbon and abrasive carbon

brushes, without any current flowing. It would be very interesting to know what rate of wear he has found with a copper graphite brush under similar conditions. It may be of interest to mention that we made a test, among very many others, with slip-ring brushes of one of the Morgan Crucible Company's grades. It was a copper graphite brush running at 100 amperes per square inch; peripheral speed 3,800 ft. per minute, and a pressure of 2 lb. per square inch. This brush was run for 44,000,000 revolutions and showed a radial wear of the ring of 0.052 inch for 20,000,000 revolutions, which is getting towards the figure given by the author for the abrasive carbon brush without current. In this case alternating current was flowing. With respect to the question of the varying contact resistance and varying friction coefficients observed at different peripheral speeds, I think the author's suggestion that an air film exists under the brush is the correct one. An extremely minute air film would not appreciably affect the contact, although it would certainly affect the contact drop. The question of the contact resistance dropping with increase in temperature might be explained by the rarefaction of the air due to heat expansion and the consequent squeezing out of the film a little more. I think it would be interesting if the author could conduct some tests *in vacuo* to settle definitely this point, because if he were sure of the ground on which this theory was based it would be very useful in designing certain classes of machines. With reference to the question of the wear of slip-ring machines, referred to on page 202, it would be very interesting if the author could give us the duration of the test on which these particular curves were plotted, and how it varies with graphite brushes, because I believe that with the latter very good results would be obtained. With respect to the sizes of brush, I should like to say that I am in thorough agreement as to very large brushes being unsatisfactory in service, but I think it is distinctly advisable to make the size as large as possible, consistent with satisfactory operation, because of the reduction effected in cost of brush renewals.

Mr. R. S. Allen: There are two points which stand out very clearly before me to-night. The first is the question of standardization of grade, and in this connection I agree with Mr. Orsettich that the number should be reduced as far as possible. The fact that he has found a series of machines to run satisfactorily with one grade of brush is evidence in this direction. Curiously he has adopted the "A" grade as a standard, whereas our experience has led us to adopt the "C" grade for most machines working at pressures from 100 to 600 volts. The second point which has not been touched upon is the advantage of low inertia of brush, especially in high-speed machinery. The continuous succession of "bumps" in commutators (the result of a cylinder built up of segments) have to be regarded, for if one has a brush which will immediately respond to those bumps, the result is less wear and general better behaviour of the commutator. I have in mind the case of a 4,000-ampere 100-volt generator which was originally fitted with "B" grade brushes, the characteristics of which are low coefficient

of friction and low contact drop; the temperature rise was, however, very considerable. On consulting the Morgan Crucible Company they produced a brush of considerably less inertia which allowed of a smaller tension on the main springs and so less friction, and at the same time the contact drop was not increased, so that the reduction in temperature which followed was very remarkable. To obtain full advantage of the low inertia, a spring leaf-metal top was fitted to the brush, which spring was so successful that we introduced its equivalent into one of our standard holders as a part of the pressure arm. By means of the subsidiary spring, a brush can associate itself much more closely with the commutator than when its movement is damped by the comparatively high inertia of the brush arm and main spring.

Mr. G. Broughall (*communicated*): I feel that there is still plenty of scope for investigation into the question of what actually takes place between the surface of the brush and the surface of the commutator or slip-ring, and that such investigation is a profitable one for further research. It has always seemed to me somewhat surprising that this question has not been more fully investigated hitherto, in view of the very important part which the characteristics of the carbon brush, particularly as regards contact drop and specific resistance, plays in the performance of commutating electrical machinery. The use of carbon in place of metal brushes has been of the greatest advantage to both the designers and the users of electrical machinery; indeed, if we except the commutating pole and compensating winding, this simple change in material has been perhaps the most important factor in the development of modern electrical machinery. In my opinion it is of great importance from the user's point of view to obtain the brush which is best suited to the commutation characteristics of the particular machines which he has in operation, and it is not always an easy matter to ascertain which is the proper brush to use. It would assist matters very much if the vendors or designers of the machines would, when selling the machine, inform the purchaser what particular characteristics the brushes should have in order to obtain the best results under normal working conditions. In my opinion it pays to buy the very best quality of brush obtainable. The curves given in the paper are very interesting and instructive, but there are so many grades containing different percentages of graphite and the method of making the brushes introduce other variable factors, so that one can only take the curves as typical and as indicating the manner in which one may expect the performance and losses to vary under different conditions of pressure, peripheral speed, and current density. I have experienced more difficulty in obtaining a brush that will work satisfactorily on the slip-rings of rotary converters than with the brushes on the commutators. There appears to be a marked tendency for the formation of flats on slip-rings, and, whilst several different kinds of brushes have been tried, the most promising arrangement appears to be to use a brush having a high metal content with a small amount of oil lubricant continuously applied

to the ring. It is possible that this tendency to form flats may be occasioned by burning of the rings at the moment of cutting out the starting motor. For some time I was puzzled by the formation of flats on the steel slip-rings of turbo-alternators, and the author's remarks on page 200 indicating that this trouble is likely to be caused by oxidization of the rings where not covered by the brush when the machine is at rest may throw some light on the trouble. Under the heading "Contact Drop" on page 195 he points out that for each quality of brush there is a critical value below which no current at all will flow. This is a very interesting point and suggests to me that "contact drop" may consist of two components. The problem may have something in common with that of arc welding. In both cases we have two electrodes or surfaces with a current flowing between them, and if the surfaces are separated an arc will be formed or will tend to form. In the case of arc welding the electrodes are separated and a voltage is necessary to overcome the counter electromotive force of the arc, in addition to that required to drive the current against its ohmic resistance. In the case of the brush and slip-ring or commutator the surfaces are probably never actually separated unless the rotating surface be out of truth; nevertheless, it is probable that even in cases of so-called sparkless collection there is minute sparking taking place between the brush surface and the commutator corresponding to some extent to an arc or a number of small arcs in parallel and requiring an electromotive force to maintain it, apart from that to overcome ohmic resistance. Of course in this case the surfaces are moving relatively to one another and there is not time for actual melting or burning of the surfaces to take place unless the current be very excessive. The phenomenon of "copper picking" at the negative brush and the transfer of carbon to the commutator at the positive brush, mentioned on page 200 of the paper, would appear to indicate that some such action as I have described does take place. I must, however, point out that the curve given in Fig. 1 does not appear fully to bear out this theory, and I merely make the suggestion for what it is worth.

Mr. G. W. Edward (*communicated*): By far the greater proportion of so-called "brush troubles" that I have met with have been found to be due to the faulty holders, or pressure springs, and sometimes to pinched design of commutator or slip-rings, rather than to faulty brushes. With regard to brush-holders, I agree with the author that the boxes should be cast, but unfortunately this type is more expensive to manufacture than the type built up of stampings. The use of holders made up of stampings is a source of a lot of trouble. They are never very regular in dimensions, and are easily distorted, which leads to the wedging up of brushes, unless an excessive clearance between brush and box is allowed for, and this excessive clearance is to be avoided. The use of stamped holders, if not altogether avoidable, should be confined therefore to small machines. All holders should be provided with an adjustable pressure device. Fig. 5 illustrates very clearly the importance of maintaining equal

pressure on all the brushes mounted on a machine, and unless the holder is fitted with an adjustable pressure device, this is impossible. One still finds a number of important units, turbo-generators and rotary converters, fitted with holders which do not render possible the adjustment of spring pressure. I should like to know if the author's conclusions with regard to the best brush angle to be used are based on experiment. The true pressure of the brush on the commutator or collector is the resultant of the applied pressure, and the force due to friction acting in the direction of rotation. Theoretically, therefore, I should imagine that brushes set reaction, with an angle of rake so chosen that the resultant true pressure of the brush

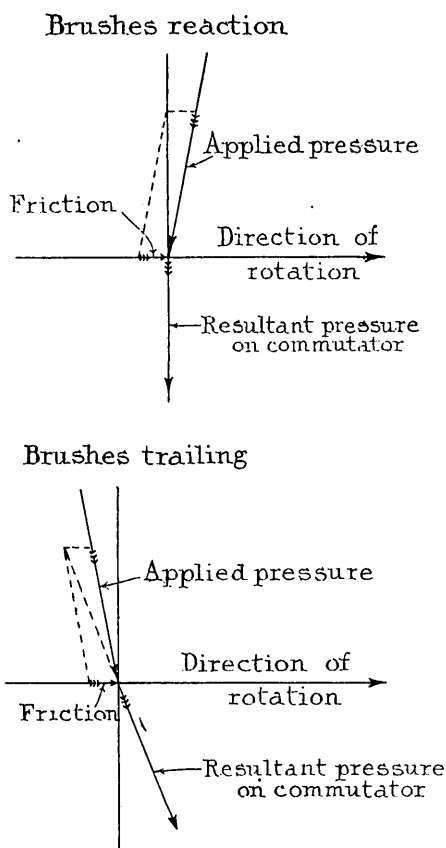


FIG. D.

on the collector is radial, should give the best results and lowest commutator losses. The angle of rake would vary for different qualities of brushes possessing different coefficients of friction, but a mean useful angle could probably be arrived at. With trailing brushes, or even with radial brushes, the resultant pressure on the commutator is not radial, and is greater for a given applied pressure than when the brushes are operated reaction. Further, this resultant pressure is at an angle such that it might lead to a wedging action between the tip of the brush and the holder (see Fig. D), greatly increasing the pressure on the commutator or collector, especially if there is any excessive clearance between box and brush. This

increased pressure means increased friction loss. A test of friction losses on a machine taken with various angles of rake, reaction and trailing, might show some interesting results. I believe that reaction-type brushes are used very largely in the United States, and at least one important French machine constructor has adopted this type for large d.c. generators and rotary converters. This constructor makes his boxes with a particularly large clearance in the peripheral dimension (approximately 25 per cent of the brush thickness). The brush has two large bevels, at the contact surface and the top, and the pressure is applied on the top bevel. The angle of rake is approximately 27° to 30° . In practice, the brush only touches the front side (direction of rotation) of the holder. I have seen several large units giving complete satisfaction with this type of holder, which has the particular advantage, by reason of the great amount of clearance in the box, of rendering the sticking of brushes in the holder impossible. The electrolytic action that takes place between the brush and the collector, and vice versa, is very carefully explained in the paper and has been frequently noticed in practice, especially with alternator slip-rings. It is also borne out on d.c. commutators where the incorrect staggering is adopted, and where one frequently finds high tracks on the commutators although these tracks are covered by brushes. One still finds that many engineers are nervous as to recessing the mica, and in some cases, when they do so, fill in the slots with an insulating composition. This should not be necessary, and it would even lead to difficulties if the composition disintegrated. The usual contention of engineers who dislike recessing the mica is that there is considerable danger of dust collecting in the slots, and that they fear to decrease their brush wear by increasing their commutator wear. With regard to collection of dust, unless the machine is particularly slow running, and then the necessity of recessing the mica is not so manifest, and provided that lubricant is not used, there is little danger to be feared from dust, as this gets thrown out of the slots in running. With regard to the commutator, there is less danger of mechanical wear when using a graphitic brush on recessed mica than of electrical wear due to sparking caused by high mica. I have also come across machines the mica of which has been slotted, so as to leave a groove V-shaped in section, the idea being that even if a little dirt accumulates in the slots it is not likely to short-circuit the commutators bars. Great care must be taken with this method that the sharp ends of the mica V be not allowed to protrude, or the results would be disastrous to a soft graphitic brush. The curves shown in Fig. 8 illustrate the advantages that accrue to the machine and brushes if the current density is kept within reasonable limits, say 40 to 50 amperes per square inch. I should like to know whether the author can explain why the negative ring wear at 100 amperes per square inch is lower than at 60 amperes. Is it the result of an isolated test, or do conditions change materially with such a high current density? It would also be interesting to know whether there is anything to show that there is any difference in rate of wear of the brushes or rings in the case of alternating

currents of varying periodicities. With regard to brush standardization, it is interesting to remember that the *Chambre Syndicale des Constructeurs de Gros Matériel Electrique* of France, an association of manufacturers of large electrical machinery, have standardized the dimensions of brushes. They are divided into 4 classes, namely, 2 types of grip-type brushes with 18 and 30 sizes respectively, and 2 types of slide-type brushes, of which one type is rectangular with 21 sizes and the other a double-bevel reaction type with 4 sizes. Although the position of the flexible connections is fixed within certain limits, there are three possible lengths of flexibles to each of those 25 sizes of slide-type brushes, and no effort has been made to standardize either the terminals or the qualities of brushes. This standardization does not include brushes for traction motors.

Mr. W. Guy-Pell (*communicated*): A paper on this subject has long been wanted by those who have to attend to dynamos and motors. The author correctly states that the "brushes" are the weakest link in the chain, and from my experience, which has been long and varied, I am of opinion that they certainly require more attention than any other part. I believe that much of this trouble could be avoided if brushes and holders of a more suitable type were adopted by those responsible for the design of the machine, and much of the advice given by the author should be of material assistance in this respect. I venture, however, to criticize some of the points as to which I am not in accord with him, the first and most important being the mechanical form of the brush and the method of conducting the current from it to the terminal of the machine. For the latter purpose he recommends the use of flexibles, or, as some of us term it, "pigtail connections"; and he recommends a rectangular shape of brush not exceeding $1\frac{1}{4}$ inches \times 1 inch for ordinary motors. Now on page 199 the author says that one of the characteristics required in brushes is "low inertia." I am not sure that this is not the most important characteristic; it is certainly not attained by adding to the carbon, which has a low specific gravity, copper and clamping terminals of high specific gravity. Moreover, on page 198 the author says that flexibles tend to make the brush sluggish. There are other disadvantages in the use of flexibles, but while speaking of inertia I would suggest that for ordinary work the dimensions generally adopted should be even more limited than those stated by the author. The peripheral width, of course, depends much upon the design of the commutator, but the axial width might well be at least 25 per cent less than the author gives. In place of the flexibles, I suggest the use of spring-controlled levers made of aluminium, to be as light as possible, the brush to be clamped between the end of the lever and face of the commutator and guided in a plain box without openings or detents at the sides. The contact between the brush and the end of the lever might be improved by the use of an aluminium washer the full size of the brush. There is no difficulty in any case in establishing a contact at this point, where the surfaces are stationary, that is at least equal to the contact between

the brush and the moving commutator. The current should be taken from the lever to the terminal by means of a flexible attached at or near the pivotal part where there is little or no movement. Apart from the question of inertia, the use of flexibles is generally costly in renewals; in many cases they more than double the price of the brush. Moreover, the methods of attaching them to the brush are as numerous as the number of manufacturers of motors, so that it is necessary to have in stock practically as many sets of brushes as there are different motors in use, whereas by using plain brushes much of their duplication would be avoided. Certainly the orders for replenishing would be much simplified; at present, sketches or samples must accompany every order, and it must be remembered that the order has to pass through a multiplication of hands before it finally reaches the workman that is to manufacture. Many users obtain tenders before ordering, in which case sketches or samples have to be sent to each of the firms tendering. Another objection to this use of flexibles referred to by the author on page 194, is their liability to break under continual vibration. This, of course, is a more potent characteristic in high-speed than in low-speed machines: it is there, nevertheless. On page 195 the author states that the decrease in the coefficient of friction that is observed at high speeds is due to a film of air. I am not clear as to what he quite means by this. I gather he attributes the film to some action of windage or suction. I suggest, however, that it is due to the simple fact that the brush is not continually in contact, and that the coefficient of friction is reduced in proportion to the amount of vibration or separation, that is to say, to the fraction of the periphery upon which the brush is touching during each revolution. In fact, further on (see page 203) the author admits that commutators are never mathematically circular and a very small mechanical defect is sufficient to cause a momentary separation between the brush and the collector. Nor do I agree with what the author describes as suction or vacuum between the brush and commutator of low-speed machines, for it appears to me that the tendency to adhere is due to perfection of contact, combined as it may be in some cases with the presence of lubricating or plastic matter. In other words, the effect is due not to a space between the brush and the commutator in which there is a vacuum, but to the entire absence of space. I agree with the author as to the importance of having equality of pressure as well as correctness thereof. It would be interesting if he would supplement the paper by a description of the sort of instrument or apparatus that he uses for measuring this pressure. He speaks of graphite as being a kind of matter distinct from carbon. This is, perhaps, misleading, seeing that graphite itself is a form of carbon. I suggest the use of the words "graphitic carbon" and "amorphous carbon." One more point—hypercritical though it may appear—is the promiscuous use of inches and millimetres. For example, he gives the size and current densities in inches and the wear in millimetres.

Mr. N. Pensabene-Perez (*communicated*): The

paper, I assume, is only a preliminary survey of the many and complex phenomena taking place, and I look forward to another paper from the same author in which a more complete analysis and critical survey of previous researches and formulæ would be made. A very interesting question is the determination of local surface voltage-drops in the case of non-uniform current distribution as found in practice when commutation is not theoretically perfect. According to Professor Arnold the local voltage drop in any point of the brush where the current density is D_x is given by $V_x = a + b D_x$, in which a and b are constants and functions only of the mean current density in the brush. Professor Arnold uses this formula for determining experimentally the variation of the current in the short-circuited coil during reversal, which is a most fruitful investigation in order to get an insight into the process of commutation. In the case of uniform current distribution many investigators attribute the falling off of the surface resistivity with increasing current densities to heating effects. The author does not seem to agree on this point. Am I right in assuming that he adopts the theory which views the conduction of current from the brush to the metallic surface or vice versa as taking place through a great number of small arcs bridging across a film of air? Has the author investigated the effect of the brush size on the voltage drop? Turning to the more practical side of the subject, I believe the problem of brush chattering is sometimes very baffling. Certainly the reason of such a trouble must be found in the brush-holder design, in the clearance between brush and holder, in the natural period of vibration of the spring, etc. When the commutator or slip-ring surface is almost perfect the chattering of the brushes is difficult to explain. I believe chattering has its origin in an oscillatory motion of the brush about its axis vertical to the revolving surface. The brush would be slightly tilted by the frictional force so as to touch the revolving surface only with its leading edge. In this position the tangential force would be reduced and the spring tension would again pull the brush back to its normal position. The process would thus continue and a tangential vibration would set in, which by lifting the brush up and down would produce also a vertical vibration. Resonance phenomena with the spring would in some cases accentuate the trouble. This explanation is sometimes confirmed by the fact that by shifting forward the point of application of the spring on the brush the vibration can be stopped. Another point which requires great attention and to which no reference has been made in the paper, is the method of connecting the pigtailed to the brush in the case of high-current high-speed commutators. In the case of a large commutator having a peripheral speed of 25 metres per second the only pigtail which gave satisfaction was one fixed to two stout plates clamping the brush by means of rivets. Many manufacturers, especially in America, in order to deal with the deleterious effects of oil vapours or acid fumes, undercut the mica between the commutator segments and fill the space with a special enamel or paste. As it is well known, oil vapours or acid fumes seem to

saturate the mica with a conducting material supplied, I believe, by the brushes, with the result that the mica is eaten away by electric discharges between the bars. One of the cures is the one above referred to, which to my mind is a very elaborate and expensive one. I wonder if the author can tell us how far the material of which the brush is made is responsible for this serious trouble. This subject is worthy of our best attention and of careful chemical researches.

Mr. P. Hunter-Brown (*in reply*): With reference to Fig. 1, Mr. Constable and Professor MacGregor-Morris expressed doubts as to the existence of a minimum voltage below which no current would flow, and the former referred to tests he had made with carbon resting on stationary copper plates. With the collector at rest I agree that some current passes even at a very low voltage, and the contact-drop curve under these conditions would pass through the origin. With the collector running, however, the conditions are radically changed. Even at the so-called points of contact between brush and collector I think that the contact is not sufficiently intimate and continuous to prevent minute arcing, and that even when collection appears to be sparkless the current passes in the form of minute arcs. Dr. Kahn's communication to the Birmingham discussion (see page 222), is particularly interesting, coming as it does from one who has very thoroughly investigated the problem of contact drop. He has satisfied himself as to the existence of a minimum voltage below which no current will flow, and the curves given in his well-known thesis bear this out. The tests illustrated in Fig. 1 were carried down to a density of 1 ampere per square inch. Very many other tests have been carried down as far as this value, the contact drop at the minimum current still remaining relatively very high. I have not specially explored the region between zero and 1 ampere per square inch, but if an investigation revealed that the curves turned down to zero below 1 ampere per square inch it would not affect the conclusions to be drawn from the curves given in the paper for practical working conditions. Mr. Atkinson states that this minimum voltage does not exist in the case of metallic brushes. I have not made any contact-drop tests on brushes of the description he is referring to, but it is interesting to note that in the late Professor S. P. Thompson's lecture on "High-speed Electric Machinery" three contact-drop curves for copper-gauze brushes are given, attributed respectively to Dettmar, Hillman, and Arnold, and all of these show a minimum voltage below which no current flows.

Referring to Fig. 6, it would naturally be concluded from these curves that no current would flow in the graphite brush if the two qualities were mounted on the same ring. To confirm this, the two brushes were actually mounted on the same slip-ring; the graphite brush was insulated from its holder and an ammeter was connected between the graphite brush and the common terminal bar. The total slip-ring current was raised to 260 amperes, but the ammeter in the graphite-brush circuit indicated no current. Obviously if two grades are selected the contact-drop curves of

which overlap, both will carry some current, but if one is highly metallic copper graphite and the other pure graphite the proportion of current carried by the graphite brush will be negligible if not absolutely zero.

The contact-drop curves were measured by the ammeter-voltmeter method. The curves in Figs. 1, 3, and 5 were taken on a short-circuited commutator with recessed mica. Professor MacGregor-Morris expressed the opinion that contact-drop curves should be taken on a complete machine under various load conditions, and proceeded to point out some of the difficulties of doing this. An interesting article bearing on this subject appeared in the *Electrician* in 1913 by Professor Hay and others. It was considered advisable to make the contact-drop tests on an armature complete with windings. The field frame was removed and the test armature driven by a suitable direct-coupled motor. Current from an outside source was passed through the test armature and the voltage was measured at the brushes. From this was deducted the I R drop in the windings, and in the original tests the remainder was considered to represent the total contact drop at the brushes. At a later date, however, it was realized that even without a field frame the armature became the seat of a counter E.M.F. due to the fact that the reversal of the current does not follow a straight-line law, and the estimation of this counter E.M.F. proved to be rather formidable. It seems to me that the object aimed at must be carefully borne in mind, whether it is the investigation of characteristics of brushes or a certain grade in combination with a certain machine, or commutation in the abstract. From the brush manufacturer's point of view the question of primary importance is to investigate the characteristics of his various grades, and not to mask the results by introducing some effect that is dependent upon the characteristics of the machine used. For this reason it would appear advisable to use a machine of the most elementary form, that is to say, to shorten the armature until the core disappears and to use a one-turn coil of the shortest possible length; in other words, to use a short-circuited commutator with the test brushes mounted on opposite sides.

Referring to Mr. Eason's remarks, in measuring contact drops there are many disturbing factors, and until the effects of each of these can be separated out and individually controlled it is not possible to formulate laws which are applicable to all cases. Scores of curves have been taken with different grades under different conditions, and these show a great variety in shape. As Mr. Broughall aptly expresses it, the curves shown in the paper are typical and indicate the manner in which one may expect the performance and losses to vary under different conditions of pressure, peripheral speed, and current density.

The apparent variation in the coefficient of friction at various speeds has been attributed to cohesion between well-fitting surfaces, but I consider it necessary to go further than this and to offer some explanation as to why this cohesion exists. Even well-bedded brushes only make contact with the commutator at a series of points, and between these we have a series

of minute cavities between brush and commutator which are normally filled with air. The suggestion is that under certain conditions when the commutator is revolving, the air is swept out from these minute cavities more rapidly than it is replaced, with the consequence that a partial vacuum is formed. If when an abnormal friction value is being observed the applied pressure is reduced to zero with the machine still running, the brush is often found to be sticking to the commutator and a perceptible pull is required to remove it. If, however, the machine is shut down before the brush is pulled off the commutator, it will be found that when the latter comes to rest the brush is not sticking to the commutator, owing apparently to the vacuum having been broken by the machine coming to rest. It is concluded that when the friction loss creeps up to an abnormal figure, it is due not to an abnormal coefficient of friction but to the fact that the total pressure is the applied pressure plus a certain atmospheric pressure. Further reasons for this conclusion are given in the paper.

Passing to the design of the brush itself, the abolition of flexibles advocated by Mr. Guy-Pell would, I am confident, be generally regarded as a most retrograde step, and the arrangement suggested appears to embody several features calculated to produce unsatisfactory operation. The loss at the top of the brush would be greatly increased, thus reducing the efficiency and producing heat just where it could not be tolerated. Moreover, the variable resistance at the top of the brush would introduce another factor tending to produce unequal distribution of load between the various brushes. The absence of a flexible imposes serious limitations upon the design of the holder. With the type recommended by Mr. Guy-Pell, at every movement of the brush the friction of the hinge pin, as well as the inertia of the pressure finger, must be overcome, and since the finger is depended upon to carry current, it would not be practicable to obviate these objections by fitting an auxiliary spring on the tip of the finger. Certainly manufacture and the problem of stock would be simplified, but this advantage is in my opinion insignificant in comparison with the disadvantages that would result. Replying to Mr. Guy-Pell's query, the pressure applied to a brush can be conveniently measured by a small cylindrical spring balance made for a suitable pressure range. When using the balance, the pull should be gradually increased and the reading taken at the moment that the grip on a piece of paper placed under the pressure finger is released.

Twisted flexibles, as pointed out by Mr. Orsettich, are to be preferred to braided, as they present a larger radiating surface and are more supple than braided. I agree with Mr. Brazil that they should be liberally proportioned, as this not only provides a margin for dealing with unduly heavy loads but also affords a valuable means of carrying away the heat from the brush. On the other hand, some judgment is necessary in the matter, and for the reason stated in the paper the flexibles should not be made unnecessarily large. I agree with Mr. Cater that if the type of connection used for attaching the flexible to the brush gives a tenfold increase of resistance at this point when

coppering is omitted, this certainly provides a strong argument for copper-plating in all such cases.

Mr. Constable has suggested a double-brush arrangement with the two brushes fitted one in front of the other. I have used this with very satisfactory results so far as effecting an improvement in commutation is concerned. I attribute the improvement partly to the extra cross-resistance and partly to the fact that one half of the combined brush can move without disturbing the other half. Mr. Atkinson and Mr. Friedlaender have referred to the fundamental difficulty of running a solid brush on a solid commutator. The double brush is a partial, but only a partial solution of the difficulty; also one brush inevitably wears faster than the other, and it is not an easy matter to design a simple and efficient brush holder to take care of the unequal wear.

Any system adopted for marking brushes should be capable of extension, and every mark should be readily expressible in words. A series of lines at various angles, as suggested by Mr. Constable, has serious disadvantages in both these respects and is also a severe tax upon the memory. The most satisfactory mark appears to be a combination of a letter and a numeral, the former denoting the class of brush, and the numeral the position in the class. If the numerals are arranged in order of specific resistance, the grade designation in itself is sufficient to give some idea of the type of brush referred to. As a rule the pressure finger and flexible occupy nearly the whole top surface of the brush, so that it becomes necessary to mark the brushes on the side.

Several speakers have referred to the question of recessing mica. It is not possible to dogmatize about this, and each machine should be considered on its merits. Of ordinary industrial motors and generators operating with commutator speeds below, say, 3,000 feet per minute, undoubtedly the great majority are running, or would run, quite satisfactorily with "flush" mica. Above 3,000 feet per minute recessing mica becomes increasingly beneficial. Above 4,000 feet per minute it has become almost universal practice to recess and, I think, rightly so. It is of vital importance, however, that the depth of the groove should not be excessive, as carbon and copper dust have a comparatively high conductivity and are liable to produce partial short-circuits if they are allowed to accumulate in the grooves, which is difficult to prevent if the grooves are made deep. The practice of making the groove V-shape is not to be recommended. It does not appear to have any value as regards preventing short-circuits, and when the mica is recessed in this way it will almost invariably be found that some of it is left adhering to the sides of the segments. Special circumstances demand special treatment, and if it is impossible to provide facilities for maintaining the grooves quite free from mica and also dust or dirt, it is advisable to avoid recessing, especially if oily vapour is present. In my experience, however, trouble very rarely arises which can be directly attributed to the mica being recessed, provided the work has been done as directed. With regard to the type of brush recommended for use with recessed mica,

Mr. Cater seems to have misunderstood the paper. A "high-grade non-abrasive graphitic brush" (no limitations as to hardness mentioned) is recommended, and in this category is most certainly included the electro-graphitic class of brushes.

The use of carbon (or graphite) brushes on slip-rings has been criticized, but I think there are circumstances under which their use is fully justified. The friction loss is very small, the contact drop does not exceed about $\frac{3}{4}$ volt, and they possess the advantages referred to in the paper.

I do not share Mr. Atkinson's view that carbon brushes would not be needed to-day if slotted armature cores had never been introduced. Quite apart from considerations of sparkless running, it is by no means uncommon for owners of machines that are fitted with gauze or foliated metal brushes to scrap both holders and brushes and equip with suitable slide-type holders and carbon brushes, simply to secure the decreased wear and tear of commutators which results from this change.

The opinion has been expressed that the passage of copper from the collector to the negative brush should not be described as being akin to electrolytic action. The paper makes it clear, however, that I do not regard this as true electrolysis, as it hardly seems likely that moisture from the air could provide the electrolyte. The point that I wish to emphasize is that in addition to the mechanical abrasion and burning which occurs under both positive and negative brushes, there exists a further action which takes place under the negative brush only and causes copper to be carried across in the direction of the current flow. Under some conditions this copper is firmly deposited on the contact surface of the brushes, and is then usually described as "copper picking." The absence of the deposit on the brushes, however, does not indicate the absence of this "electrolytic" or arc effect.

Mr. Edward raises a point as to the influence of periodicity upon the rate of wear. I have not investigated this directly, but general observations made upon the behaviour of the slip-rings of rotary converters and induction motor rotors (which work at widely different periodicities) have not suggested that the rate of wear is influenced by this if the rings are non-magnetic.

Brush-potential curves are invaluable for adjusting commutating poles and giving one an idea of what is occurring under the brush, but it must be recognized that they have their limitations and are useful in a qualitative rather than a quantitative sense. The voltmeter indicates the average value only, and the current does not vary directly as the voltage. To investigate commutation we require to know what is happening in the short-circuited coil. Mr. Pensabene-Perez quotes a formula for determining the local voltage drop at any point under a brush which Professor Arnold used for estimating the current in the short-circuited coil, but the method of investigating this by measuring the I R drop in the short-circuited coil with an oscillograph (suggested originally I believe by Professor Robertson) appears more practicable. One of the oscillograph leads is passed back along the path of the armature coil selected for observation, so that

the voltage measured is the I R drop only. With regard to the influence of brush size upon contact drop, I think that in practice the contact loss is undoubtedly less with many small brushes than with few large ones, the nominal current density being the same in both cases. The actual area of contact between brushes and commutator is larger with many small brushes, and the actual contact drop is therefore less.

Referring to Mr. Edward's queries with regard to brush angles, the figures given in the paper are the result of experiment. If a trailing brush is inclined at more than 15° it is apt to wedge in the holder, due to the combined action of the spring and the friction, and a reaction brush is likely to chatter if inclined at less than about 20° .

Mr. Orsettich referred to the very high brush-tip voltages mentioned in Mr. Lamme's paper. The value of 30 volts was given as permissible by Mr. Lamme on the understanding that 90 per cent of this was neutralized by the commutating poles, leaving 3 volts to be taken care of by the brushes. These seem very high values, but Mr. Lamme was referring to extreme overloads, apparently at least 100 per cent and of very short duration.

With regard to commutating poles, it is obviously possible to proportion these so that the commutating flux is substantially correct from no load up to the load at which the first trace of saturation occurs. I think, however, it is common practice to err on the large side with the number of turns to ensure having sufficient commutating field at heavy overloads when the assistance of commutating poles is most required. Under such circumstances the value of the commutating flux is correct at one value of load only, and even Mr. Pollock speaks of adjusting the commutating-field strength to give a brush potential curve of constant value on machines of 100 kw. and upwards only. With copper-graphite brushes, as well as with other classes, the influence of current density upon rate of wear is very large. No-load tests on highly metallic brushes made under the same conditions as described on page 197 gave a wear of 0.005 mm. The duration of each test shown in Fig. 8 was 20 million revolutions.

I regret that Mr. Pollock has received the impression that I consider designers haphazard people, as nothing could be further from the truth and I am at a loss to understand what has given him this impression.

With regard to abrasion, Mr. Cater seems to have overlooked the fact that I have gone to considerable pains to show that even with so-called abrasive brushes the abrasive action is very slight. Mr. Cater states that for any particular machine suffering from proud mica the application of abrasive brushes is at times a remedy, but the case is an isolated one. With this

statement I am in full agreement, and I think, therefore, that Mr. Cater's remarks on abrasion do not call for any further comment.

Mr. Friedlaender has referred to the difference in behaviour at the positive and negative brushes of small high-speed motors. An interesting note bearing upon this appeared recently in the *Technical Supplement to the Review of the Foreign Press*, which was based upon an article in a German paper. According to this, experience in running the Berlin tramways has shown that there is a marked difference in behaviour at the positive and negative brushes and arcing over is always initiated at the positive brush. The motors have four poles and the usual two-brush stud arrangement on the upper quadrant of the commutator. It was therefore found preferable to arrange the polarity of the brushes so that the commutator moved in the upper quadrant from the negative to the positive brushes, and when this change was made a considerable reduction in the number of cases of arcing over was observed. The phenomenon was explained in the following manner:—

"In an arc, particles of carbon are detached from the positive electrode and their impact on the negative electrode causes local heating. In an analogous manner, if sparking occurs under a negative brush, the arcing is concentrated on a point under the brush and spreads out from there on to the commutator, and owing to the relatively small heating on the commutator, the arc is not drawn along by its motion. On the other hand, if the brush is positive, the concentration of the arc takes place on the commutator, and by the intense local heating causes the arc to be drawn along in the direction of motion of the commutator. This fact is corroborated by cinematograph photographs made by the author. On this account arcing-over will always be initiated at the positive brush, and it is more dangerous to run the commutator from the positive to the negative brush than in the reverse direction." Various references are made in my paper to brushes containing, or not containing, carbon in the special form known as graphite, and I think there is no ambiguity as to the type referred to in each case. With a view to greater precision, Mr. Guy-Pell suggests the use of the terms "graphitic carbon" and "amorphous carbon." Since, however, graphite is a form of carbon and some graphite is amorphous, the term "amorphous carbon" could be applied with accuracy to certain graphite brushes. The term "amorphous carbon" therefore does not appeal to me, and if greater precision is desired I would prefer to adopt the terms "graphite," "graphitic carbon," and "non-graphitic carbon" to indicate carbon brushes made entirely from graphite, partly from graphite, and wholly without graphite respectively.

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 18 DECEMBER, 1918.

Mr. W. Lawson: It is to be hoped that this exceedingly practical and valuable paper will come under the notice of all manufacturers of electrical machinery. In my opinion it rests with the manufacturers to provide their machines with brush gear so designed that when fitted with a specified form and grade of brush

a much higher degree of immunity from brush troubles than has been so far obtained will be ensured. Unfortunately these troubles cannot always be detected on test, and they frequently do not arise until after the machine has been in service for some time, and it is left to the purchaser to determine by experiment

how best he can get over the trouble. This means that he is put to a good deal of expense and inconvenience and has probably had to sacrifice, by repeated grinding, an appreciable depth of the commutator bars of his machine. This is not as it should be, and I believe this paper, with the wealth of information it contains, will lead to a closer study of the question, and will ultimately result in the elimination of most brush trouble. Until that happy state is arrived at, the question of standardization should be approached with the utmost caution. On page 198 the author refers to the excessive wear sometimes produced on the top of the brush by the pressure finger, and ascribes this to electrical rather than mechanical effect. He does not state his reason for this opinion, and it is difficult to account for it in this way, as the greater part of the current passes along the flexible connection. In none of the cases that have come to my notice has there been any evidence of electrical effect. The author's experiment proving the existence of some kind of electrolytic effect is extremely interesting and important, and one that calls for further investigation. I have noticed an analogous effect, and one that is not explained or even referred to in textbooks, in meters of the mercury-motor type. In this case we have an amalgamated copper disc immersed in mercury. Two copper conductors amalgamated at the ends make contact with the mercury, and the current passes from one conductor through the mercury and the copper disc, and out by the other conductor. Under certain rare conditions electrolytic action takes place; one of the copper conductors is eaten away, and a heavy deposition of copper by transference takes place on the copper disc. I have never known of a case of this happening with a meter of less than 50 amperes' capacity, so that it appears there is a critical value of current below which no deposition can take place. It would be interesting to know if the author has observed a similar characteristic in the electrolytic effect which he mentions. Is there a point in the value of the current below which electrolytic action completely disappears? Further investigation might establish the analogy between these two effects, and also throw some light on the possibility of there being some relation between the speed of the conductor and the strength of the current determining the condition under which electrolytic effects can take place.

Mr. E. J. Kipps: Can the author give a reason for the statement made in the paper, under the heading of "Properties of Carbon Brushes," that a small proportion of copper in the carbon brush increases its resistance, and can he state the proportion of copper to carbon by volume at which the resistance diminished with the addition of copper?

Mr. W. F. Higgs: On page 194 and also, I think, elsewhere in the paper, the author refers to atmospheric conditions. We had a case of a 25-h.p. motor at 460 volts, the peripheral speed of the commutator being about 3,000 ft. per minute. The machine was installed on two girders, 8 ft. above the floor, about two years ago. The brushes would run about 10 days and then collapse all at once. Many different qualities of brush were fitted, with no improvement. The

commutation with regard to sparking was perfect, and this was a repeat machine, of which we had made dozens of the same construction mechanically and electrically. The machine was taken off its girders and put on a concrete foundation in the same shop, and the trouble still continued. It was moved into another shop, and has been running satisfactorily with the same brushes for 12 months. A second machine was installed where the first one was taken from, an exact duplicate, and the same trouble occurred. We think we are right in putting this down to atmospheric conditions. On page 198 the clearance of 0.2 mm. and 0.3 mm. in brush holders suitable for taking a brush 1 inch \times $\frac{1}{2}$ inch or larger Link One, Morganite, is, I consider, not sufficient. The author mentions in several places about the undercutting of mica. This is not a practical job to be done by machinery, and is rather a tedious job by hand. It is quite a good arrangement to build the commutator up with mica about $\frac{1}{8}$ inch lower than the bars, and it can be done if suitable tackle be used. We find it good practice to fit the brushes to suit each individual machine as it goes on to test. There is one other question I should like to ask the author, namely, what is his opinion of die cast brush-holders? Has he had any experience with them, and, if so, is he in favour of them or not? I am inclined to adopt them, but I am afraid of crystallization of metal taking place, due to vibration or some other such trouble. Is there any foundation for my fears?

Mr. W. N. Y. King: I notice that no reference has been made to a well-known property of carbon which has an important bearing on the subject under discussion. I mean the negative temperature coefficient, i.e. that as the temperature increases the electrical resistance decreases. Two prominent examples of this effect have come under my observation in large direct-current generators, one of 1,500 kw. and the other of 1,000 kw. capacity. In each case trouble was experienced with commutation at full load and over. Severe sparking and flashing occurred and overheated the brushes. One brush in a row would take more current than the others and get red hot, with cumulative effect due to the negative temperature coefficient, until the brush or flexible lead burned away. Then another brush would undergo the same process, and so on until it became questionable whether the machine would run till shutting down time without renewing the brushes while the machine was on load, and this is not a desirable thing to do. In one of the cases mentioned the trouble was eliminated by substituting Morganite, Link Three, for carbon brushes. It would be interesting to know whether the temperature coefficient of the Morganite brush is negative, and how it compares with carbon.

Mr. F. Forrest: It is well known that the thermal conductivity of carbon and graphite materials is very low, and it is quite possible for the forward tip of a carbon brush to be very hot, in fact glowing, whilst the rear edge of the brush may be comparatively cool. This great difference in temperature causes the brush to buckle to a certain extent on its face, and is one of the causes of sparking taking place. In order, therefore, to get the heat away from the forward tip of the

brush, it is advisable to use a metal brush-holder of the box type, which extends down to even something under $\frac{1}{4}$ inch of the commutator, and this metal box can assist in conducting the heat away from the hot portion of the brush and effect a great improvement in the commutation of the machine. It is also well known that the contact resistance of the positive brush is higher than that of the negative brush, and cases are known where the commutation has been quite satisfactory with a certain type of brush when connected to the positive pole, but has been unsatisfactory when the same type of brush has been connected to the negative pole. As a general rule the negative brush will always be found to be hotter than the positive, and the face of the negative brush will be more highly polished than the face of the positive brush. The expansion of the negative brush will therefore be greater than the positive, and in connection with this it would have been interesting if the author had included in the paper the temperature coefficient for expansion for brushes made of carbon or graphite material. It is of the greatest importance that all brushes on the same machine should bear on the commutator with equal pressure, and I can strongly support the author's suggestion that the brushes should be individually adjusted with a spring balance. This method of adjusting the brush pressure has been in use for some years in the stations of one large supply undertaking in the Midlands, with very beneficial results.

Mr. A. T. Bartlett (*communicated*): Generally I agree with most of the paper, and my remarks will, as it were, only underline a few of the author's points. I should like, however, to caution members against using some of the curves given in the paper for purposes of design of machines, as the curves I refer to are, as the author points out, the results of experiments made under laboratory conditions such as are not met with in general practice, and are of greater use to the manufacturers of brushes than to the designers of machines. I am much interested in the author's theory of air suction being the cause of the increase in the coefficient of friction at lower speeds. With perfect laboratory conditions it is quite conceivable that there may be a measure of "optical" contact, as it were, between the brush and the commutator, but, as the author points out, one is not likely to get such conditions in practice. I suggest that another reason for the shape of this friction curve is that brushes are not, in practice, really in good contact all the time, and that at the higher speeds this imperfect contact is increased. I will describe an experiment which I made some 12 years ago when engaged on the commutation difficulties of direct-current turbo-generators. A commutator with all its segments connected to a common ring was mounted on a special shaft. The common ring was connected to a slip-ring, so that current from an outside source could be passed into the commutator and leave at the brushes pressing on the commutator in the normal manner. Very special attention was given to the truth, surface, and balance of the commutator at full speed, and also to the bedding of the brushes. Readings were then taken with, as far as I can remember, the following result: One brush

was first put down and loaded to its normal current density, the drop was measured, and we will represent it by unity. A second brush was then put down and the current doubled in order to eliminate any effect of change of current density. The drop was then roughly one-seventh. A third brush was put down with less change, the figure being then about one-fifth. I think the only explanation can be the one I have given, viz. that brushes are off the commutator for a considerable time, and this would cause the retarding effect of the brush to be decreased. It would be interesting if the author would describe briefly the method he adopted to measure the friction coefficient. This leads me to the question of the size of brushes and the design of brush-holders. The ideal conditions for perfect running as regards these are an infinite number of brushes of no mass, and holders with no mass in their moving parts. As designers we have to compromise, and I favour a short brush of either $\frac{3}{8}$ inch or 1 inch in axial length, and a clock spring with its end pressing directly on the top of the brush, as fulfilling most completely the conditions of light moving parts. In my opinion a spring can be too lively or resilient, a slight hysteresis being an advantage. Current density is undoubtedly a factor in the wear of both brush and commutator as well as in the commutation, but, as the author says, the current density in a brush can seldom be measured by the current it delivers to the external circuit. In the early days of carbon brushes I once had a machine in which the brushes were loaded, nominally, to 35 amperes per square inch—the makers' rating—but they sparked and glowed excessively. I changed to brushes of half the width, thereby bringing up the nominal density to 70 amperes per square inch—double the makers' rating—with quite satisfactory results, and those machines ran well for years. Here apparently we had increased the nominal density, but actually had decreased it. Much attention is now being given to the current distribution in brushes by designers of motors and generators. It is quite common to find machines, even when they apparently commute perfectly, running with brushes in which the current density departs greatly from being uniform over the section, the variation being easily as much as 1 to 5; with a well-designed machine and correctly proportioned and adjusted brushes and interpoles, this departure may often be reduced to 1 to 1.5. I have gradually come to the conclusion that the differences in the behaviour of two similar machines, as mentioned by the author, is very often due to want of care in the adjustments referred to above, which results not only in perhaps poor commutation but certainly in greater wear of both brush and commutator. As an instance, two turbo-generators made at the same time were running side by side. One of them gave no trouble and the other was not nearly so satisfactory, there being a slight sparking and much wear. After much experimenting the brush density was improved and there was no further difference between the machines. The author mentions the presence of symptoms suggestive of electrolysis, and attributes copper "picking" to this phenomenon. No doubt it does, but I am

inclined to think an irregular current distribution is more often the larger factor. Electrolysis, or a pseudo-electrolytic effect, undoubtedly occurs, and I believe I was one of the first to come across a really definite case some 10 years ago. A heavy-current low-voltage generator was fitted with copper-graphite brushes having a large copper content. On test, after running about 10 hours the commutator developed a salmon-colour matt surface; and the brushes, if not the commutator, began rapidly to be transferred in the form of powder to the bedplate and machine generally. The trial had to be stopped, and afterwards a careful examination of the brushes and commutator was made. At rest the appearance of the commutator was as stated, the surface of the positive brushes was quite metallic and bright, whilst the negative brush surface looked as though it had been painted with dead lamp-black. No trace of the copper content was visible; it had apparently been transferred by the current to the commutator exactly as in normal electrolysis. The negative brushes were replaced with graphite brushes, and fortunately for the makers it ran most successfully, as the commutator would have been too hot with all graphite brushes. The author remarks on the importance of having similar pressures on all brushes of a machine, as this has an importance which even skilled attendants and erectors do not fully appreciate. I am glad he has referred to the common error of assuming that hardness and abrasiveness are synonymous terms. I have known apparently the most innocent-looking soft brush wear a commutator in the most aggressive manner, certainly many times faster than the most abrasive hard brush I have ever met.

Dr. M. Kahn (*communicated*): I should like to hear the author's opinion regarding the physical explanation of current transmission between brush and collector. The following facts give certain indications about this question. The voltage drop between the collector and the brush is comparatively constant over a large range of current density, and shows a minimum value below which no current passes. If one compares the curve for the drop given in Fig. 1 with corresponding curves of electrical arcs one finds a great similarity. Another indication is the phenomenon usually called copper picking, described in the paper. It is a very disagreeable trouble which is sometimes experienced on high-current machines. On the face of it this feature looks like an electrolytic action. It is, however, so far as I know, quite independent of the presence of moisture or traces of acid, which are ordinarily present in connection with an electrolytic process. A similar action is also found in the electric arc, the material of one electrode being carried in the direction of the flow of current to the other electrode. A third indication is the difference in contact drop between the positive brush and the collector and the negative brush. I find that the author has not gone into this question and I should be very interested to hear his observations about this point. The phenomena mentioned show that the flow of current from a carbon brush to a collector differs entirely from the conduction of electrical energy along a metallic conductor, which follows the ohmic law. It seems

to take the form of a large number of minute electric arcs which in the ordinary way do not contain sufficient energy to be visible to the eye. With increasing voltage between brush and collector the energy in these arcs increases very much more than the voltage, as can be seen from Fig. 1. An increase from 2 volts to 2.5 volts doubles the current in the contact surface; that is, an increase of 25 per cent in voltage produces an increase in energy of 150 per cent. Due to the large increase in energy the arcs become visible, when the voltage between brush and collector is increased beyond a certain limit, in the form of small sparks, which get larger the higher the voltage. The arcs or sparks can be observed in various intensities on badly collecting machines. They are, however, always present, although they may not be visible, wherever current passes from a brush to the commutator, and they may cause wear of the commutator and brush, copper picking, and disintegration of the brush surface, even though the machine may appear to collect perfectly. It follows from these remarks that the phenomena of sparking depend on the voltage drop at any point between the brush and collector, and this can easily be proved by measuring this drop when sparking occurs. The selection of a suitable brush for a given dynamo or motor does not offer any difficulty on ordinary electrical machines. In special cases like high-speed dynamos geared to turbines or rotary converters, the demands on the brushes are very exacting. The difficulties encountered in such cases are, however, often more of a mechanical than of an electrical nature. The principal requirement is to get a brush with low friction coefficient and small inertia which will ride smoothly on the commutator and not chatter. The brush should be self-lubricating, as resort to commutator lubricants only effects temporary improvements in case of brush vibration, and the application of lubricants at short intervals is undesirable. Apart from the fact that a machine requiring constant application of lubricants would rightly be regarded as a burden by the running staff, the lubricant has a tendency to accumulate at certain parts of the brush gear and to mix up with carbon and copper dust. Finally I should like to refer to the question of standardization. If one approaches this question in wholesale fashion and tries to arrive at standard brushes for everybody and everything, the task appears hopeless. A better way is to select a few suitable sizes of brushes as standard sizes and settle definite dimensions of flexibles for these brushes. All manufacturers of electrical machinery could then be asked to adopt these as far as possible on new types which are brought out, and in any other case where it can be done. The manufacturers of carbon brushes would have to select certain grades of brushes which are generally used in commercial work, and keep a stock of these brushes in all standard sizes. If the manufacturer knows that he can get these brushes any time from stock it will be a big inducement for him to adopt them whenever possible, and it would of course be a great advantage for motor users to be able to buy such standard brushes in case of replacements. This would presumably in time lead to a more and more universal use of the standard

brushes. I understand that steps have been taken to arrive at a satisfactory solution of this problem.

Mr. P. Hunter-Brown (*in reply*): The opinion expressed in the paper, that the wear which sometimes occurs on the top of a brush is more an electrical than a mechanical effect, is the outcome of actual observations. It is true that the resistance via the flexible is very much lower than via the finger, but the latter will carry a small amount of current, and a very little current greatly exaggerates any tendency there may be for wear to occur. If there is extremely severe chattering a brass plate affords more protection than a piece of insulating material. Provided, however, there is no unreasonable chattering, insulation stands better than a brass plate; in fact, the pressure finger will often bore its way into a brass plate as readily as into the brush material itself. In traction work the pressure fingers sometimes produce heavy wear on the tops of brushes that are not fitted with flexibles; in such cases the addition of flexibles has very greatly reduced the wear. Replying to Mr. Lawson's query, I have not made any tests to determine whether there is a critical current value at which the "electrolytic" effect disappears.

The increase in resistance produced in a brush by the addition of a small proportion of copper seems to be due to its homogeneity having been broken up to some extent, the particles of copper apparently introducing a series of minute contact resistances. The proportion of copper required to produce an increase in conductivity is influenced by the other ingredients of the brush and the method of manufacture. Mr. Higgs states that a clearance of 0.2 mm. in the thickness and 0.3 mm. in the width is not sufficient for a Link One brush. These figures were intended to apply to ordinary carbon and graphite brushes. Link One is a quite special brush and must be made to a special scale of clearances depending upon its size. Regarding methods for recessing mica, I have found a hand-applied circular milling cutter, motor driven, very satisfactory, and, failing this, good work can be done by hand with a portion of a hack-saw blade suitably mounted in a wooden handle. Even if the commutator is built with the mica below the surface the question of recessing the mica will recur when the copper wears down. I have not had any experience of die-cast holders, but have heard fears expressed in more than one quarter similar to those voiced by Mr. Higgs.

Mr. King mentions two interesting cases of what is often described as selective action. It was no doubt caused by a decrease in the contact drop, as well as in the resistance of the material itself. The temperature coefficient of "Link Three" material is also negative, and I think the fact that this grade eliminated the trouble on one of the machines was probably largely due to the reduction of circulating currents and the better distribution of current across the face of the brush produced by the special characteristics of this grade.

Mr. Forrest and Dr. Kahn have both referred to the difference in contact drop at the positive and negative brushes. The following figures relate to a test on carbon brushes working at 40 amperes per square inch

and mounted on a commutator running at 3,500 feet per minute, mica recessed, the pressure being 2 lb. per square inch.

Contact Drop in Volts			Direction of Current
Brush No. 1	Brush No. 2	Total	
0.73 (neg.)	1.18 (pos.)	1.91	Metal to Brush No. 1
1.11 (pos.)	0.80 (neg.)	1.91	Brush No. 1 to metal
0.76 (neg.)	1.11 (pos.)	1.87	Metal to Brush No. 1

The interval between tests was very short; the contact drops in the third test do not quite return to the same values as in the first test, but the figures appear to show that the direction of current had a definite influence upon the contact drop. On the other hand, other tests made with carbon brushes in a similar way have shown a greater drop at the negative than at the positive brush. I have read statements from various sources which agree that there is a difference in the contact drop at the positive and negative brushes but do not agree as to which is the greater. One or two observers (including Dr. Kahn, I believe) have noticed that the greater drop does not always occur at the same pole, and this accords with my own experience. Speaking generally, with reference to a very large number of tests each lasting several days, in the majority of cases with copper-graphite the drop at the positive brush is much greater than at the negative, but with carbon brushes the drop is greater at the negative than at the positive perhaps more often than not, but I do not find any universal rule to be applicable.

Mr. Bartlett mentions several very interesting points in his communication. It is unfortunate he was not able to give the actual contact-drop figures taken on the turbo-dynamo commutator to which he refers. A variation as large as 7:1 when a second brush was added seems very difficult to account for, and it would appear that the increase in contact drop following the fitting of a third brush must have been due to some extraneous cause. The friction measurements referred to in the paper were taken by a combined electrical and mechanical method. The test brushes were fitted in brush boxes at the end of a carefully balanced lever mounted on ball bearings. The friction force could be neutralized by adjusting a spring balance, the amount of the force being read on the balance. As a check on this, the difference of input to the motor with and without the test brushes in place (after certain small corrections had been made) gave a measure of the friction force. Mr. Bartlett gives definite figures relating to the distribution of current in each individual brush. These figures are very interesting, but a description of the method used in obtaining them would have very greatly added to their interest.