THE DESIGN OF BRUSHES FOR THE HOMOPOLAR GENERATOR AT THE AUSTRALIAN NATIONAL UNIVERSITY

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by

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We wish to acknowledge the helpful co-operation received from Professor Sir Mark Oliphant and all the members of his staff, particularly Mr. R.A. Marshall, during our stay at Canberra.

SUMMARY

The authors were invited by The Australian National University to visit Canberra in order to advise on the practicability of using brushes for current collection on the very large homopolar generator under construction at the Research School of Physical Sciences.

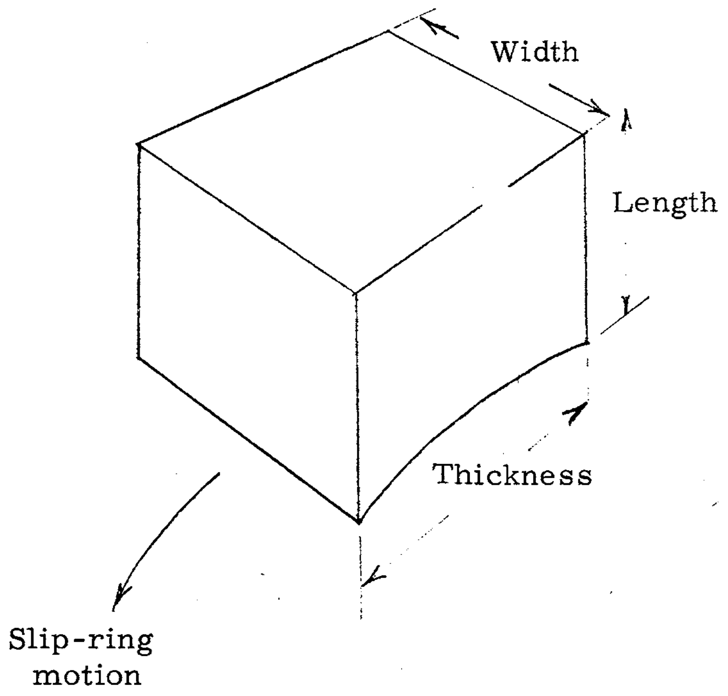
Experimental programmes were organised both at London and Canberra in order to evaluate various brush grades for the abnormal conditions associated with this application; as a result it was shown that the copper-graphite grade CM1S would operate under the required conditions of speed, current density and load and this grade was therefore chosen for initial trials on the generator.

We have considered in detail the proposals by the University for brushgear design, and the conditions of brush operation. We conclude that thermal stress of the rotor is a major problem at the rated output of the generator. Much further work on brushgear design and the effects of magnetic forces is required before the use of brushes can be said, with confidence, to be practicable.

FOREWORD

Terminology for Brush Dimensions

The terms 'length', 'width' and 'thickness' as used in this report correspond to the definitions generally accepted in brush technology, as illustrated by the following diagram:



1. Introduction

The homopolar generator which is being constructed at the Research School of Physical Sciences, Australian National University, Canberra, is a novel form of pulse generator in which energy is stored in a system of two contra-rotating steel flywheels, each 12 feet in diameter and weighing 40 tons. The flywheels rotate in an axial magnetic field so that they act as the armature of a homopolar generator, and are rapidly brought to rest when electrical energy is extracted in the form of a high current pulse. The machine was designed to power the orbital field coils of a 10 GeV proton synchrotron. However, with the development of alternative methods of accelerating protons to this energy the allied synchrotron project was abandoned, and it is now proposed to use the generator for other purposes; e.g. the study of plasmas. In this role it would have a stored energy of 500×10^6 joules, which is greater than that available from any existing capacitor bank, and would be capable of delivering a pulse lasting two seconds and reaching a peak current of 1.6×10^6 amps.

Although in principle a simple form of machine, the development of a generator of this size is a major engineering project, and its construction, which started in 1951, is not yet completed. Most of the engineering problems have been overcome, but the method to be used for collecting current from the rotating members remains undetermined. A system using a sodium-potassium alloy, which is liquid at room temperature, was developed for this purpose, and was successful in collecting currents up to 1.8×10^6 amps from one of the rotors of the machine. The hazards associated with the use of this material caused this approach to be abandoned in 1962.

At this time it was suggested that conventional solid brushes might be used for current collection, and experiments were carried out on simulative test machines. The results were encouraging, and an arrangement of brushes, brush holders and their associated actuating mechanisms has been proposed for use on the homopolar generator.

In December, 1963 The Australian National University invited Drs. A. Stebbens and H. Ward (of Morganite Research and Development Ltd. and Morganite Carbon Ltd., respectively) to visit Canberra in order to examine these proposals, to recommend suitable brush materials for experimental purposes, and to assess the overall feasibility of this method of current collection. The conclusions and recommendations resulting from this visit are set out in this report.

2. Terms of Reference for Brush Consultants

These can be summarised as follows:

(a) to consider the detailed proposals put forward by Mr. R.A. Marshall of A.N.U. Mr. Marshall has used brushes under conditions simulating those which occur during operation of the generator, and has recommended on the basis of these experimental results what form the brushes and brush holders should take. This work is summarised in a report "The Design of Brushes for the Canberra Homopolar Generator", issued in January, 1964, and is referred to hereafter as Marshall's report;

(b) to propose, on the basis of an experimental programme carried out by Morganite in London, a range of brush materials for evaluation;

(c) to initiate an experimental programme at Canberra to assist in the final choice of brush material, and to study at first hand the problems of brush mounting and the conditions required for optimum brush performance;

(d) to give an opinion, based on our experimental observations and previous experimental work at Canberra, on the feasibility of carrying out current collection using solid brushes;

(e) to give an opinion, as far as it is possible to do so, on whether the proposed use of brushes, in addition to being feasible, would result in a machine which would be capable of practical and reliable operation as an energy source;

(f) to comment upon any other aspects concerned with the construction and operating conditions of the generator which might be of assistance.

3. Conditions under Which Brushes Operate

3.1 General

For reference purposes a brief description of the generator, its operating cycle, and the conditions under which the brushes would operate, is given in this section.

Figure 1 is a schematic cross section showing the position of the rotors and the method of connection through eight sets of brushes, which gives an open circuit voltage of 800 V at 900 r.p.m. The lettering of the rotors and numbering of brush positions follows that used by Marshall.

Figure 2 shows the rotors and pole pieces approximately to scale. Brush groups (1) and (8) each operate on a copper slipring and the sole access to the brushgear is between rotor and pole piece through apertures in the air bearing pad. Groups (2), (3), (6), and (7) can work only over a limited band on each rotor due to the effect of the fringing field, which gives rise to a potential gradient in an axial direction at the rotor periphery. These bands are indicated in Figure 2. Groups (4) and (5) are situated in the gap between the discs B and C, and connect them electrically. Details of the brushgear are discussed in Section 6. Magnetic fields and

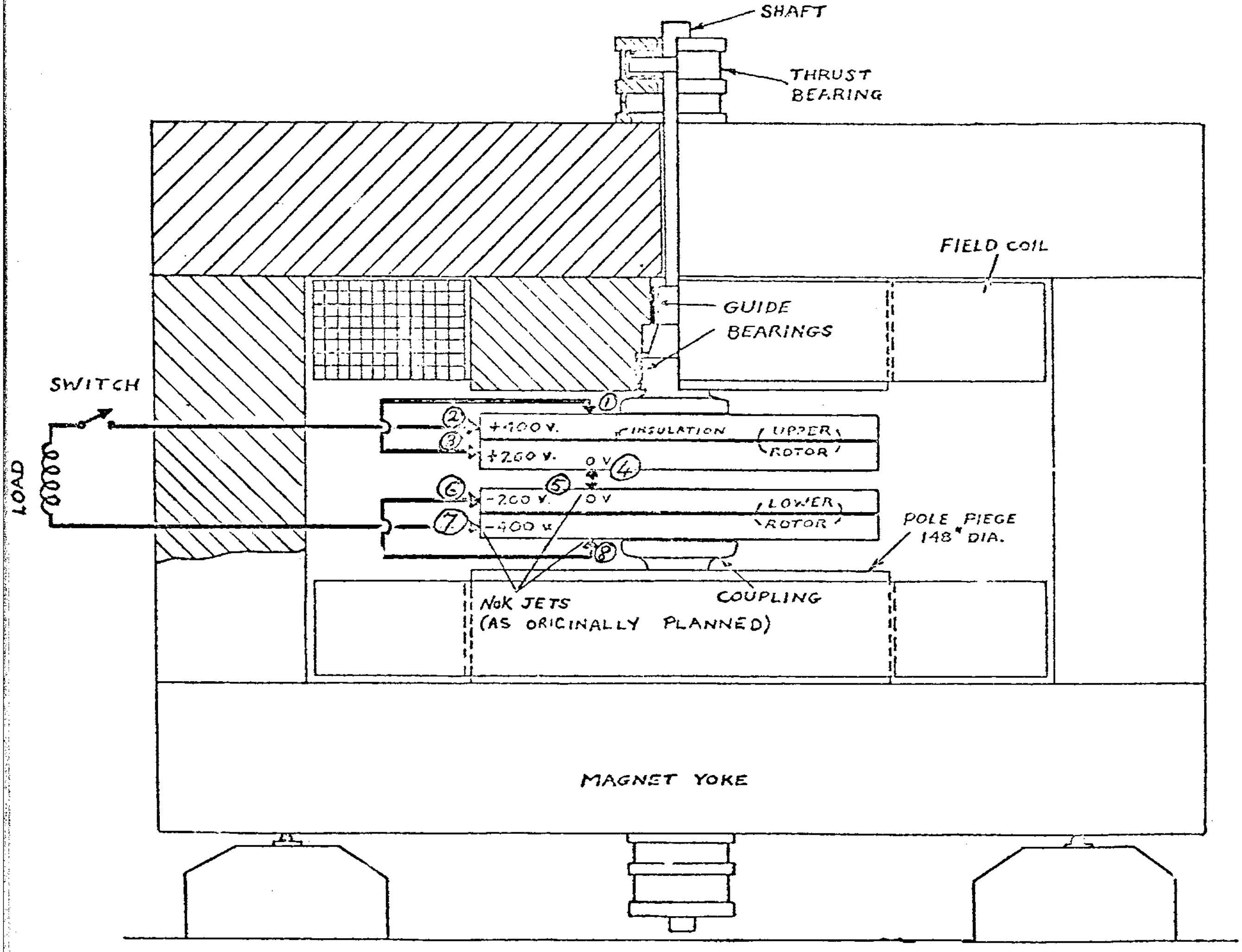


Fig. 1: General Layout of Homopolar Generator

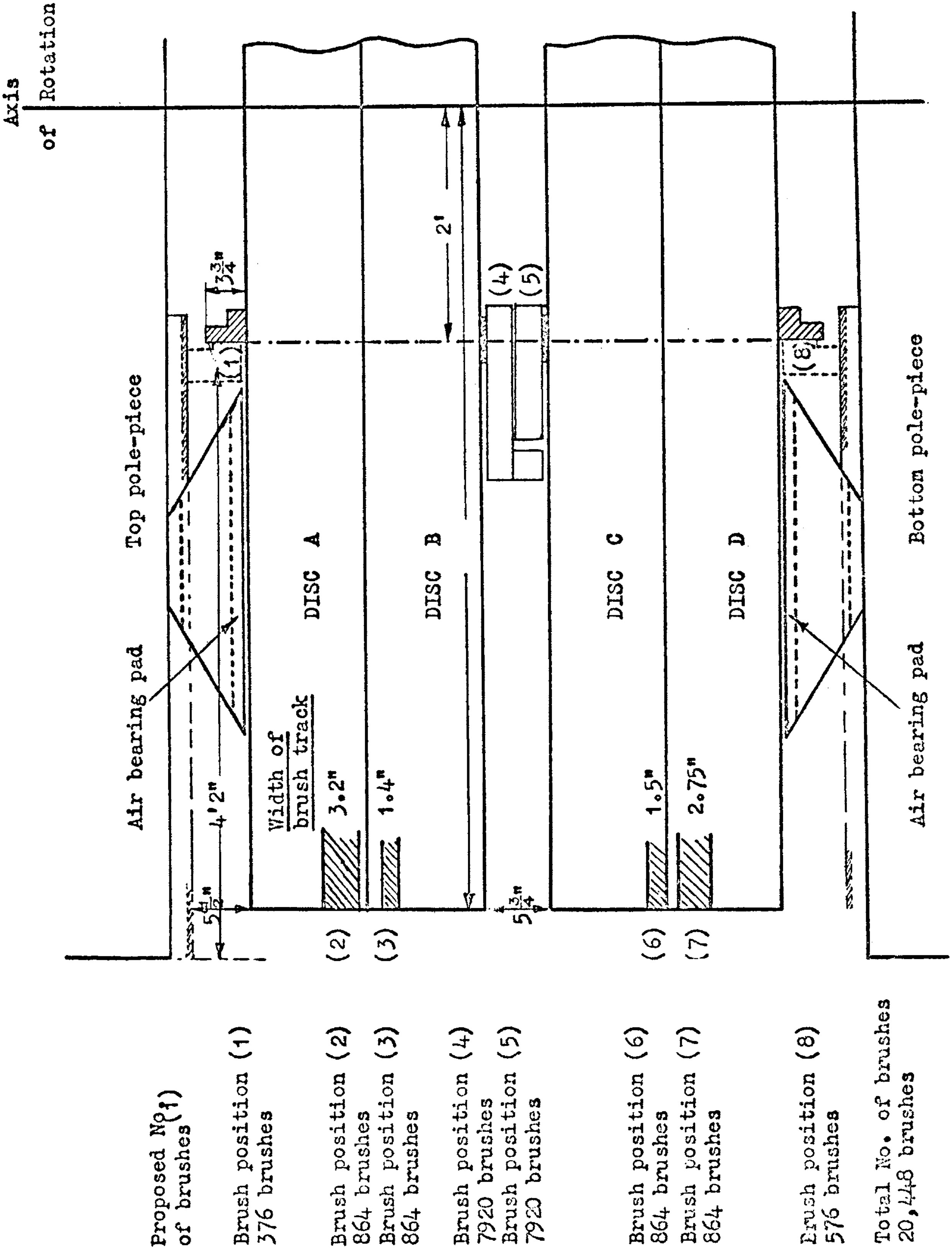


Fig. 2: Rotors and Pole-Pieces of Homopolar Generator (Scale 0.2cm = 1 inch)

voltage gradients are also indicated in Figure 2 wherever they have a bearing on the design of brushgear.

It is proposed to operate the machine as follows. Direct current is applied to discs A and D through sets of brushes working on the periphery of the rotors and on slip-rings fitted to the stub shafts. These slip-rings and brushes are not shown. With the main field excited and all other brushes lifted, the rotors are brought to 900 r.p.m., rotating in opposite directions. The output busbars are connected through a switch to a load, which will be assumed to be the inductive load of the synchrotron winding. To obtain a pulse, all brushes (sets 1-8) are brought into contact (with the correct brush force) in about $\frac{1}{4}$ second, the switch is closed and current begins to flow. After $\frac{3}{4}$ of a second the current has risen to its peak of 1.6×10^6 amps and the speed has fallen to about 250 r.p.m. As the current decreases the synchrotron field begins to collapse, and energy is fed back into the rotors. They come to rest in the next $\frac{1}{4}$ second, then reverse their direction of motion and after a further $\frac{3}{4}$ second, when the current instantaneously reaches zero and the switch is opened, they are rotating at 400 r.p.m. The brushes are then lifted.

From this brief description of the operating cycle of the generator, the problems of current collection can be deduced. The brushes are to operate at high sliding speeds and high current densities, and they must have a reasonable life under these conditions. The brushgear not only has to lower and raise the brushes in $\frac{1}{4}$ - $\frac{1}{2}$ second, but must apply an equal load to each brush in a set to ensure that the current distribution is uniform. Brushes must be held in such a way that they maintain a stable contact while the rotors reverse, carrying at the same time nearly the peak current. Also the forces due to interaction between the local magnetic fields and currents in the brush and the leads must not disturb the contact.

In addition to these problems there is a possibility of thermal fatigue occurring at the periphery of the rotors due to rapid heating caused by frictional forces and voltage drop at the sliding contact during a pulse. This problem has been treated thoroughly by Marshall and will be considered in Section 7.

3.2 Comparison with Normal Conditions

The surface speeds and proposed brush current densities for the homopolar generator are abnormally high. There are three distinct types of brush position on the machine (Figures 1 and 2) and the proposed[1] conditions of operation for these positions are shown in Table 1. The values of 'force per brush' and 'brush pressure' are the nominal applied values and neglect electromagnetic forces; in certain cases these latter forces are very high, as discussed in Section 7.

The limiting values are for practical commercial operation and generally do not coincide with limits for failure. The peripheral speed of both commutators and slip rings is limited by mechanical stresses and conventional factors of

TABLE 1

Brush positions	Rotor dia. (in)	Rotor surface speed (ft/min)	No. of Brushes per position	Brush Size (in) (LxWxT)	Force per brush (lb)	Brush pressure. (lb/sq. in)	Current per brush @ 1.6 x 10^6 A (A)	Brush current density @ 1.6 x 10^6 A (A/sq. in)	Rotor material
2,3 6,7	140	33,000	864	0.2x0.4 x0.4 (approx.)	8	51	1,850	11,600	Steel
4,5 (Slide out system)	48	11,300	7,920	? x.08 x0.375	0.5	17	202	6,730	Steel
1,8	48	11,300	576	0.4x0.4 x0.875	4	11	2,780	7,950	Copper

Typical and limiting values for surface speed, brush current density and brush pressure on conventional machines are given in Table 2. Note that the limiting values given would not normally occur together on a particular machine.

TABLE 2

Type of machine		Surface speed (ft/min)	Current density (A/sq. in)	Brush pressure (lb/sq. in)	Typical brush life	Slip-ring or commutator material
D.C. Commutator machines (Continuous ratings)	Typical	5,000	60	$2\frac{1}{2}$	10 months	Copper
	Limiting	12,000	100	10	4 " (min)	Copper
Turbo Alternator Slip-rings (Continuous ratings)	Typical	14,000	80	$2\frac{1}{2}$	6 "	Steel
	Limiting	18,000	120	4	3 " (min)	Steel
Car starter motors (Pulse condition)	Typical	1,500	1,200	16	50,000 starts	Copper

safety different to those in the case of the homopolar generator. The current densities quoted are limited by consideration of brush wear, commutation quality and temperature rise. A typical requirement on conventional machines is for at least six months brush life on continuous full load, or in the case of car starter motors, for 50,000 starts without replacing brushes. Obviously, if such brush life requirements are to be waived, and provided that excessive temperatures are not encountered, then the brush current density may be increased far above what are normally regarded as limiting values.

The very high brush current densities on the homopolar generator necessitate the use of high copper content brushes. Brushes with a high silver content may be marginally better since they have a very slightly higher electrical conductivity, but the cost of silver brushes is so much greater that it is not recommended that they be seriously considered. On the basis of experience on conventional machines it could be forecast, before examining the experimental results given in the next two sections, that the brushes most likely to give optimum performance would be of the following two types:

(a) Automobile starter brushes

This application is the most well known of all 'pulse' applications for brushes involving higher than normal current density. High copper content brushes are always used. A typical composition is:

copper - 85%
lead - 10%
graphite - 5%

(b) Heavy duty slip ring brushes

These commonly operate at continuous brush current densities up to 150 A/sq. in. There are two main types, firstly, copper/lead/graphite grades similar to those used for automobile starter brushes and, secondly, copper/lead/tin/graphite grades. A typical composition for the latter is:

copper - 80%
lead - 5%
tin - 5%
graphite - 10%

They are usually referred to as 'bronze graphite' material. However, the conditions on the homopolar generator are so different from conventional applications that experience alone was not sufficient to indicate which of many possible high copper content grades would be the optimum. Experimental work was initiated at Battersea in order to give an indication of the optimum grade when choosing between high copper content grades with marginal differences in composition.

4. Experimental Programme Carried Out by Morganite at London

Prior to our departure at short notice for Australia, an urgent programme of experimental work was initiated at Battersea in order to select the optimum brush grades for running under conditions of high speed, current density and load. The apparatus used and test conditions were:

Tests on Copper slip-rings

Apparatus:

Copper slip-ring, 9 in. diameter, 1-1/8 in. wide
128 axial slots each 0. 8 mm wide x 1. 6 mm deep
Directly driven by d. c. motor
4 brush holders, 1 in. x 3/8 in. section, 8° trailing
2 positive and 2 negative brushes connected in parallel with alternate positive and negative brushes around the slip-ring periphery.
Details of the brush design are shown in Figure 3: half of the brush face was cut away in order to double the current density compared to that normally obtainable.

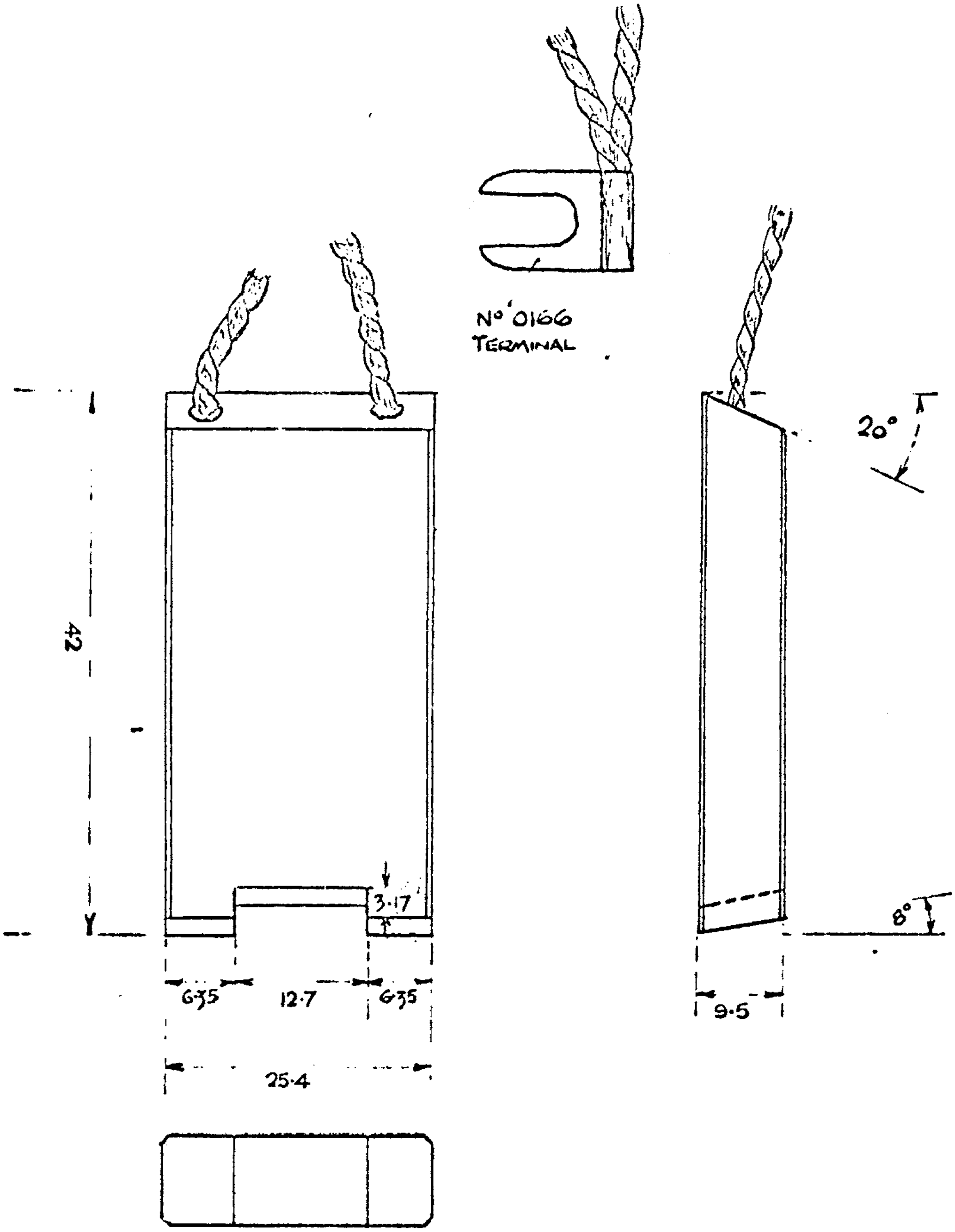
Test conditions:

(1) Continuous running:	peripheral speed	8000 ft/min
	brush pressure	8 psi
	current density	240 A/sq. in.
	current/brush	45A
(2) Pulse current test:	current pulse duration	5 seconds
	no current for	30 seconds
	repeated for one hour	
	pulse current density	1000 A/sq. in.
	subsequently increased to	2000 A/sq. in.

Test procedure:

Prior to each test the rings were turned with a diamond tipped tool and their slots lightly 'veed'. The rings were then polished with well worn 100 grit Carborundun paper. Each brush was, in turn, radiused with 100 grit Carborundum paper and finished with 320 Durex paper. After bedding, the machine, brushes, and brush boxes were wiped clean to remove copper and carbon dust.

After preparation the brushes were run at the test condition (1) for a bedding period of approximately 18 hours, during which time running performance was closely observed. The brush lengths were measured at the end of the bedding period and the test proper commenced. Hourly readings of positive, negative and total contact voltage and coefficient of friction were made. Following a test period of approximately 48 hours running, a contact drop - current density curve was taken up to



Two 3.0 m/m 45 S.W.G FLEXIBLES
100 m/m LONG.
B4 CONNECTIONS.

Fig. 3: Test Brush

approximately 1000 amps/sq.in. Any brush grades which did not spark during the measurement of the contact drop - current density curve were then subjected to current pulses for not less than one hour at 1000 amps/sq.in. and for not less than 35 minutes at 2000 amps/sq.in., during which time a pen recording was made of the total contact voltage. The pulsing was so arranged to give a 5 second current pulse followed by 30 seconds at no current (condition 2). At the end of the pulsing tests, the machine was shut down and final brush lengths measured.

Grades tested:

Tests were carried out on six standard Morganite grades - CM+O, CM-O, CM, CM1S, CM2 and SM7938. The CM grades listed all have a high proportion of copper: 80-90% by weight. The SM7938 contains a high percentage of silver. These grades were chosen for test on account of their high electrical conductivity and low contact drop as required for the very high pulse current densities on the homopolar generator. Typical physical properties for these grades, and friction and contact drop test results under standard conditions, are given in Table 3.

Tests were also carried out on a denser than normal version of CM1S - denoted CM1S(DE): also on brushes having a 1.5mm dia. hole vertically in the centre of each section of the two running faces per brush (Figure 3). These drilled brushes are denoted (DR). The aim of the holes was to alleviate the possible build up of air pressure at the contact face under these high speed conditions. The results are given in Table 4.

Four specially formulated variants of CM1S and CMO were prepared and tested, but since the results were not better than for the standard grades these will not be detailed. The code numbers for these grades, some of which were also tested at Canberra, were VH496 E1251, VH496 E1253, VH496 E1255 and VH496 E1257.

Results: The results are summarised in Table 4.

It will be observed that the only grade which performed satisfactorily up to the 2000 A/sq.in. pulse condition was CM1S. The CM1S(DE) gave a significantly lower rate of brush wear but was associated with occasional 'spitting' at 2000 A/sq.in. It must be pointed out that only one test could be done on each grade in the short time available. On the basis of experience of relatively short term tests of this nature any difference in average values of contact drop or friction less than 10% between grades is not significant, and any different in wear less than 25% is not significant.

The inability of CM+O and CM-O to run satisfactorily under continuous loading is in agreement with general experience. These grades are designed for automobile starter motors. However, since this pulse type of duty is similar to that on the homopolar generator their inability to run on continuous load is not particularly relevant.

The results do not indicate that the drilling had any significant effect. In order to confirm that the performance of CM1S was satisfactory on steel slip-rings the following test was carried out at the continuous loading of 240 A/sq. in. This grade is not normally run on steel slip-rings.

Tests on high speed grooved steel slip-ring

This slip-ring is a replica of a turbo alternator type of slip-ring.

Ring details:

Steel slip-ring material to B.E.A.M.A. Spec. (Grade 2)
Ring dia. 26 in. (66 cm)
Ring width $2\frac{3}{4}$ in. (7 cm)
Turned with one helical groove 1/8 in. wide x 3/16 in. deep
Pitch = $\frac{1}{2}$ in.

Test conditions:

Peripheral speed - 15,000 ft/min
Continuous current density - 240 A/sq. in.
Spring pressure - 8 lb/sq. in.
No. of brushes - 12
Brush section - As for Figure 3
Brush holders - As for tests on slotted copper rings.

Results:

Grade	Coefficient of friction Ave.	Range	Average C.D. (V) +ve	-ve	Average brush life (hrs/in)
CM1S	.09	.07/.11	0.36	0.37	700

Occasional slight pin point sparking was observed on some brushes.

Brush surface descriptions:

Track 1 (positive)
Smooth, very highly polished surface of a light chocolate colour, with slight sparking marks.

Track 2 (negative)
As for Track 1 but some surfaces had a few small dull areas.

Ring surface descriptions:

Track 1. Smooth, very highly polished surface of a light copper tarnish. One darker band observed.

Track 2. Smooth, very highly polished surface with only very slight trace of copper.

Other tests

We just had time to carry out two brief experiments to assess the behaviour of brushes at even higher currents. In the first a static contact between a brush and a mild steel surface was pulsed at peak currents of 700 amps to obtain an approximate value of contact drop. The brush section was 0. 2 in. x 0. 2 in. and the load approximately 60 psi. Pulse duration was 2 milliseconds. Contact drop was measured in this way for three grades, CMO, CM1S, and CM2, and the values obtained were 0. 45v, 0. 54v and 0. 51v, respectively.

Dynamic tests were carried out at 2500 ft/min. using two brushes operating on a flat mild steel slip-ring. Provision was made for passing current pulses up to 2000.amps through the brushes, which were 0. 2 in. x 0. 2 in. section. The grades used were CMO, and CM1S, and the applied load 6 psi. At this load CMO was found to spark vigorously during a pulse of 70 amps for one second. CM1S generally gave less sparking, and at 10 psi would operate at 200 amps with only slight sparking.

These experiments showed that the stiffness of the leads, which it was necessary to fit to the brushes in order to carry 2000 amps, disturbed the stability of contact. This may well be a problem when using brushes guided by a holder even with more favourable brush dimensions.

Conclusions

The ability of CM1S to withstand 2000 A/sq. in. pulses at 8000 ft/min and 8 lb/sq. in. was regarded as promising and worthy of further testing at Canberra under conditions nearer to those on the homopolar generator. It was also considered that CM+O and CM-O should be tested at Canberra, in spite of the poor results at Battersea--there not being sufficient time to test these grades thoroughly under pulse conditions.

5. Experimental Programme at Canberra

Before an experimental programme was initiated to assist in the choice of a brush material for the homopolar generator, Mr. Marshall outlined the results of his experiments on two test rigs, both of which are described in his report. One has a 2 in. diameter rotor which can be operated up to 60, 000 r.p.m. This is fitted with 8 brushes and has been used to investigate thermal fatigue of rotors and methods of water cooling. The other has an $18\frac{1}{2}$ in. diameter mild steel rotor operating at 6, 000 r.p.m., giving a surface speed of 32, 000 ft/min, and is fitted with two brush holders which are basically similar to those proposed for positions 2, 3, 6 and 7 of the homopolar generator. Conditions on the $18\frac{1}{2}$ in. diameter rig are more nearly comparable with those of the generator, although it will not simulate the thermal loading required, and it was decided to use this rather than the 2 in. rig for the evaluation of experimental brush grades.

TABLE 3

Properties of Morganite Brush Materials

Not to be published without permission from Morganite Carbon Ltd., London. These figures are averages from a large number of test results.

	CMO	CM	CM1S	CM2	SM7938
Compressive strength (lb/sq. in.)	18,800	12,500	19,500	8,580	
Shear strength (lb/sq. in.)	3,790	3,180	6,240	2,710	
Modulus of Elasticity in Compression (lb/sq. in.)	$0.91\text{x}10^{6}$	$1.0\text{x}10^{6}$	$0.82\text{x}10^{6}$	$0.04\text{x}10^{6}$	
Izod impact (ft-lb)	0.29	0.29	0.62	0.20	
Soleroscope hardness	4-7	5-7	7-11	13-17	10-13
Bulk density (gm/cc)	6.5	6.1	5.5	4.7	7.4
Air permeability (cm/sec)	$3\text{x}10^{-8}$	$3\text{x}10^{-8}$	$1\text{x}10^{-8}$	$3.2\text{x}10^{-8}$	
Thermal expansion per $^{\circ}$C	$17\text{x}10^{-6}$	$17\text{x}10^{-6}$	$16\text{x}10^{-6}$	$15\text{x}10^{-6}$	
Thermal conductivity (cal/cm^{2}/sec/($^{\circ}$C/cm))	0.30	0.30	0.18	0.33	
Specific heat (cal/gm$^{\circ}$C	0.089	0.092	0.096	0.11	
Rockwell hardness	47	35	37	-	
Specific resistance	$2.5\text{x}10^{-6}$	$3.5\text{x}10^{-6}$	$15\text{x}10^{-6}$	$5.5\text{x}10^{-6}$	$1.3\text{x}10^{-6}$

9 in. dia. slotted copper ring. 2 lb/sq. in. (Brushes 1 in. x 3/8 in. section)

	CMO	CM	CM1S	CM2	SM7938
Friction coefficient (55 A/sq. in.)					
3500 ft/min	0.19	0.10	0.09	-	0.09
17500 ft/min	0.23	0.18	0.16		
5000 ft/min				0.08	
2500 ft/min				0.13	
Contact drop/brush (3500 ft/min)				(5000 ft/min)	
55 A/sq. in.	0.18	0.13	0.16	0.17	0.10
27.5 A/sq. in.	0.10	0.09	0.11	0.15	

TABLE 4

Experimental Results on 9 in. Dia. Copper Slip-Rings

Grade	Continuous load: 8 lb/sq. in., 8000 ft/min 240 A/sq. in.						Pulse load		Remarks
	µ		Contact drop(volts)			Brush life (Hrs/in)	Range CD V/Br. @1000 A/sq. in. pulses	Range CD V/Br. @2000 A/sq. in. pulses	
	Avg.	Range	+ ve	- ve	mean				
CM+O									Both shut down after approx. 2 hrs. due to poor op. i. e. cont, spark & occ. spitting
CM-O									
CM	.07	.05/.08	0.09	0.09	0.09	-	-	-	Not pulsed. Sparked @ 700 A/sq. in.
CM1S	.15	.13/.18	0.021	0.051	0.036	+ 485 - 740	0.12 - 0.185	0.36 - 0.58	No spark. obsérved @ 2000 A/sq. in. pulse (35 min duration)
CM2	.10	.10/.11	0.22	0.09	0.16	-	-	-	Spit. & spark. @ 5000 A/sq. in.
CM1S(DE)	.15	.11/.18	0.031	0.034	0.033	+1040 -1160	0.106 - 0.19	0.36 - 0.56	Occ. spit @ 2000 A/sq. in. pulsing
CM1S(DR)	.14	.12/.15	0.053	0.052	0.053	+ 820 -1000	.10 - 0.16	0.33 - 0.56	
CM1S(DE) (DR)	.16	.11/.18	0.021	0.045	0.033	+ 600 -1200	.12 - .20	.33 - .58	
SM7938	.15	.11/.18	0.02	0.03	0.025	Approx. 400 hrs/in.	0.08 - 0.17	-	Heavy brush wear with consid. spit'g. @ 2000 A/sq. in. pulsing
SM7938(DR)	.18	.15/.20	0.012	0.023	0.018	+ 360 - 195			

DE = Denser
DR = Drilled

Drilling: 1 x 1.5 mm dia. hole vertically in the centre of each section of running face.

The questions to be resolved fall into three groups. What are the operating conditions and brush materials which give the best performance, i.e. maximum life, minimum damage to the rotor surface, and minimum dissipation at the interface? How stable is the proposed brushgear for positions 2, 3, 6, 7, will it bring brushes into good contact with the rotor and avoid sparking; will the contact remain stable when the rotor reverses and under the action of mechanical and magnetic up-setting forces? What are the optimum conditions for the brushes in positions 1, 8, and 4, 5?

It was decided that the last question could be answered from the experiments already carried out at Canberra and London, and the experimental programme was therefore designed to answer the first two questions, and is set out below.

(1) Measure the following properties of each of the proposed brush grades on the $18\frac{1}{2}$ in. test rig under pulsed conditions (Figure 4);

  (a) voltage-current characteristic during pulse for positive and negative brushes;

  (b) friction coefficient, with and without current;

  (c) wear rates of positive and negative brushes with and without current;

  (d) bulk temperatures attained by brushes, with and without current.

(2) Examine the bedding of the brushes and conditioning of the rotor surface during these tests, and assess the damage caused after repeated pulsing.

(3) Ascertain the minimum load needed to maintain stability of the brush during pulses with a view to increasing brush life and reducing frictional heating.

(4) Examine the effect of reversing the direction of rotation of the rotor while maximum current flows through the brushes.

Experimental

Two brushes 0.47 cm x 1 cm x 1 cm (0.185 in. x 0.4 in. x 0.4 in.), length x width x thickness, were used in each test, and were first brazed to copper backing plates 1 cm square and about 2 mm thick through which a 6BA screw was fitted. They were then mounted on the holder, consisting of a flexible strip of beryllium-copper which served to locate the brush and hold it from the surface of the rotor, and a number of strips of 0.002 in. copper foil which led current to the brush. Figure 5 shows the arrangement of one brush and holder on the $18\frac{1}{2}$ in. rig. A thermocouple can be also mounted in the brush.

Brushes were brought into contact with the rotor by supplying compressed air to the bellows. A uniselector controlled the time sequence of each current pulse,

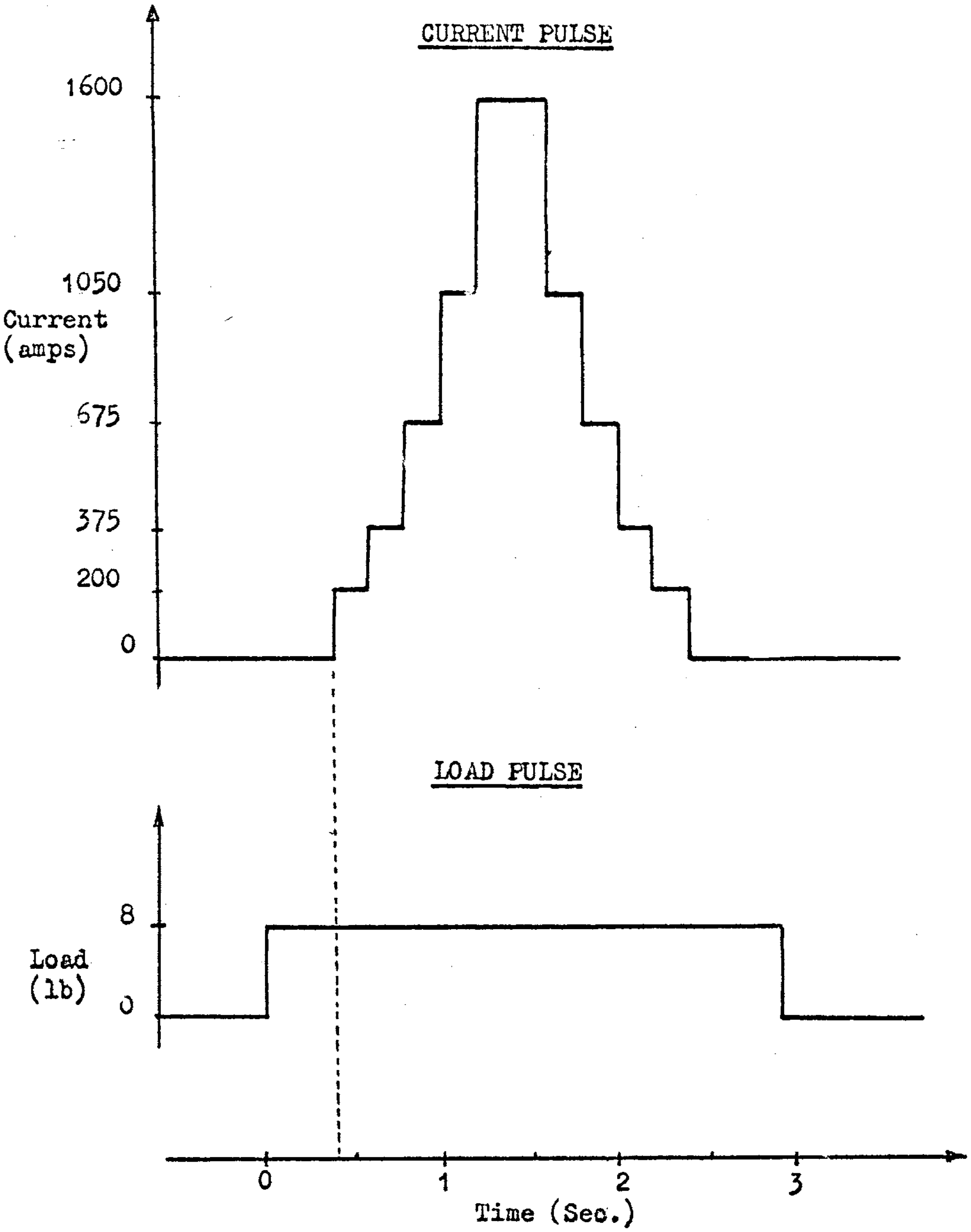


Fig. 4: Pulse Conditions for Experimental Programme at Canberra

applying the brushes 0.4 second before the current, which increased in steps to a maximum of 1600 amps and then decreased to zero over a period of 2 seconds. After a further 0.5 second the air supply was cut off and the brushes were lifted from the rotor under the action of the spring. Current was supplied from a 24 volt heavy duty battery.

The contact voltage of each brush was measured with respect to the rotor using a mercury cup, and the current by means of a standard shunt. Friction coefficients were calculated from the deceleration of the rotor during a pulse, using an electronic counter to count the number of 100 kc/s pulses per revolution. The accuracy of friction measurement was ± 10%. Wear was calculated by weighing the brush before and after a series of pulses, usually 30 or 50. The brushes were bedded before this measurement.(Accuracy ± 5%). Temperatures in the brush, about 0.1 in. (2.5 mm) from the rubbing surface, were measured on a high speed U. V. recorder.

Particular care was taken to ensure that the brushes were parallel to the surface of the rotor when in their rest position and a constant distance, about 1/16 in., away from it. The wear rates were such that about 20 applications of load, each of 3 seconds' duration, was sufficient to give bedding over the whole area, and this procedure was adopted in all subsequent experiments.

In the first few experiments the behaviour of brushes with low applied loads was investigated with the aim of increasing brush life and reducing the total thermal dissipation in the rotor surface. Loads of 2 lb and 4 lb per brush were used. At 2 lb the brushes were not held in contact with the rotor in a stable manner, and with a current of 700 amps it was possible to observe hot spots moving about the edges of the brush. When the current was increased to 1600 amps violent sparking almost invariably occurred, with severe transfer of copper to the surface of the rotor, and although the copper could be cleared with emery paper there was some permanent damage to the rotor. (It may be noted that these early experiments were carried out on a part of the rotor which already had a rather rough pitted surface.) At the higher load, 4 lb, operation was more stable, and sparking occurred in a few experiments only. However, in view of the damage caused by sparking, it was thought advisable to increase the load to 8 lb per brush, a value which Marshall had found in earlier experiments to be the lowest at which operation was completely reliable. All later experiments were carried out at this load, and with the brushes operating on a smooth part of the rotor surface.

There seemed to be no clear reason why such a high load should be necessary (50 psi compared to a maximum of about 10 psi on conventional machines), even allowing for the stiff leads to the brush. The truth of the rotor periphery was therefore measured using a capacitance gauge to see whether vibration could be causing brush instability. This measurement was not exact, but indicated a displacement of about 0.004 in. peak-peak at 6,600 r.p.m. (0.005 in. peak-peak at 3,300 r.p.m.). This is excessive for slip-ring operation at such a high rotational speed, and dynamic balancing would appear to be called for. We recommend that the eccentricity should

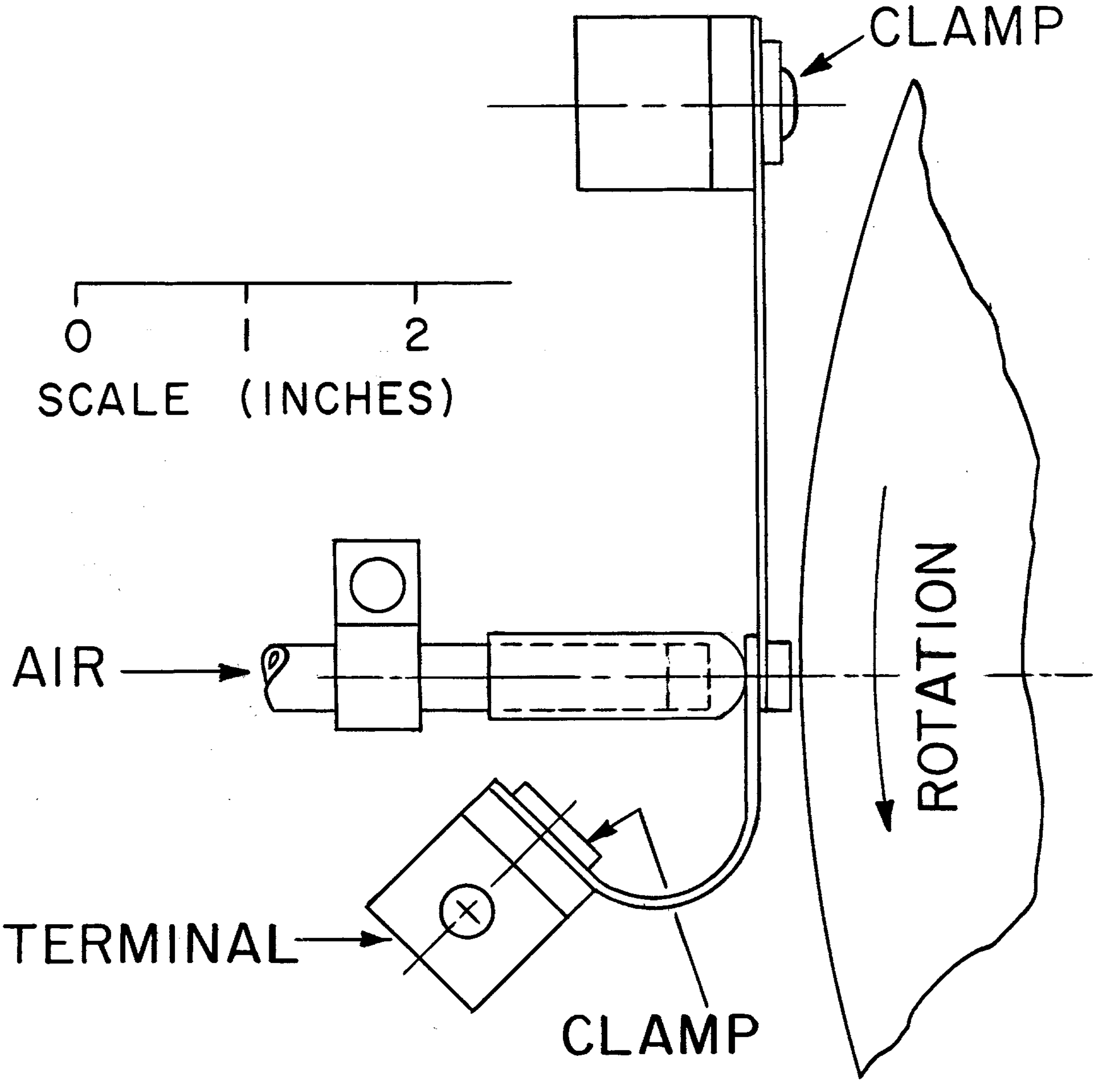


Fig. 5: Brushgear on 18.1/2 inch Diameter Rig

not be more than 0.001 in. Following dynamic balancing the effect of working at reduced loads could usefully be investigated. A reduction in load from 8 lb to 4 lb, which should still be high enough in relation to magnetic and frictional force to ensure stability, would approximately double brush life and halve the frictional heating with only a slight increase in contact drop.

The main series of experiments was then carried out using the following standard and experimental brush grades:

CM1S
CM-O
VH496 E1257 (CM903)
CM+O
CM1s(DE) (CM902)
CM904

After bedding, the brushes were applied to the rotor for 3 seconds without passing current, and with 30 seconds between each application. After 30 or 50 pulses, during each of which the friction coefficient was measured, both brushes were weighed and their wear rates calculated. The brushes were subjected to a further 30 or 50 pulses with current flowing. Friction coefficients and wear rates were again measured. A summary of the results obtained is given in Table 5.

The effect of reversing the direction of rotation of the rotor while the brushes carry maximum current (1600 amps) was investigated, to see whether the brushes maintained a stable contact, or whether overheating or burning took place. After modifying the brush holders to locate the brush correctly in both directions, the rotor was oscillated slowly to and fro by hand with the current on. There was no evidence of sparking, and only a slight increase in contact drop at the instant of reversal. No sign of burning or other damage was visible on the rotor.

Conclusions

1. On the basis of the experimental results obtained in London, and those described above, we select CM1S as being superior in performance to the other grades tested, and we therefore recommend this grade for trial on the homopolar generator.

Referring to Table 5 it will be seen that the wear rates per pulse for CM903, CM+O and CM904, were significantly greater than for the other grades CM1S, CM1S(DE), and CM-O. Further, CM1S(DE) suffered from high friction without having any compensating advantage in wear rate or contact drop relative to CM1S and CM-O.

CM1S has a higher friction coefficient than CM-O, but slightly lower wear rate However, the slope resistance (i.e. the slope of the voltage-current characteristic) at the working current is greater with CM1S than CM-O, and offers an advantage in helping to suppress uneven current distribution due to the voltage gradient on the rotor. CM-O did not behave satisfactorily in London, and Marshall has found, in some of his earlier experiments, that the friction and contact drop of CM-O did not always remain steady, and that sparking sometimes occurred. For these reasons CM1S appears preferable.

2. Under the conditions used in these experiments, which were similar in many respects to those proposed for the rotor rim brushes of the homopolar generator, all the brush grades tested were found to perform satisfactorily for a total of several hundred pulses. There was no sparking; the rotor surface became polished rather than damaged; friction coefficients were constant for each grade and independent of the passage of current.

3. Wear rates were generally consistent for both brushes used in each experiment and, except for CM903 and CM904, were not significantly altered by the passage of current. Where the distribution of current in a brush is not uniform, i.e. when it operates in the presence of a potential gradient, the fact that wear is independent of current is of considerable importance. Many of the outer rim brushes for example will operate under these conditions.

The mean wear rate of CM1S was 0.00019 in. per pulse, giving a theoretical brush life of 1000 pulses (0.2 in.) at positions 2, 3, 6, and 7.

4. With a load of 8 lb per brush there was no sign of contact instability at any time, and it was also possible to reverse the direction of rotation of the test rotor without causing burning or sparking. We therefore consider that the form of brush holder proposed for brush positions 2, 3, 6, and 7, which is similar to that used in these experiments, is likely to be satisfactory. However, we recommend that the final form of brush holder be tested for stability with the spring in a vertical position as it would be on the homopolar generator.

5. The results obtained by using a reduced load of 4 lb per brush were encouraging, and we recommend that further tests be carried out at this load, preferably on the homopolar generator using an external power supply.

6. Brush Design

There are three distinct brush design problems on the homopolar generator, namely:

(1) Rotor rim brushes (positions 2, 3, 6, and 7).
(2) Top and bottom inner brushes (positions 1 and 8).
(3) Mid inner brushes (positions 4 and 5).

These problems will be considered separately. This section mainly deals with mechanical aspects of the brush design; magnetic, electrical and thermal effects are considered in detail in Section 7.

TABLE 5

Results of Experiments at Canberra on 18½ in. Dia. Test Rig

(All results at 6,600 r.p.m., except where indicated)

Grade:		CM1S		VH496 E1257 (CM903)		CM1S(DE) (CM902)		CM-O	
μ	no current	0.221		0.196		0.278		0.17	
	current	0.205		0.198		0.271		0.20	
Polarity		+	-	+	-	+	-	+	-
Brush temp. (^{o}C)	no current	106.3	75.3						
	current	139.5	128.0						
Wear per pulse(x10^{-3}in)	no current	0.174	0.185	0.309	0.279	0.244	0.242	0.285	0.073
	current	0.212	0.175	0.557	0.514	0.197	0.251	0.248	0.175
Contact volt drop at 1650 A approx.	pulse No.	1	1	1	1	1	1	1	1
	volts	0.725	0.85	0.75	0.8	0.725	0.725	0.7	0.8
	pulse No.	30	30	30	30	30	30	30	30
	volts	0.70	0.725	0.6	0.70	0.65	0.725	0.63	0.68
Slope resistance (ohmsx10^{-4})		2.5		1.8		3.8		1.0	

Grade:		CM+O		CM904		CM1S repeat		CM1S (3300 rpm)	
μ	no current	0.198		0.19		0.25		0.249	
	current	0.20		0.17		0.22		0.238	
Polarity		+	-	+	-	+	-	+	-
Brush temp. (^{o}C)	no current							61.0	55.5
	current							124	123
Wear per pulse(x10^{-3}in)	no current	1.3	1.2	0.47	0.40	0.138	0.189	0.064	0.060
	current	1.1	0.76	0.76	0.82	0.22	0.138	0.085	0.076
Contact volt drop at 1650 A approx.	pulse No.	1	1	1	1	1	1	1	1
	volts	0.55	0.75	0.8	0.75	0.75	0.85	0.75	0.70
	pulse No.	7	7	30	30	30	30	30	30
	volts	0.50	0.775	0.75	0.70	0.70	0.75	0.55	0.6
Slope resistance (ohmsx10^{-4})		2.6		1.0		2.5		3.0	

6.1 Rotor Rim Brushes (positions 2, 3, 6 and 7)

In general, we are in agreement with the specification and comments given on pages 12-17 of Marshall's report.[1] However, we draw attention to the following:

Brush Losses - With the proposed design the brush current density of 11,600 A/sq.in. is almost twice that for the brushes in the other positions (Table 1). In addition, the proposed nominal force of 8 lb per brush results in a pressure of 51 lb/sq.in. which is three times that for any other position: due to the higher surface speed the necessity for a higher brush pressure in order to maintain brush contact stability would be expected, but we question whether the proposed pressure is not excessive: Marshall calculates the power loss per square cm. of rotor surface at full speed and peak current current for a 1 cm wide band of brushes to be:

(a)	due to friction:	0.94 kW
(b)	due to contact volt drop:	0.80 kW

Since friction heating is so important for the rotor rim brushes, and on the basis of results discussed in Section 5, we recommend that, firstly, the possibility of reducing the brush force be reconsidered; this would have the effect of reducing the rotor temperature and increasing brush life. Secondly, we recommend that increasing the brush area by increasing the brush thickness be considered; this would necessitate staggering the brushes axially in each brush unit. The effect would be to reduce the friction and contact drop losses per unit area of the brush, with consequently reduced brush temperatures and increased brush life. The minimum tolerable brush pressure must be assessed by experiment, the minimum being that at which rotor surface imperfections and electromagnetic forces on the brush system lead to sparking due to instantaneous loss of contact between brush and rotor.

Brazing - The brazing of 864 brushes to brush mounting strips, for each of four positions, is a formidable operation. It is recommended that meticulous attention be given to the inspection procedure for assessing the quality of these joints. It is suggested that the electrical resistance of the joint may be a useful non-destructive test of quality, but in addition a destructive test of mechanical strength should be undertaken on at least 5% of the brazed joints.

Fatigue - A test should be initiated to determine any possible fatigue effects on the brush mounting strips associated with the continual application of the brushes. The mechanical and fatigue strength of all components of the brushgear should be beyond doubt since the development of loose pieces during operation of the homopolar generator could have serious consequences.

Series Resistors - We endorse the use of these for both the reasons given[1]: i.e. to improve the sharing of load current between brushes and to minimise the effect of the voltage difference on the brush track.

Brush stability - Care should be taken to ensure that the proposed brush length of approximately 0.2 in. is not exceeded by an excessive amount since this could lead to brush chattering associated with friction force - in spite of the 'anti-topple' strip, which may not have sufficient damping to obviate this danger.

Fitting of Brushes - Care should be taken that they are fitted 'square' relative to the rotor and that the nut on the back of each brush is locked in position.

Brush Length - With brushes of equal initial length the gaps between the rotor and individual brushes in a unit of twelve brushes would not be equal, with the brushes raised - see Figure 12 of Marshall's report. This necessitates having brushes initially longer than nominal (0.2 in.) and then bedding them to the correct curvature on a suitable machine so that all the brushes in each unit initially contact the rotor satisfactorily. The alternative, apart from appropriate redesign of the brushgear, is to have brushes of different initial length for each position in a unit. This is possible, but would greatly complicate manufacture and maintenance.

Staggering of Brush Positions - The axial stagger of the brushes should be such that each part of the rotor surface in contact with brushes sweeps under the same number of brushes. If this rule is not observed then unequal wear and film formation will occur at different axial positions on the brush track.

Brush Pusher Mechanism - We are generally in agreement with the proposed design (Figure 12): however, we have not considered all the details involved. The material for the brush pusher cap is not specified in Marshall's report - it must be both an electrical insulator and able to withstand the high temperatures in the vicinity of the brushes.

6.2 Top and Bottom Inner Brushes (Positions 1 and 8)

We have the following comments on the specifications as given on pages 33-35 and in Figure 15 of Marshall's report:[1]

Slip-rings - The 48 in. diameter copper slip-rings should preferably be forged, rolled, or cast and then rolled, in a continuous ring. We understand from discussions at Canberra that it is proposed to produce rings with a soldered joint. A permanently jointed slip-ring of this nature for carrying heavy current is outside our experience other than for temporary purposes or for carrying light current signals. It should be noted that, firstly, any jointing material (hard or soft solder) coming to the surface of the slip-ring may cause a local contact irregularity which may become cumulatively worse and thus lead to failure. Secondly, if a mechanical, rather than a metal joint, is used then we would anticipate difficulty in avoiding a step at the joint. We recommend that any step should be less than one ten-thousandth of an inch at full speed, which is the generally accepted tolerance between adjacent commutator bars for commutators of roughly this diameter (48 in.). If a jointed ring has to be used

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because of difficulties in Australia with the other suggested manufacturing techniques, then we suggest that, if feasible, it be copper welded. The hardness of slip-rings is important and we recommend a Vickers' hardness of not less than 90. The maximum hardness obtainable with pure cast copper is in the region of 45 and a cast ring must be rolled, annealed, and rerolled to increase the hardness above this figure.

Brazing, Fatigue, Series Resistors - See our comments in (6.1) which also apply to this section.

Brush Stability - There is a risk of oscillatory brush motion if the cantilever brush mounting strips do not have sufficient rigidity. The metal to be used for these strips is not specified in the report, nor are the dimensions. We recommend that the provision of adequate rigidity be carefully considered in the specification of these strips.

Locking of Nuts - There are two nuts per brush and it is important that these be securely locked in position. No provision for locking these nuts is indicated in Figure 15 of Marshall's report.

Staggering of Brush Positions - Refer to (6.1).

6.3 Mid Inner Brushes (Positions 4 and 5)

There are two possible systems for these brushes mentioned in Marshall's report, firstly, to use slip-rings and brushes similar to those for positions 1 and 8 (slip-ring system), secondly, to use a very large number of small brushes, running directly on the rotor surfaces, mounted in slide out units (slide-out system).

Slide-out System - The 'slide-out system' is described briefly on pages 36 and 37 and by Figure 17[1]. We consider that this system, as proposed, has three distinct disadvantages:

Number of Brushes - It is proposed to fit 7920 brushes per position, i.e. a total of 15,840 brushes for the two mid inner brush positions, each with a brazed spring finger. This, of course, is not impossible. However, we question whether it would be practicable to make reliably all the small brazed joints for these brushes to the exacting standards required. In addition, there would be a considerable problem in supervising and inspecting the fitting of these brushes. Failure of one joint could lead to severe arcing and damage to the steel rotor surfaces. In view of the voltage gradient of 1V per cm, the width of the brushes cannot be increased significantly above 0.08 in. There is, therefore, little possibility of substantially decreasing the number of brushes with this system.

Rotor Surfaces - The rotor surfaces would be relatively difficult to machine in this position in the event of damage - as might be caused by failure of one of the 15,840 brazed joints. In the event of serious damage, e.g. deep pitting, direct running on the rotor surface would probably have to be abandoned. These objections do not apply if replaceable slip-rings are used.

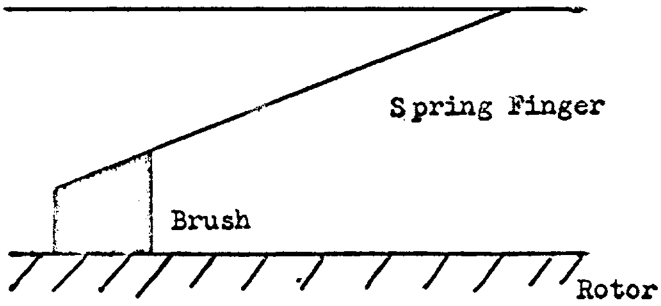
Brush Contact - With reference to Figure 17 of Marshall's report, slight differences in the vertical position of the pulse jack, when the brushes are in contact with the rotor, would result in the brushes only making line contact with the rotor. The principle involved is illustrated in Figure 6 of this report. The pulse jack would have to be positioned with an accuracy at least as good as ± 0.001 in. in order to obviate the danger of line contact. We consider it unlikely that this accuracy could be achieved. It is difficult to put into quantitative terms the effect of varying degrees of line contact, the degree probably varying at random between successive pulses. However, we consider that the particular design proposed is fraught with the danger of brush sparking and burning due to line contacts and should be subjected to careful testing on a suitable rig should it be considered desirable to proceed with it further for other reasons. The possibility of having line contacts would not exist if spiral springs, or some other form of vertically acting spring, were used: however, we consider this to be impracticable. Another suggestion is that the brushes should remain permanently in contact with the rotor. This would overcome the difficulty of line contacts but would lead to overheating of the brushes and rotor due to friction losses during no-load periods were the machine operated continuously. Should an application for the homopolar generator develop which only requires very intermittent pulses, or pulses smaller than the design value, then it may be of value to consider further the possibility of the brushes being permanently in contact with the rotor.

In addition to the above major points we draw attention to the following:

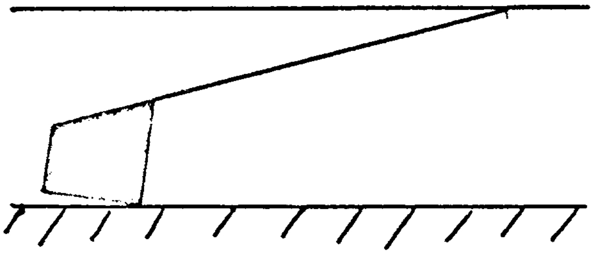
Insulation between Spring Fingers - The cantilever spring fingers are in close proximity to each other and it is important that there be adequate insulation between them: otherwise, should they touch, the use of the series resistors is negated. Provision for insulation is not shown in Figure 17.[1]

Equality of Brush Pressure - Equality of pressure between brushes depends on the equality of the cantilever brush springs. It seems unlikely that, in practice, this type of spring could be readily made and fitted with the high degree of accuracy necessary to ensure reasonable equality of pressure - say ± 10%. Greater inequality than this would lead to a significant variation in brush life which would necessitate more frequent inspection and maintenance than would otherwise be necessary.

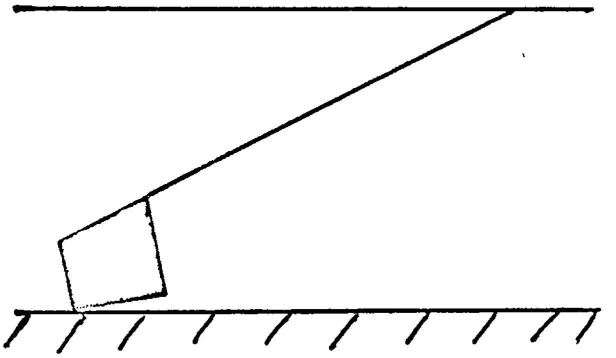
Slip-ring System - No detailed proposals are made[1] for possible designs for the slip-ring system. We will therefore only comment on some principles involved, though, with reference to the last sentence on page 37 of Marshall's report, we



(1) Correct position



(2) Too Close to Rotor



(3) Too Far from Rotor

Fig. 6: Effect of Variation in the Vertical Position of the Pulse Jack: Positions 4 and 5

believe that each system will have to be designed completely to enable the relative advantages of each to be assessed.

Thermal loading - This would be high if the brushes were run on a band one in. or so wide on each ring. Marshall has calculated a temperature rise for the slip-ring surface of 230°C. This assumption of a brush track approximately one in. wide is presumably based on consideration of the gap between the rotors ($5\frac{3}{4}$ in.) and the use of cantilever brush mounting strips as for positions 1 and 8. Provided brushes with spiral pull-off springs could be used the width of the brush track on each ring might be approximately doubled to about 2 in. and the thermal loading correspondingly reduced.

Spiral springs - We recommend that the use of spiral pull-off springs for positions 4 and 5 be considered in conjunction with the slip-ring system. This would involve the use of radial brush holders. The brush pushers would have to act through the centre of the springs. The connection to the brush could not be of the conventional tamped pattern, but would involve the brazing of a copper foil connection which must not interfere with free movement of the brush. Magnetic forces on the brush and connections would be appreciable and this aspect would have to be investigated (see Section 7.1).

Number of Brushes - The number and size of the brushes with the slip-ring system could be of the same order as for positions 1 and 8. We suggest approximately 600 brushes per position, each approximately 0.4 in. wide x 0.8 in. thick, arranged in groups of four brushes side by side around the slip-ring.

There is no doubt that the difficulties of brushgear design for positions 4 and 5 are severe and warrant greater attention than has been given to them so far. The conditions of operation at the brush interface are similar to those for positions 1 and 8, and less spectacular than for positions 2, 3, 6 and 7: it is perhaps partly for these reasons that the brushgear design for positions 4 and 5 has not yet been formulated in sufficient detail. It should be borne in mind that the proposed 'quarter machine test', not involving positions 4 and 5, will neglect what is perhaps the most difficult brushgear design problem on the homopolar generator.

7. Magnetic, Electrical and Thermal Effects

There are three effects which it was not possible to investigate during the experimental programme since they will occur only on the homopolar generator itself. Each has an important bearing on the efficient operation of brushes, and they are discussed here in relation to Marshall's proposals for brushgear.

7.1 Interaction between Magnetic Fields and Currents in Brushgear

All the brushgear used on the homopolar generator will be situated in a magnetic field, and in consequence will be subjected to electromagnetic forces during each current pulse. One component of force results from interaction of the current in each brush mounting strip with the main field of the generator. The other component of force results from interaction between the current in each brush and mounting strip and the 'pinch' field. The pinch field is induced by current flowing in the rotors during a pulse, and is in the form of a system of circular lines of flux concentric with the rotors. Other electromagnetic forces occur due to leakage flux, and current flow in conductors adjacent to the brushes; we have not considered these forces.

It is clearly most important that electromagnetic forces do not disturb the stability of brush contact during a current pulse. In calculating the forces approximately we have used the values of pinch field given in Marshall's report; we comment on this point later.

Positions 2, 3, 6 and 7

The forces acting on the brushes are relatively small - a circumferential friction force of 1.6 lb (8 lb load, $\mu = 0.2$) and a circumferential force of 0.6 lb due to the main field (1,000 gauss in this region).

A further force of 2.8 lb acts radially inwards on the current carrying part of the brush mounting strip due to the pinch field. Part of this force will be applied to the edge of each brush adjacent to that part of the strip carrying current, and Marshall's estimate of 1.4 lb (ref. 1, page 13) appears reasonable.

These forces should not unduly affect contact stability with an applied force of 8 lb.

Positions 1 and 8

These brushes operate in the main field (16,000 gauss) and in an estimated[1] pinch field of 5,100 gauss at maximum current.

The circumferential force due to the main field is approximately 10 lb per brush, and this will tend to twist the cantilever mounting strips. We strongly recommend that the stability of the brushgear is checked experimentally with this relatively large transient force of 10 lb applied to the brush.

Pinch forces act radially inwards on each of the brush mounting strips during a current pulse, and range from 12 lb per brush on the innermost track to 24 lb per brush on the outermost track. A detail drawing in Figure 15[1] shows how it is proposed to share the forces between brushes by allowing the support strips to press on one another. This arrangement will require very careful adjustment if the loads are to be properly equalised. The average additional load on each brush will then be about 15 lb which will give rise to a transient circumferential friction force having a maximum value of about 3 lb.

It is clearly impossible to be certain, without carrying out experiments to simulate these conditions, whether this brushgear system will give satisfactory contact under pulse conditions, particularly when reversal of the rotor is also involved.

Positions 4 and 5

A 'slide-out unit' design involving a total of 15, 840 small brushes is one of the proposals for positions 4 and 5. At each position 22 brushes are mounted in each of 360 connection boards (ref. 1, page 36). The lateral force on each brush mounting strip due to the main field is about 1 lb, i. e. 22 lb per board, and therefore some form of support at both ends of each board appears to be necessary. As proposed, the inner ends are unsupported.

Forces totalling nearly 4 tons act on each set of 7, 920 brushes, and since these forces act in opposite directions in positions 4 and 5, respectively, the actuating mechanism must be capable of withstanding 8 tons during a pulse.

The pinch force is approximately 1/3 lb per brush.

If radial brushes and slip-rings are substituted for the 'slide-out' system, using brush holders instead of cantilever strips, then lateral forces due to the main field will push the brushes against the sides of their holders. Sufficient load must then be applied to each brush to overcome friction between the brush and holder -- amounting to approximately 2 lb for a 1 cm long brush -- and to ensure that a stable contact is maintained.

In practice a brush is seldom guided perfectly by the sides of its holder, but generally takes up an equilibrium position determined by the forces which act upon it. Thus, if the brush is temporarily constrained by magnetic forces to one side of the holder, it may tilt from its equilibrium position and lose contact over the greater part of its area. A similar effect can also occur when the direction of rotation is reversed. Great care is required in selecting suitable brush proportions for operation under these conditions where a loss of contact could cause serious damage, but provided that the length to thickness ratio is sufficiently small, as for the other proposed brush designs for the homopolar generator, this should not be a problem.

'Pinch'Field

In estimating the 'Pinch' forces which act on brushes and leads we have used values for the pinch field given by Marshall.[1] These appear to be theoretical values based on a simplified model for radial current flow in a disc, and we are doubtful whether these values are applicable in the immediate vicinity of each brush holder. We suggest that the whole question of magnetic forces be reconsidered to take into account the physical arrangement of the actual brushgear, and its position in relation to current paths in the rotors, brushes, leads and adjacent busbars.

Electromagnetic repulsion

Electromagnetic repulsion is an effect which is generally negligible in practice but may become important where high currents flow through a brush. Due to the sharp constriction which the current paths undergo when a brush contacts a slip-ring, the two components mutually repel one another. Hohm[2] has calculated the magnitude of this effect. Under the present condition, e.g. a brush 1 cm square carrying 2000 amps, we calculate that the repulsion force will vary from about $\frac{1}{2}$ oz, assuming there are 20 points of contact each 2×10^{-3} cm diameter, to about $\frac{1}{2}$ lb, assuming that there is a single contact only. Provided that the brush load appreciably exceeds $\frac{1}{2}$ lb, this effect can be neglected.

7.2 Voltage Gradients

Positions 2, 3, 6 and 7

It is proposed[1] that brushes should operate only over a narrow band on the rim of each rotor. These bands are shown shaded in Figure 2. The reason for this limitation is that a voltage gradient exists across the rotor periphery due to the fringing flux of the main field. Under these conditions the current distribution over the section of the brush is not uniform, taking a time average, but becomes concentrated towards one side. Marshall has considered this problem and suggests that the potential difference across the width of a CM-O brush should not exceed 0.2 volts, i.e. a potential gradient of 1 V/cm for a brush 1 cm wide. He has calculated the current distribution in the brush from the voltage-current characteristic.

A further consideration which applies under these conditions is that brushes on different tracks within one of these bands work at different potentials, and cannot therefore be connected together directly without giving rise to unequal sharing of current. Suitable ballast ('series') resistors are necessary to equalise the currents.

A simple calculation has been carried out to show how effective these measures are in limiting variations in the current distribution between brushes and within individual brushes. Three brushes, 1, 2 and 3, are assumed to operate on separate tracks having a potential difference of 0.3 volts between them, and the two outer brushes have a potential of 0.2 volts across their width. The arrangement is shown diagrammatically in Figure 7, and represents approximately the situation in disc D of the homopolar generator. For simplicity the outer brushes have been divided into two parts, (a), and (b), in order to estimate the current distribution.

From experiments described in Section 5, a voltage-current characteristic of CM1S has been plotted. Very approximately this can be represented by the equation $V = 0.35 + 2.5 \times 10^{-4} I$, where V is in volts and I in amps. Ballast resistors are taken as 5×10^{-4} ohms and the total current shared by the three brushes is assumed to be 6000 amps.

The currents are found to be distributed as follows:

Brush 1	(a)	977 amps)	total current 2354 amps
	(b)	1377 amps)	
Brush 2		--	total current 2088 amps
Brush 3	(a)	977 amps)	total current 1554 amps
	(b)	577 amps)	

i.e. the ratio of maximum to minimum current within a brush or between brushes does not exceed 1.7 to 1. Provided that the brush wear is substantially independent of current this current distribution can be tolerated. If not, then the use of the self-aligning brush holders proposed for these positions will result in uneven wear taking place, with a possible reduction in contact on one side of each outer brush.

Should it be desired to widen the operating band, in order to reduce thermal loading of the rotor, it will be necessary to operate brushes in regions of the rotor surface having a greater potential gradient than 0.2 V/cm, and there will be a greater potential between brushes. A very approximate calculation has been carried out for three brushes working with a total potential difference of 1.2 volts between them, and a gradient of 0.4 V/cm where the outer pair operate. This arrangement is shown in Figure 7.

The distribution of currents is as follows:

Brush 1	(a)	956 amps)	total current 2712 amps
	(b)	1756 amps)	
Brush 2		--	total current 2177 amps
Brush 3	(a)	956 amps)	total current 1112 amps
	(b)	156 amps)	

Under these conditions the current distribution is unsatisfactory; Brush 1 carries an excessive current, and the ratio of maximum to minimum current within Brush 3 approached 6 to 1. We would not recommend operating under these conditions. We consider that the proposed limit of 0.2 volt is reasonable for CM1S, as well as CM-O. Setting this limit defines the total width of the band over which brushes may be operated and also fixes at 1 cm the maximum brush width which can be used at the edge of the band.

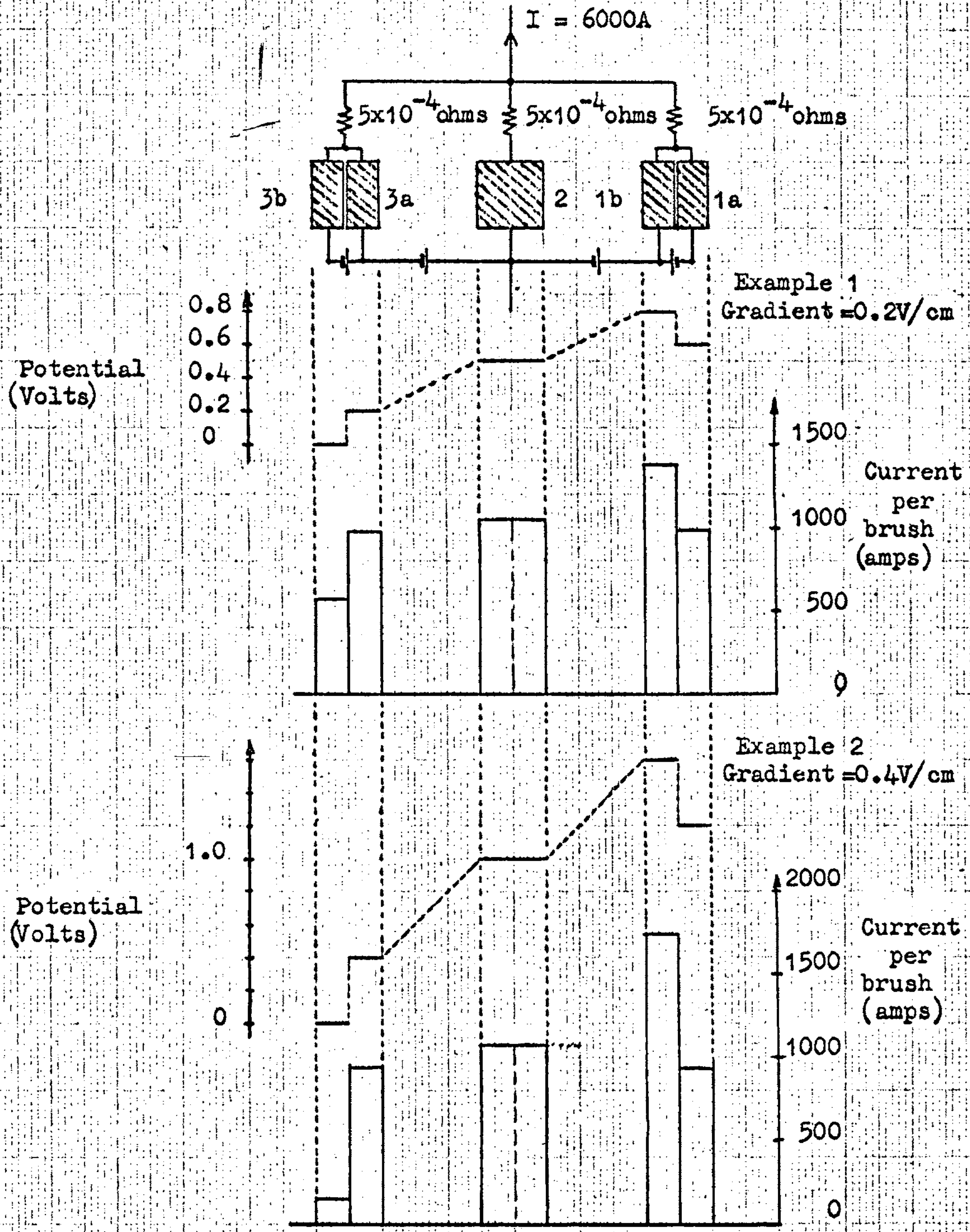


Fig. 7: Distribution of Current between Brushes due to a Potential Gradient

Ballast resistors are necessary to equalise the currents in all the brushes across a band, and also to suppress any selective collection by individual brushes due to incorrect loading or other abnormal conditions. The ballast resistance suggested, which drops 1 volt at peak current, seems satisfactory. The values of resistance could be adjusted for individual brushes to give the optimum current distributions for a particular distribution of voltage across a band, but this would not improve the current distribution within individual brushes, and the gain does not appear to be worth the extra complication.

We suggest that the optimum location of the bands be verified experimentally with the rotors of the homopolar generator rotating at full speed. This could be done by using suitable probe brushes.

It will also be necessary to verify that brushes working in a potential gradient wear reasonably uniformly across their sections and do not overheat at the edge carrying the highest current density.

Positions 1 and 8

There is no significant voltage gradient.

Positions 4 and 5

Since the voltage gradient on the face of each rotor will be 1 V/cm at full speed, the width of the brushes will be severely limited. Taking the criterion of 0.2 volt discussed above, the width becomes 0.2 cm, as proposed by Marshall, and the number of brushes required to carry the peak current is accordingly great (Section 6.3).

7.3 Thermal Loading of Rotors and Slip-rings

Positions 2, 3, 6 and 7

Marshall has calculated (ref. 1, Section 5) the temperature rise which can be expected to take place at the surface of a rotor during a current pulse due to friction and electrical losses at the brush-rotor interface. Under the operating conditions which have been assumed, viz. a load of 8 lb per brush, friction coefficient = 0.2, voltage drop = 0.55 volts, current = 1850 amps max. per brush, and total width of band 6 cm, the maximum temperature rise is found to be 180^{o}C.

It has been shown by Marshall (ref. 1, Section 6 and 7) that repeated cycling over a temperature range of 180^{o}C is likely to induce fatigue failure in the surface layers of the rotor, and that if cracking is to be avoided the rise in surface temperature should not exceed about 115^{o}C.

One aim, of the experimental programme described in Section 5 of this report, was to determine whether the load on the brush could be reduced from

8 lb to 4 lb, and although the results were not conclusive it appeared that under better mechanical conditions this might be possible, assuming that magnetic forces would not make it impracticable. Friction losses are halved in this way, and the maximum surface temperature therefore reduced.

Marshall has calculated the effect of such a change (ref. 1, Section 7), and finds that the maximum temperature rise becomes 120°C, which is more reasonable.

The calculations apply specifically to disc D, where the brushes operate over a band 6 cm wide. On disc A, the band is 8 cm wide and the temperature is reduced correspondingly. However, on discs B and C the bands are only 3.6 and 3.8 cm wide, respectively, and the maximum temperatures, even with a 4 lb load, are about 190°C.

A further factor which must be taken into consideration, is the additional temperature rise due to reversal of the rotors during a pulse (ref. 1, Section 8). The rotors come to rest while peak current is flowing through the brushes, and certain areas therefore are subjected to an additional thermal stress. Marshall estimates that the additional temperature rise could approach 60°C. This means that some areas on discs B and C could attain a temperature of 250°C. Even allowing for any approximations which have been made in these calculations, it appears that the problem of thermal stress is a critical factor in the successful operation of the homopolar generator. We have, therefore, considered possible ways of reducing this temperature rise:

(a) Gas cooling of rotors and brushes
(b) Water cooling of brushes
(c) Water cooling of rotors
(d) Increasing the width of the operating band
  (1) by increasing the potential gradient limit
  (2) by reducing the fringing flux
(e) Reducing the contact drop

(a) Gas cooling of rotors and brushes - During the course of a current pulse (1.6×10^6 A peak) nearly 10^6 cals would be liberated at the surface of each disc within 3 seconds, and it would not appear practicable to extract a reasonable proportion of this heat in 3 seconds by using a gas as coolant. With air the flow rates required would be several million cubic feet per minute.

(b) Water cooling of brushes - The large number of brushes and their need for renewal at fairly frequent intervals makes direct water cooling of individual brushes impracticable.

(c) Water cooling of rotors - Marshall has carried out experiments on a 2 in. diameter test rotor which was water cooled by flooding its surface with water, and reports that the cooling was efficient and did not interfere with brush operation.

The most serious objection to water cooling the homopolar generator in a similar manner is the difficulty of ensuring that lift due to hydrodynamic lubrication of the brushes does not occur. If some brushes happen to be tilted against the direction of motion at the instant they come into contact with the rotor surface then lift can readily take place, with a consequent reduction in the total number of brushes available to carry the current and the possibility that this will cause overloading and breakdown of the remainder.

Further objections to water cooling are, first, the possibility that corrosion will occur, second, the difficulty of maintaining insulation between discs, and finally, the necessity of having a tank round the rotors to catch the water flung off. The total pumping rate required would be several hundred gallons per minute. We consider that further investigation would be required before it would be possible to give a final assessment of water cooling.

(d) Increase the width of the operating band -

(1) by increasing the potential gradient limit:

The effect of increasing the potential gradient from 0.2 to 0.4 volts/cm has been described in Section 7.2, but does not seem to be a practical solution since the current distribution is then very non-uniform. Marshall has suggested that brushes $\frac{1}{2}$ cm wide could be used to enable the operating band to be widened. It would be possible in this way, but at the expense of mechanical complication, to nearly double the band widths on discs B and C, and with a 4 lb brush load bring the temperature rise close to the limiting value. This suggestion is worth further investigation.

(2) by reducing the fringing flux:

We have discussed with Mr. J. Blamey of A.N.U., the possibility of using some form of magnetic shielding to reduce the potential gradients on the rotors. One possibility is to cut a deep slot in the rotor surface, the sides of which magnetically shield the bottom of the slot, which forms the working track for the brushes. However, machining the rotor is undesirable, the brush track is then inaccessible, and the design of the brushgear would need complete revision. An alternative method is to surround the brushgear with a hollow magnetic shield in the form of an annulus. This again interferes with access to the brushgear. In addition, severe magnetic forces act on the shield; Mr. Blamey has calculated that this might be about 40 lb per inch of shield.

A method not discussed at Canberra is the possibility of fitting magnetic shields, of the type shown in Figure 8 adjacent to the brushgear. We suggest that this is worthy of further consideration.

(e) Reducing the contact drop - If the contact drop of the brushes could be reduced then the maximum temperature would also decrease. There is only one known atmospheric condition in machine practice where an abnormally low contact drop may be obtained[3, 4, 5]; this is in synchronous condensers where a hydrogen atmosphere is used for cooling purposes. Under these conditions a lower contact drop and a significant increase in brush life are usually obtained. We have no experience of operating metallic brushes at high current densities under these conditions, but it seems unlikely that the reduction would be as great as for the non-metallic brushes normally used.

Positions 1 and 8 - No potential gradient

Positions 4 and 5

Potential gradient 1 V/cm at full speed. The limitation in brush width has been discussed in Section 7.2

8. Maintenance

The following points relate to maintenance of the brush and slip-ring system.

Slip-ring maintenance - The slip-ring surfaces may possibly be damaged during operation. Superficial damage, such as light burning or sooting, may be removed by the application of Carborundum paper (300 grit) with the machine rotating. However, when applied manually, this will eventually lead to 'waviness' and other departures from truth. We therefore recommend that the surfaces be finely turned with a diamond tipped tool after not more than three applications of abrasive paper. It should be noted that if a satisfactory uniform 'film' develops on the slip-ring surfaces then this should not be removed at any time - including when the brushes are changed. Any deep damage to the rings should be removed by turning as soon as possible after being observed, since such damage usually will rapidly become worse during operation.

Brush bedding - On conventional machines it is common practice to 'bed in' the brushes by means of abrasive paper or abrasive cloth or by means of a bedding stone; i.e. the brush contact surfaces are artificially worn prior to use so that they make intimate and uniform contact with the commutator or slip-ring. We recommend that, in the case of the homopolar generator, the brushes are not bedded in with abrasives since this should not be necessary - assuming that the brushes are produced with contact surfaces having approximately the same curvature as the slip-rings (in the case of positions 2, 3, 6 and 7 the brushes need 'preliminary' bedding to produce the correct curvature - see Section 6.1). The series resistors will assure uniform distribution of current between brushes during initial running, and the initial rate of brush wear, of the order of 10^{-3} in. per pulse, should be sufficiently high to cause the brushes to bed satisfactorily within about ten pulses. We recommend that the first few applications of the brushes, for bedding purposes, be without current.

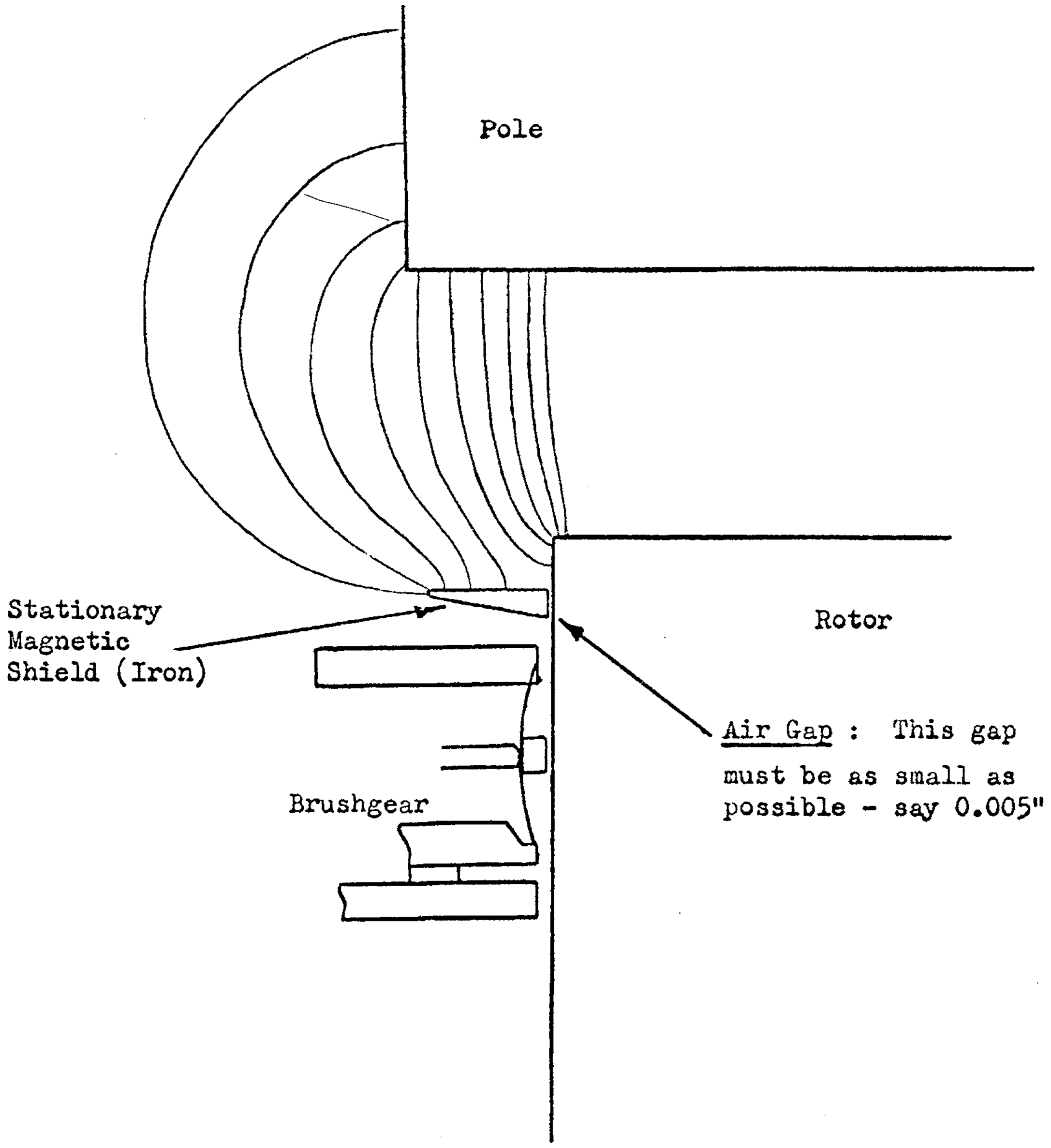


Fig. 8: Suggested Magnetic Shield (not to scale)

Brush wear dust - It is unlikely that the normal ventilation of the homopolar generator will carry away the wear dust from the brushes, particularly since the majority of this will be copper dust. It will therefore be necessary to remove this dust at regular intervals. These periods will depend on the frequency with which the machine is used: it is suggested that the dust be removed at least twice as frequently as the brushes are changed. Using Marshall's proposed brush design figures (Table 1), the volume of material worn during the life of the brushes (say 60% of actual brush volume) would be nearly 200 cubic in. This dust should either be blown out of the machine, removed by vacuum cleaning, or by other suitable techniques.

Cleanliness of air - The air supply to the brushgear should be maintained clean: in particular, it should be free from any significant amount of oil mist from the bearings or from the compressors supplying air to the air bearings. If necessary, and if possible, filters should be used to ensure cleanliness. Extremely small percentages of oil from the bearings are normally encountered in the vicinity of large electrical machines and do not harm brush contact performance. However, we observed that the pole faces and other parts of the homopolar generator had a substantial oily film on them, which we understood came from the bearings. This would be considered to be highly unsatisfactory on a conventional machine. The presence of unduly large concentrations of oil spray in the vicinity of cummutators and slip-rings on conventional machines is a recognised cause of brush contact irregularities leading to damage of the contact surfaces. We recommend that the cleanliness of air in the vicinity of the slip-rings be carefully considered. In addition to oil, the presence of abrasive dust - e.g. cement dust - is another cause of trouble.

Cleanliness of slip-rings - When fitting new brushes, or undertaking other maintenance work, it is most important that men working on the machine should not dirty the slip-ring surfaces - particularly with oily finger marks and smudges. Subsequently, these are likely to lead to burnt patches on the slip-ring surfaces. If the rotor is removed from the machine for maintenance we recommend that the slip-ring surfaces be covered with suitable paper to keep them clean. On no account should oil or other dirt be removed with carbon tetrachloride. This solvent destroys brush films and induces high rates of brush wear even in very small quantities. The most suitable solvent for removing oil is probably petroleum ether.

Changing brushes - It should not be necessary to change all the brushes on a particular slip-ring simultaneously. The series resistors will prevent any significant current selection between old and new brushes. Therefore, when the machine is in regular use, if it is more convenient to change a fraction of the brushes at regular intervals, rather than all the brushes at one time, then this is permissible.

Hold-off springs - We recommend that an inspection system be devised for systematically and regularly checking the efficiency of all brush hold-off springs: all weak springs (spring fingers) should be replaced without delay. Spring failures are likely to be associated with rapid brush wear and, subsequently, damage to both the spring and slip-ring when the brush is worn away and the spring contacts the slip-ring.

9. Conclusions

We have discussed in this report the results of the experimental programmes carried out to assess the performance of solid brushes under conditions associated with the duty cycle of the homopolar generator. We have also commented on the proposals made by Mr. R. A. Marshall[1] and have made many detailed recommendations on the use of brushes. Our general conclusions are summarised below.

9.1 Design and Performance Details

Selection of Brush Grade:

From the experimental results we conclude that CM1S is the most suitable brush grade for trial on the homopolar generator.

Operating conditions:

In experiments simulating the current density, surface speed, and brush load for the homopolar generator, CM1S and certain other grades with a high copper content behaved reliably without sparking and without damaging the surface of the test rotor. Steady readings of friction, wear and contact drop were obtained. We conclude that reliable brush operation may be expected under these test conditions. However, the effects of magnetic forces and voltage gradients were not measured, and the measurements of rotor heating were for rather different conditions than on the homopolar generator. Magnetic forces and rotor heating are major problems, the effects of which must finally be measured on the homopolar generator since they cannot readily be simulated on test rigs: in particular, the transient nature of the magnetic forces affecting brush stability does not appear to have been considered in detail at Canberra. With Marshall's proposed design we consider that the effect of potential gradients, resulting in the non-uniform distribution of current, should not be a serious problem.

Brush life:

The minimum brush life will probably occur at positions 2, 3, 6 and 7, and from the test results would appear to be of the order of 1000 pulses. We therefore conclude that brush life should not be a major problem, provided that mechanical stability is maintained.

Thermal effects:

The problems associated with thermal stressing of the rotor have been discussed in Section 7.3. Assuming that an unlimited life is required from the rotor without fatigue-cracking of the surfaces taking place, i.e the maximum temperature cycle during a pulse not exceeding 115°C[1], then steps must be taken either to reduce the total dissipation of heat during a pulse, or to force cool the rotor.

In the case of positions 2, 3, 6 and 7, we consider that the most promising way of reducing the total dissipation would be to reduce the brush load, and we recommend that this be tried experimentally on the homopolar generator. On discs

A and D the maximum temperature approximates to the required limit if the load is reduced to 4 lb per brush, assuming the rotors do not reverse, but further measures are needed for discs B and C. Marshall's proposal to use brushes $\frac{1}{2}$ cm wide on the outer tracks is worth investigating, as also is the possibility of using magnetic shields to reduce the potential gradient. The operational limits in the case of rotor reversal appear to require further consideration.

We do not consider that forced cooling of the machine in order to limit the temperature rise during a pulse will be practicable (Section 7.3). However, forced air cooling to assist in limitation of the ultimate temperature rise of the rotor appears to be practicable, and desirable, if the machine is to be operated continuously. We do not consider that the advantage of more effective cooling gained by using a hydrogen atmosphere would offset the resultant complex modifications required at this advanced stage in the construction of the machine. We have no information on the performance of high copper content brush grades for these operating conditions in a hydrogen atmosphere; however, though the brush contact drop in hydrogen is normally reduced in the case of carbon and graphite grades, we would not expect it to be reduced by a significant amount for copper grades under the conditions considered.

Brushgear design:

The proposed[1] type of brushgear for positions 2, 3, 6 and 7 should give satisfactory performance subject to our criticisms on points of detail (6.1). In the case of positions 1 and 8, the magnetic forces are very large, approximately 10 lb per brush acting circumferentially and between 12 and 24 lb per brush acting radially. The effect of these forces on brush stability and current collection for the proposed design has not yet been investigated at Canberra; this presents a formidable problem which will have to be surmounted if the machine is to operate satisfactorily. We consider the 'slide out unit' design for positions 4 and 5, requiring 15,840 brushes, to be impracticable in the form proposed because of manufacturing and maintenance difficulties, excessive magnetic forces on the individual brush springs, and because of the danger of line contacts due to variations in the vertical position of the pulse jack. The alternative slip-ring design for positions 1 and 8 also involves many difficulties. We recommend that both types of design be investigated further in much greater detail than hitherto; there is no doubt that the design problem for positions 4 and 5 is very difficult and its detailed solution, inevitably involving much experimental work on prototype designs, will require great effort.

Maintenance:

Maintenance of brushgear on the homopolar generator would be a major problem in terms both of the amount of work involved and the degree of practical skill and care required by the maintenance workers. However, we consider that maintenance would involve no intrinsic technical difficulties.

9.2 Practicability of Current Collection with Brushes

We consider it practical to use brush grade CM1S for current collection at the high current densities, speed, and brush loads proposed for the homopolar generator. However, we do not consider that a practical design for the brushgear at positions 4 and 5 has yet been formulated; also, the brushgear design for positions 1 and 8 has not been proved to be satisfactory in the presence of transient magnetic forces.

The work to date has resolved the more obvious problems concerning current collection, but much further work on brushgear design and the effects of magnetic forces is required before the use of brushes can be said, with confidence, to be practicable. This work involves so many detailed design problems, that, even assuming a practicable solution is possible, we consider that the chance of achieving satisfactory operation of the homopolar generator at its full rating, within a reasonably short time, is very small without an appropriate increase in the number of staff employed on the project.

The manufacture of brushgear and subsequent maintenance would be major undertakings - but not impracticable.

Thermal stress of the rotor remains a major problem at the rated output of the homopolar generator, unless a very limited life for the rotor surfaces can be accepted.

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