USE OF THE HOMOPOLAR GENERATOR TO POWER XENON DISCHARGE TUBES AND SOME ASSOCIATED SWITCHING PROBLEMS

EP-RR 23

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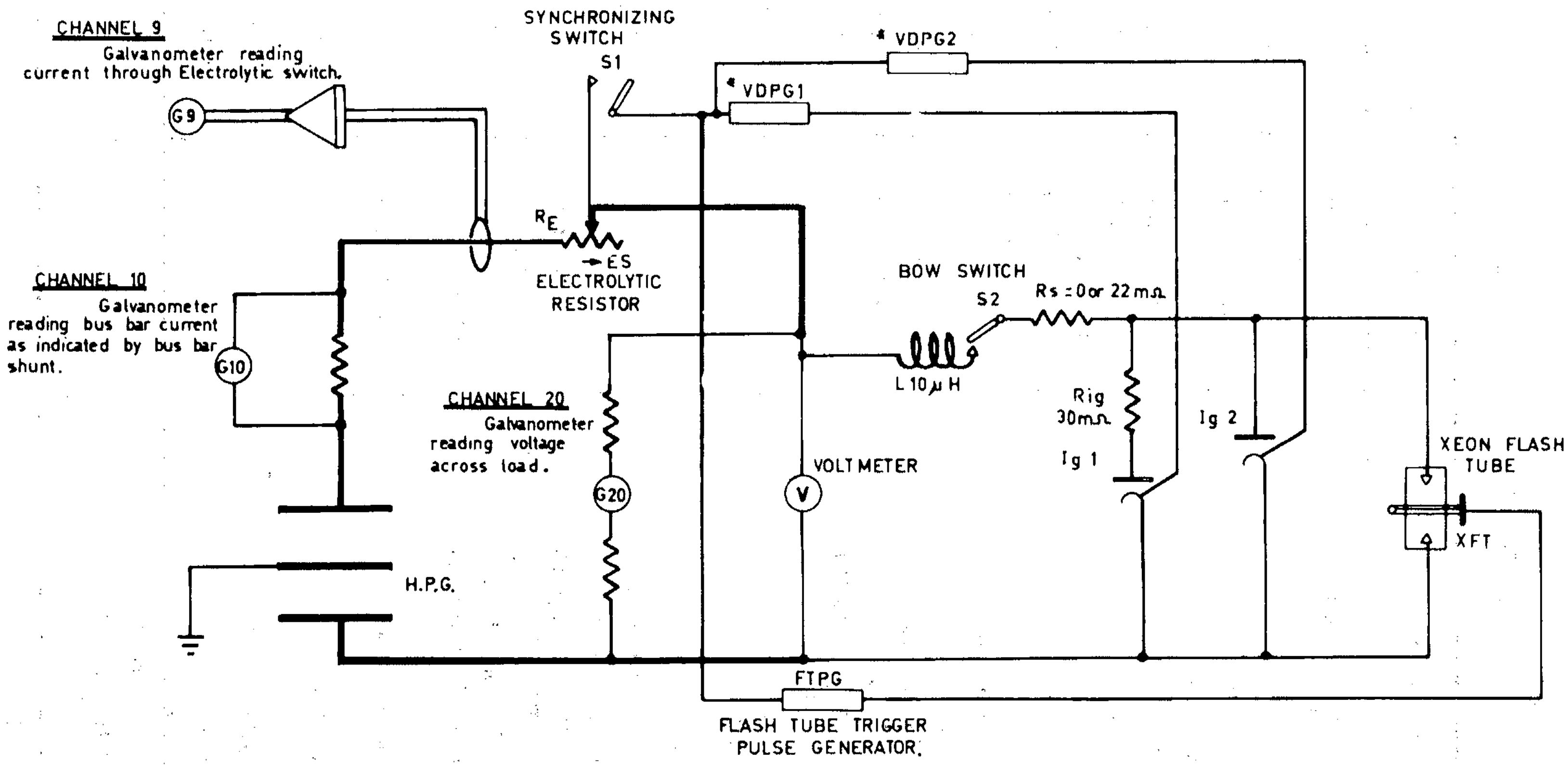
SUMMARY

In the experiments described herein, the homopolar generator was used for the first time with its four rotor discs connected in series to power xenon flash tubes being developed for high-power low-voltage operation. An arc developed in the electrolytic switch being used to terminate the pulse. Voltage surges produced by this and other arcs in the flash tube circuits, caused the bus bars to arc over and the current exceeded the capacity of the light duty brushes being used in the generator. Damage within the generator allowed currents of several millions of amperes to flow and these led to damage to the rotors and bearings. This report gives an interpretation of the records of the event and outlines what the author considers to be the probable sequence.

RECORDER CHANNEL ALLOCATION

No.	Function	Sensitivity	Galvanometer*
1	Electrolytic Tank Potential	100 V/cm	1400
2	B2 Potential	50 V/cm	250
3	Motoring Voltage	100 V/cm	1400
4	B4 & B5 Potential	100 V/cm	500
5	B0 & B9 Potential	50 V/cm	500
6	B6 Potential	200 V/cm	500
7	B3 & B7 Potential	100 V/cm	500
8	dI/dt	500 kA/S/cm	250
9	$\int(dI/dt)dt$	10 kA/cm	1400
10	Bus Bar Current	5 kA/cm	250
11	Top Radial Throw North		130
12	Switch Trigger		1400
13	Electrolytic Tank Position	2"/cm	130
14	HPG Cam Position	360^{o} /2 cm	130
15	B1 & B8 Air Valve Position		130
16	Air Valve Travel		130
17	B2 - B6 Potential	100 V/cm	130
18	B7 Rotor Temperature		130
19	Rate of charge of voltage across ES		130
20	Arc Potential	100 V/cm	130
21	Top Air Pad Pressure		250
22	Bottom Air Pad Pressure		250
23	Top Thrust Piston Temperature	$28.2^{o}C/cm$	130
24	Bottom Thrust Piston Temperature	$28.7^{o}C/cm$	130
25	Top Air Pad Temperature	$28^{o}C/cm$	130
26	Bottom Air Pad Temperature	$25.4^{o}C/cm$	130
27			1400
28	B2 Rotor Temperature	$25^{o}C/cm$	130
29	Top Rotor Lift		130
30	Top Rotor Tilt N-S		130
31	Top Rotor Tilt E-W		130
32	Top Rotor Radial 240^{o}		130
33	Bottom Rotor Lift		130
34	Bottom Rotor Tilt N-S		130
35	Bottom Rotor Tilt E-W		130
36	Bottom Rotor Radial 240^{o}		130

* High frequency cut-off.



* VARIABLE DELAY PULSE GENERATOR.

Figure 1 Flash tube and control circuits.

1. INTRODUCTION

Rapid development of powerful lasers has reached the stage where the cost of energy storage condensers is setting a limit to further increases in size. The homopolar generator is an exceptionally economical energy store capable of storing much more energy than can be used in any conceivable laser and since it is available, it provides a unique opportunity to power a large laser or other equipment in which an extremely powerful burst of visible radiation is required.

An efficient light source for such work is a bank of xenon filled flash lamps. The voltage recommended for available xenon lamps is in excess of 750 V (although they will operate at lower voltages). Since the upper voltage limit for convenient operation of the homopolar generator is 800 V, it would be valuable to obtain experience on operating xenon lamps at these low voltages.

A demountable annular tube was built and used to pump a neodymium glass laser rod 1.25 cm diameter and 15 cm long(1).

After the successful operation of this tube and laser, tests were conducted on linear xenon lamps (type No. FX-67B-6.5) made by Edgerton Germeshausen & Grier, to show the feasibility of using these lamps at less than 800 V, and to investigate any mutual effect caused by operating a closely packed group of lamps. These tests were interrupted when the electrolytic switch arced over and so failed to limit the power delivered from the homopolar generator into the lamp circuit. This was followed by a sequence of events which led to excessive currents flowing within the generator itself. The records do not show conclusively this sequence, but a possible description of the events as deduced from the records is given in this report.

2. ARRANGEMENTS AND OPERATION OF THE EQUIPMENT

A coaxial xenon flash tube made in our own workshop was tested using the circuit shown in Figure 1 . Some pulses were taken with $Rs = 0$, others with $Rs = 22\ m\Omega$. Some were run without triggering Ig1, and in some cases the bow switch was operated and in others it was not.

The current in the tube was 10 kA to 18 kA, and the supply voltage was varied between 500 V to 820 V.

The current through RE did not drop to the value where the ignitron went out until about 90-100 msec after the electrodes would have left the undisturbed electrolyte surface. During this time the current decreased in a smooth fashion with a smooth decrease in di/dt until the ignitron extinguished at a current which could not be observed with the sensitivity used to record current (Figure 2).

When the ignitron stopped conducting at the end of most pulses, the voltage across RE dropped to a low value, then settled to a figure determined by the leakage over the insulators of RE and the voltmeter resistance (Figure 3). During some pulses, RE opened the circuit and the voltage across it did not drop to a low value

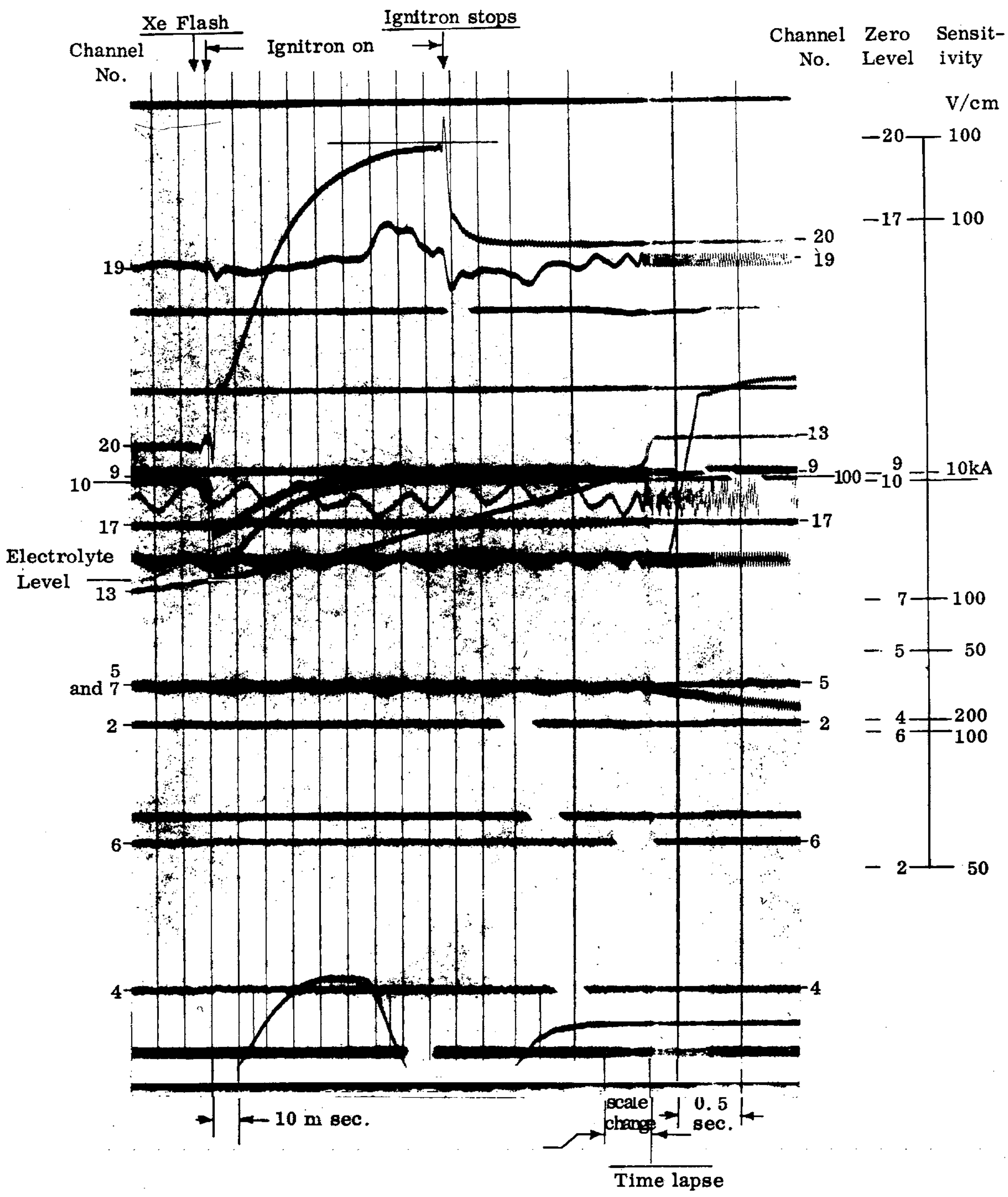


Figure 2 Reproduction of section of the recording galvanometer chart for pulse 16 on 27/11/68. This was typical of the pulses where the switch stopped conducting before the ignitron.

(Figure 2).

This performance was observed for more than 140 pulses at various voltages, made up as follows:

42	pulses	at	550 V
82	"	"	660 V
20	"	"	770 V
3	"	"	820 V

For these tests, the electrolyte in ES was raised to immerse the electrodes by about 2". Before the pulse the tank rested with the electrodes $6\frac{1}{2}$" clear of the electrolyte surface, so that the tank had to rise a total of $8\frac{1}{2}$" - this took two seconds. The lift then stopped, and the tank was allowed to fall at its usual speed of about 33 inches per second. The acceleration at the top was low and the whole tank cycle took $2\frac{1}{2}$ seconds. The flash tube was triggered when the electrodes were immersed less than one inch.

This slow cycle required the brushes to contact the rotors of the homopolar generator for $3\frac{1}{2}$ seconds, which caused the outer rim of the rotors to be heated quite rapidly when operating at 700 r.p.m. The rate at which the tank was raised and the acceleration at the top of the stroke were increased to shorten the cycle time, by fitting a cam to the tank level control in place of the solenoid which had been used up to the 26th November (1968) to operate the lift control.

On 27th November, 14 pulses were run into a small flash tube and the current through RE was as expected (see Figure 3, which is the record of the pulse before the first flash-over in ES). During the 15th current pulse, (Record No. 17, Figure 4), 20 msec after the ignitron was triggered, the current dropped rapidly due to a very rapid increase in the electrolytic resistance (RE) (see channel 19 which indicates the time rate of change of voltage across the electrolyte). The reduction of current was not due to the ignitron becoming a high resistance, since such changes reduce, not increase, the voltage across RE. The increase in voltage across RE was followed by an arc in it, which persisted for about 0.32 sec. and extinguished 1.7 sec. before the brushes of the generator were withdrawn from the rotors. The records show that valves, controlling the air pressure on the brushes, started to close 0.2 sec. after the current ceased.

When the arc started in the electrolytic switch, the current to the load (made up of Rs = 22 mΩ in series with Rig = 30 mΩ and the ignitron Ig1), rose to 9,000 A. The voltage recorded shows the load resistance to be 51 $\pm$ 5 mΩ, showing that the ignitron and load circuit were intact. During the next 120 msec the current fluctuated in the usual manner for a current in such an arc, and the mean value fell constantly to about 6,000 A. The arc then changed, passing a higher and steadier current (9,000 A), with a lower voltage drop, for 40 msec, while the load resistance remained about 58 $\pm$ 5 mΩ. The current then fluctuated and fell to

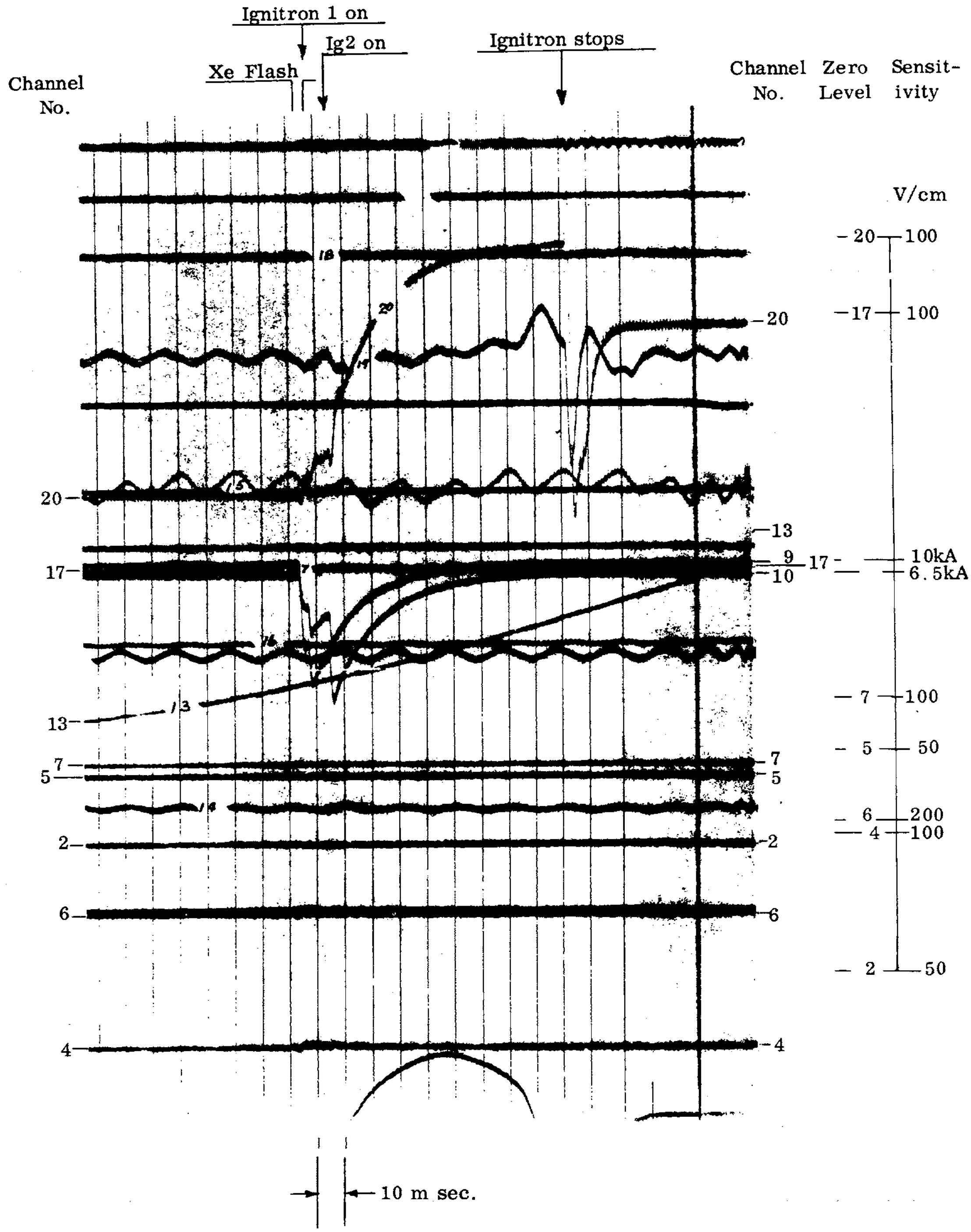


Figure 3 Reproduction of part of the records for pulse 04 on 21/11/68. This was a typical pulse in which the ignitron stopped while the switch was still conducting.

zero, but the voltage transmitted via the switch rose to the output voltage (600 V) from the generator. When the resistors were examined later, both had melted at points where the current concentrated to give high current density regions. The melting resistors had apparently broken the circuit, (see Channel 19 of record) but the electrolytic switch still supplied enough current to maintain the voltage.

This failure of the electrolytic switch to break the supply to the load was a cause for great concern. One of the major worries was that a similar fault could allow current to flow until the brushes were withdrawn from the rotors of the generator. Such an event was considered likely to cause serious damage to the rotor surfaces. Consequently as a safeguard against breaking a current by withdrawing the brushes, an interlock was arranged to stop the brush actuating cam during the time that a current of more than 1, 000 A was flowing.

Because more than 140 pulses had been run without fault, but with the previous slow cycle of the electrolytic tank, there was some indication that waves caused by the faster operation of the tank may have started the arc. The rate of rise and the acceleration at the top were therefore reduced, and a smoother action achieved.

It was also decided that the bow switch would be set to open to end each pulse and that if an arc started again, the field of the generator would be turned off as rapidly as possible.

With these changes, the generator was run up to pulse at 600 r.p.m. on 28th November. The first three current pulses ended as planned. The bow switch opened and a small restrike arc followed as is usual for this switch at voltages in excess of 400 V . The fourth current pulse (record pulse No. 5, Figure 5) was at 522 r.p.m. and the current through Ig2 was not quite enough to break the bow switch, the peak value being 13, 000 A . The current decreased as the electrolytic resistor increased, for fifteen milliseconds at the rate observed during the previous pulses. Then the rate of change of current suddenly increased and this was accompanied by a rapid increase in the voltage across the electrolytic switch. The current went down to less than 500 A and at least one ignitron was conducting when the electrolytic switch suddenly broke down and a current of 16, 000 A flowed into the load circuits, mainly via Rs and Ig2, which presented a load of 25 mΩ (i.e. the ratio of voltage to current). This current was sufficient to open the bow switch and the follow-up arc in it carried about 1, 500 A for 15 msec; after this, an arc apparently started between the supply terminal of the bow switch and the load end of Rs. The current rose sharply to 17, 000 A for 5 msec, during which time the actual load resistance was about 20 mΩ , probably due to the arc from the terminals of the bow switch extending to the terminals of Rs and shunting it. The latter bridge apparently extinguished, leaving the load consisting of the arc across the bow switch in series with Rs and Ig2. This had an equivalent resistance of 73 mΩ and the current fluctuated about a mean value of 8, 000 A for 130 msec. By this time the temperature of Rs reached its melting point and the sharp increase in voltage across it may have caused an arc between the bus bars at the top of the arc enclosure, reducing the equivalent load resistance, V/I, to

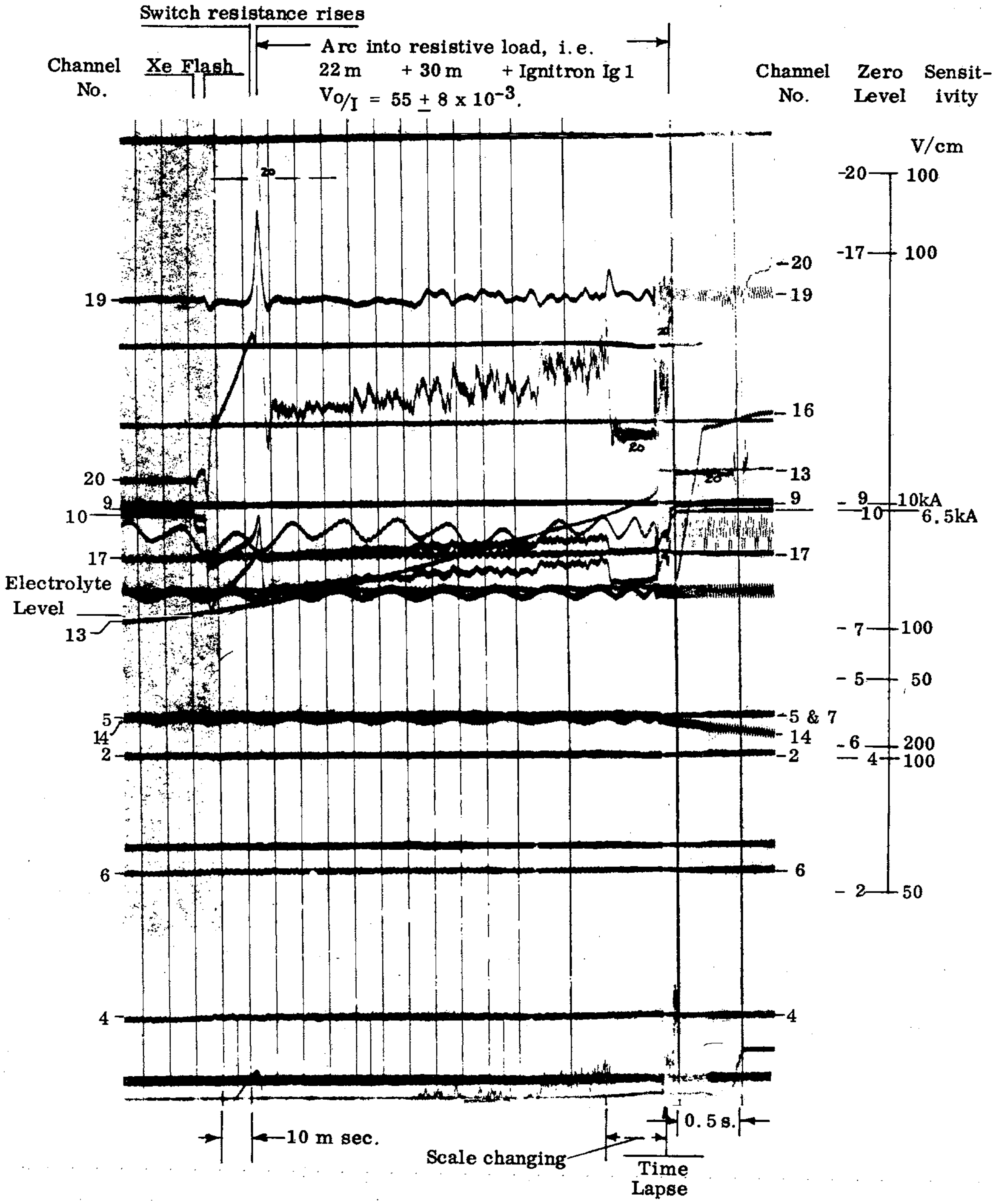


Figure 4 Records of pulse 17 on 27/11/68. This was the first time the switch resistance increased rapidly and an arc developed between the electrodes. The current stopped when the stainless steel resistors melted.

22 mΩ . A current of about 20,000 A continued to flow for approximately 0.36 sec. before dropping to a very low value. This is the last current value that can be measured reliably on the records. About 40 msec later the voltages on all terminals of the generator dropped sharply and after a further 30 msec destructively large currents flowed within the generator and bus bars. Since there was no sign of an arc shunting the ignitron, it apparently carried all the current up to the time that the bus bars flashed over, about 170 msec after the arc started between the electrodes of the switch.

3. INTERPRETATION OF RECORDS AFTER ARC-OCCURRENCE IN THE SWITCH

Before looking closely at the records, it is necessary to draw attention to three confusing features which were built into the recording system. Firstly, channel 20 records the voltage at the load end of the bus bars. When the voltage changes, due to changes in RE, the potential of only one polarity bus bar changes with respect to earth. If this change occurs rapidly, unbalanced capacitive currents to earth produce a deflection of the galvanometer in the opposite direction to that subsequently resulting from the change in potential. Thus, in all the records where an increase in the current has caused a reduction in voltage, there is an apparent transient increase in voltage. For example, in Figure 2, when the ignitron fires, the voltage drops, but the record shows a momentary increase on channel 20 . When the ignitron stops conducting, the record shows a drop in voltage, whereas in fact the voltage increases immediately.

Secondly, the recorder paper drive was programmed to speed up, during a pulse, to 20 inches per sec. (that is, 10 msec per time marker line), and then to reduce to 1 inch per sec. at the end of the pulse. During the change of speed, the paper sometimes pauses for 40 msec, and the traces are blurred, due to vibration, just after the slow speed is reached. The main overload in the generator occurred during this confused blurred period.

Thirdly, the reproduction of the records are made by emulsion to emulsion contact prints and are mounted so that time elapses from left to right. Because of this, the output voltage V_0 recorded on channel 20, the current recorded on channels 9 and 10, the generator voltage on channel 17, the potentials of all the brush rings B2, B3 and B7, B4 and B5, and B6 are deflected downward on the record by increases in the value of the variable being recorded. In the case of Figure 5, the current record on channel 9 was reversed so that in that figure an increase in current produced an upward deflection of the trace.

The sequence of events during pulse 05 on 28th November, 1968, can be divided into five consecutive time intervals (see Figure 5). We will look at these intervals in greater detail and consider some alternatives to the sequence of behaviour. The intervals are:

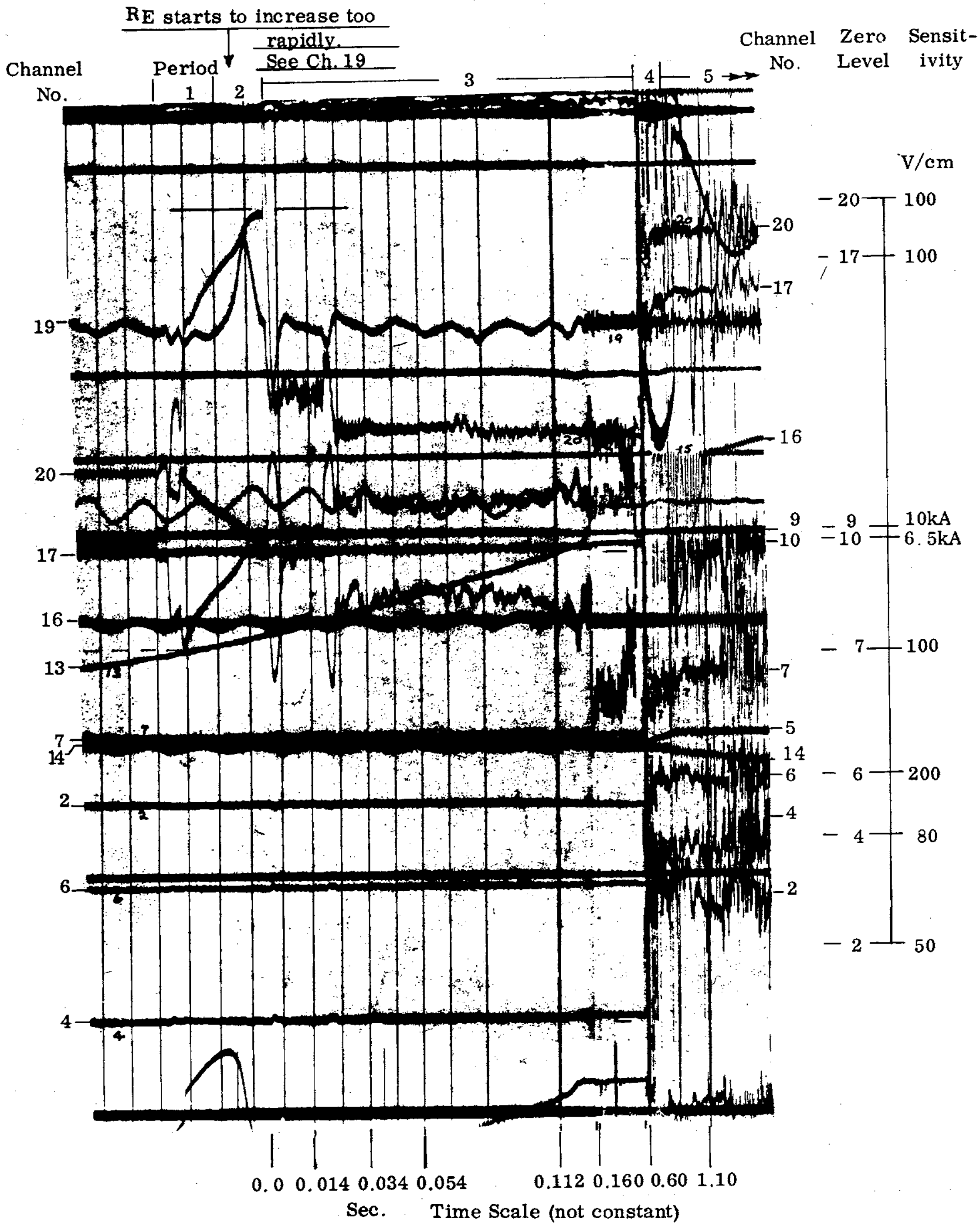


Figure 5 Records of pulse 05 on 28/11/68. An arc developed between the electrode of the switch and was followed by arcs in the busbars and generator.

(1) The normal operation of the xenon tube, the two ignitrons and the electrolytic switch. A period of 0.020 sec.

(2) An abnormal increase in the resistance of the electrolytic switch causing the current to decrease more rapidly than usual from 3,000 A to 500 A (see reference 2). The current remained at about 200 A for about 3 msec. The resistance of the electrolytic switch then rose to about one ohm. A period of 0.015 sec.

(3) A sudden abnormal decrease in the resistance of the switch to a value of 8 m ohm for 4 msec. Thereafter the voltage across the switch remained about 100 V to 120 V and was independent of the current passing through it. A period of 0.50 sec.

(4) The onset of currents within the system large enough to destroy the small number of brushes used in positions 4-5, followed by those in rings 2, 3, 6 and 7. This gave rise to currents of millions of amperes within the generator. A period of 0.20 to 0.25 sec.

(5) The generator running on without magnetic field, with water supplied to the air bearings. The top rotor stopped within 40 sec., the lower rotor ran for 40 minutes.

During the first period in which everything operated normally, the total current through the ignitrons and flash tube was about 9,000 A (channel 9), when the electrodes of ES would have left the undisturbed surface of the electrolyte, and it continued to drop in the usual way for a further 10 msec, during which time the tank would have dropped a further 0.3 inches. The voltage across the load was dropping as usual and had reached a value of 140 volts (see channel 20). The ratio of voltage to current was 25.5×10^{-3}, in reasonable agreement with the circuit through Rs in series with, Rig plus Ig1, Ig2, and XFT in parallel. This was the condition at the end of period (1).

At the start of period (2) the most noticeable abnormality was the rapid increase in the voltage across RE, as shown by channel 19, (Figure 5) and the corresponding drop in current, shown on channels 9 and 10. The usual behaviour was as shown in Figure 2, while the abnormal occurred even more sharply in Figure 4. The fairly rapid fall in current would have been quite convenient and could have been sought on every pulse had it not been followed by an arc developing in the ES on the two occasions on which it occurred[2]. The current was steady at 200 A for about 3 msec before the arc.

The third period started with the rapid increase in current to the load. The load circuit was still intact, having a V/I ratio of $(24.5 \pm 3) \times 10^{-3}$, as in period (1). The current rose to a peak of 16,000 A and the bow switch opened, but an arc followed across the terminals and a current of $1,000 \pm 500$ A continued through this arc for 14 msec. The zero of the time scale marked on Figure 5 is at the time the arc started in ES. The voltage across this arc was the same when the current was

16,000 A and 1,500 A : see channel 20 from time 0.00 to 0.019 sec., where the voltage across the arc is shown as the deflection of trace 20 from its original level at the left of the record (the sensitivity is 100 V per cm).

Other traces which are relevant at time 0.00 are:

(a) Trace 19 (the time derivative of voltage across RE) shows a rapid decrease in the voltage across RE simultaneously with the increase in current.

(b) Trace 20 is initially deflected to indicate a negative voltage across the load. This is a false indication due to the response to the change in the common mode voltage of the galvanometer. If in addition to the common mode swing there was a negative voltage across the load, it could arise only due to ES rapidly interrupting the small residual current, about 200 A, still flowing at that time. If this occurred and was followed in less than 1 msec by an arc across ES, the records would not enable the delay in the onset of current to be observed. If, for example, a residual current of 200 A through the 10 μH in the load circuit were interrupted in 10^{-5}sec., an induced voltage of more than 200 V would add to the potential across ES. Such a rapid break does not seem likely, since the conduction at this time would have been via streamers or sheets of electrolyte which, if one millimeter thick, would have extended for 240 cm along the edges of the positive electrodes and 240 cm along the negative ones. The electrolyte would have travelled through the sheet in 0.08 sec. and the temperature would have risen about 12^{o}C during its fall. If these current sheets had been uniformly distributed, there would have been no effective transverse forces on them, and normally the current fell smoothly until the ignitron extinguished.

(c) The output voltage of the generator, trace 17, the potentials of B2 on trace 2, of B3 and B7 on trace 7, of B4 and B5 on trace 4, and of B6 on trace 6, all show the small voltage changes due to the current flowing in the brush resistors and contacts.

At time 0.018 sec., the current rose rapidly to 18,000 A and the ratio of V/I for the load fell to 19 x 10^{-3}, indicating that the arc between the terminals of the bow switch had swung over to the resistor terminal which was about 4 inches away, and shunted Rs. The arc must have extinguished and transferred to a longer path, from the input to the bow switch to the input to Rs, so raising the V/I ratio to 73 x 10^{-3}. This circuit continued to draw current which fluctuated, and slowly increased to an average value of 10,000 A at time 0.130 sec. The current through Rs would heat it to melting point by time 0.130 $\pm$ 0.040 sec. At time 0.140 sec., the voltage across the bus bar, record trace 20, increased momentarily and the current fluctuated around 20,000 A for 0.36 sec. before jittering down to about 200 A at time 0.50 sec. This current apparently passed through an arc between the bus bars at the top of the coaxial arc chamber where the damage to the aluminium bars is commensurate with that produced by a current of this magnitude flowing for about 0.3 sec.

Further points to note from the records up to time 0.50 sec. are:

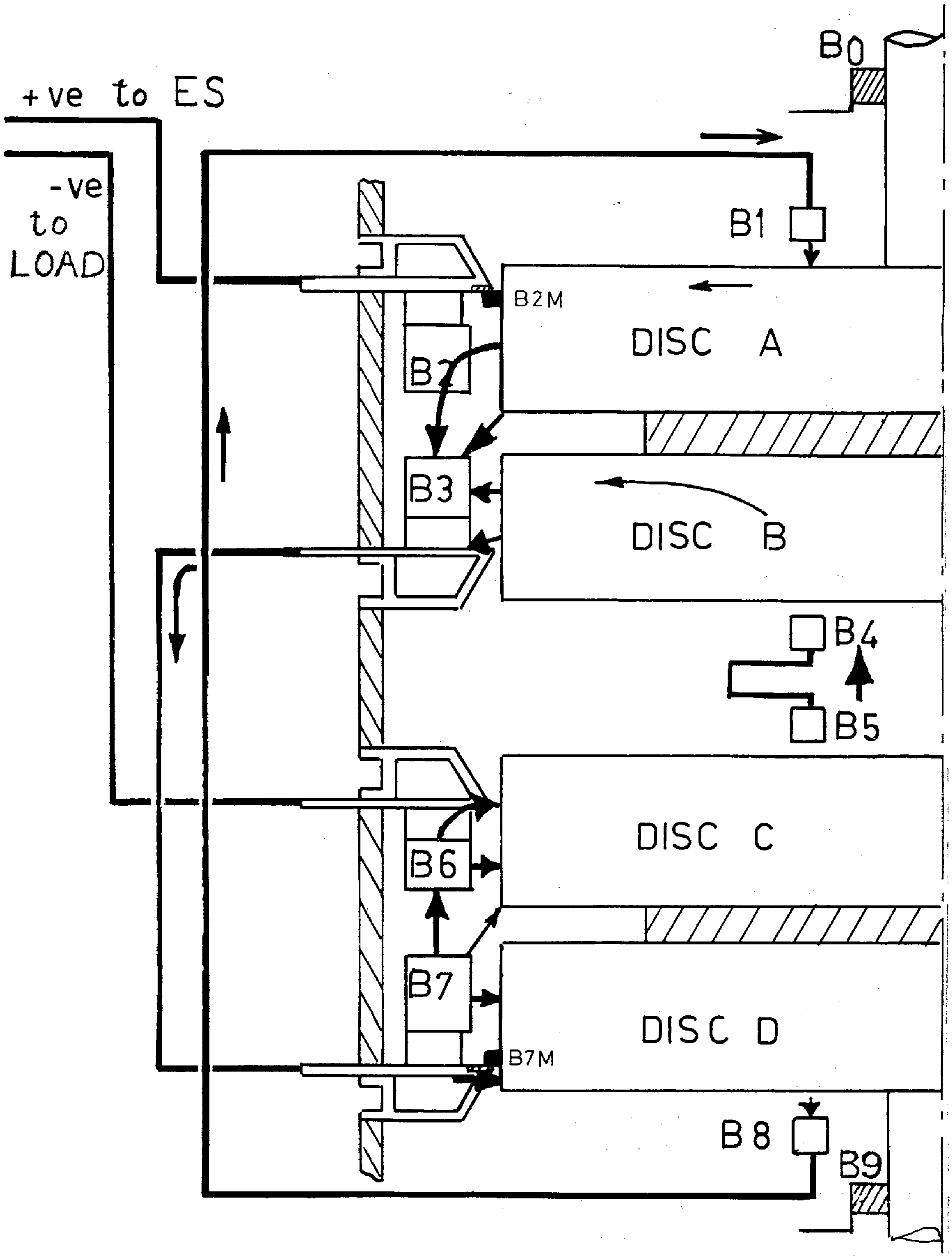


Diagram of brush and rotor identification. The circuits in which the fault currents could flow are shown by the arrows.

(i) Traces 17, 2, 4, 6 and 7 indicate that the correct voltages were present at all stages of the generator up to 0.50 sec. from 0.00. The resistive voltage drops were as expected, and therefore the circuit of the generator was intact and not overloaded up to this point.

(ii) Arcs developed over long gaps when the current was supplied via the arc in the ES, but they had not done so when the current was controlled by conduction through the electrolyte. For example, the high current at time 0.019 sec. started across a gap of about 10 cm, admittedly in the neighbourhood of an existing arc.

(iii) The voltage across the arc in the ES changed only a small amount when the current changed from 1,500 A to 18,000 A at time 0.018 sec., and it did not change at all when the current increased from 8,000 A at time 0.10 sec. to 20,000 A at time 0.20 sec. Therefore, the arc must have developed to a stage where it had a low impedance, and it is not clear what limited the current between the bus bars to 20,000 A, at time around 0.2 sec.

Period (4) starts at time 0.58 sec., with the correct output voltage from the generator, the load current very low and the correct potentials with respect to earth being recorded for all the brush rings. (The Diagram opposite shows the circuit of the generator and the numbering of the brush rings.) Then all the potentials dropped very sharply and fluctuated. The trend 0.030 sec. later was:

B2	down from V_1	=	140 V	to	70 V,	i.e.	to	0.5 V_1
B3 & 7	down from V_2	=	-140 V	to	-70 V,	i.e.	to	0.5 V_2
B4 & 5	down from V_3	=	-280 V	to	-80 V,	i.e.	to	0.28 V_3
B6	down from V_4	=	-430 V	to	-70 V,	i.e.	to	0.16 V_4

These values are inconsistent with each other since B4 could not be -80 V when B6 was -70 V; B4 would have to be near to zero or even positive with respect to earth. This implies that the confused record at time 0.58 to 0.65 has been mis-read. It is clear from Figure 5 that B4 and B6 do go through zero on many fluctuations much earlier than B7 or B2.

The records overlap and are too blurred to justify positive statements about the current at the time when the potentials start to drop, but trace 9 does not show any current through the load at this time. However, there is a faint trace, as could be made by a fast deflection on channel 10, which could indicate current flowing in the bus bars. Although it cannot be proved from the records, it is possible that the bus bars which rise from the south-west corner of the generator, but which were disconnected from it on the 28th November, could have arced over due to a voltage surge coupled to them from the common input to the ES. Such an arc would be a very low impedance load on the generator, drawing current without it having to pass through ES. The current could rise rapidly to a value sufficient to twist the sliding brushes and the twelve outer brushes being used, so that they would have broken away from their supports.

The rupture of the active brushes then could have led to the formation of arcs carrying several million amperes within the generator, slowing the rotors by at least 220 r.p.m. in 0.2 sec. By time 1.2 sec., that is, 0.6 seconds after these arcs started, the speed of the upper rotor was 330 $\pm$ 20 r.p.m. and the lower one 300 $\pm$ 20 r.p.m.

Examination of the generator subsequently showed that very high current arcs occurred between the brush units on rings 2 and 3, and on 6 to 7 . Comparable arcs occurred between the centre of the inner discs of each rotor, at the point where one half of the sliding brush structure which formed brushes 4 and 5, had been. There are two circuits within the generator which involve these arc circuits, and millions of amperes could have passed through each of them simultaneously or sequentially. Referring to Figure 6, these circuits are, firstly, from B8 to B1, through disc A to B2, then via an arc to B3, both from brush units on each ring and directly from the corner of disc A to brush units in B3. B3 is solidly connected to B7 and so the circuit is completed via disc D. Discs A and D were generating 130 volts each in this circuit and the current could have been several million amperes.

Secondly, the circuit from B3 to B7 and then to B6 or the edge of disc C via arcs, through disc C and brushes B5 to B4, until they were replaced by an arc, then via disc B to complete the circuit at B3. Both discs B and C were generating 130 volts and the current could have been nearly as large as in the first circuit,the difference being due to the voltage across the arc which took over from B4 and B5. These two circuits are similar and could occur in parallel. This is implied by the voltages listed above at time 0.61 sec. Since brushes 4 and 5 were structurally the weakest, an over-current would have caused this unit to break first. It would have been replaced immediately by an arc developing from parts of the structure contacting the rotor and the current would have continued to increase into the external circuit until units in the outer rings failed and arced to the adjoining discs or brushes.

The change in voltage recorded on trace 5 from time 0.6 to 0.82 sec. shows that the lower rotor changed speed rapidly during this time, with possibly two moments of high deceleration near the start and end of this period. If the combined current in the two circuits is assumed to be constant for 0.2 sec., a value of 2.5×10^6 A would be required to slow the rotors from 520 r.p.m. to 300 r.p.m. Trace 5 indicates the peak deceleration could be about three times the mean so that a peak current of 7.5×10^6 A could have occurred for 0.030 sec.: 2.5×10^6A of this current could have passed through the circuit involving discs B and C on the western side of the generator, while the remaining 5×10^6 A may have been in discs A and D and concentrated to the east of the generator. If this unfortunate coincidence occurred the two currents would have produced additive tilting forces on the rotors. In fact the upper rotor tilted upward and the lower one downward on the west by very large amounts. The amount indicated by the deformation of the western upper tilt probe, was the incredibly large figure of more than 3/8" in three feet.

A comparison of trace 14 in Figures 4 and 5, shows how the current interlock stopped the cam on the generator until time 0.75 sec., so maintaining air pressure on the brush actuators until after the valves closed at time 0.95 sec., as shown by trace 16 in Figure 5.

It has always been understood that currents of this magnitude could flow in the generator, but it was not considered that they would occur so as to produce an extreme tilt. The bearings were designed to withstand the force of 400 tons produced by a current of 5×10^6 A uniformly distributed around the rotor. The upper guide and thrust bearings and the fixing screws were distorted by the load, which may have been as great as 500 tons at the bearing, but did not break. Both air bearings suffered minor distortions, corrected by relining and machining.

4. GENERAL ROTOR AND BEARING BEHAVIOUR

Because of the weight of the rotors, the top bearing carries an axial load of 80 tons more than the lower bearing, when equal forces are applied to each rotor so as to tilt them on the air bearings, or to force them away from the air bearings.

During the overload on 28th November, the heavy currents in the rotors caused tilting and produced a load in the top bearing large enough to distort the bolts holding the bearing into the pole and the screw (cross sectional area 49 sq. in.) holding the rotor to the shaft. This indicates that the load must have reached about 500 tons. This could arise from a current of 3 to 4×10^6A in discs A and D, mainly on the eastern side of the rotors. The top rotor may have tilted 0.4 inches in 30 inches and applied a load of 300 tons to the air bearing. The elastic component of this deflection would have relaxed in less than 0.02 sec. and would have continued for a few cycles of damped oscillation. While this was happening, the gyroscopic forces produced would apply loads of up to 300 tons to the air bearing. These forces apparently lasted for such a short time that they account for the loss of only about 30 r.p.m. of rotor speed. About 0.3 sec. after the heavy current started, both rotors were running at approximately 300 r.p.m. The lower bearings did not suffer any significant distortion and the lower rotor ran almost normally. However, the upper bearing had distorted, allowing the rotor to move away from the air bearing and it could have remained tilted more than 0.5 inch across a diameter, and bearing against the air bearing under the influence of the gyroscopic force produced by the couple resulting from the friction and its reaction in the guide bearing. This would have caused the rotor to precess contra to the direction of spin and remain in contact with the air bearing. The records show the rate of precession of the tilt to be 110 r.p.m., a few seconds after the overload.

Oil flowing into the support for the top thrust bearing would have taken many seconds to raise the rotor and hold it against the air bearing with the usual force of 40 tons. When this occurred, a braking torque of 51,000 lbs. ft. would have resulted, if the coefficient of friction was 0.2, and the rotor would have decelerated at 10 r.p.m. per sec., so stopping in 30 seconds. It actually stopped in 41 sec. from the time when the bearing was damaged.

Several effects, such as eddy currents in the rotor and magnet poles, gyroscopic forces, and the disintegration of the lining of the thrust bearing, followed by the consequent welding of the bearing faces, combined to increase the braking of the top rotor. Of these, the seizure of the bearing produced the largest torque. It could have been as much as 30,000 lbs. ft. when the rotor was not held firmly against the air bearing and 60,000 lbs. ft. after the clearance had been taken up. Since the rotor came to rest from 300 r.p.m. in 41 sec., the load on the air bearing could not have been present until 20-25 sec. after the damage to the bearing.

Since the energy in the rotor at 300 r.p.m. was dissipated by friction at the bearing faces and around the fixing screw, the rotor was checked for damage due to local heating. If the energy went into the volume of rotor 10 cm thick and equal in area to the air bearing, the average temperature rise would have been 33°C. When the speed was 300 r.p.m. the temperature gradient would have been 150°C per cm. The lubricating water was turned on about 6 seconds after the current flow and therefore before the rotor was held up to the air bearing and before the surface temperature was higher than 100°C above ambient.

5. THE DESIGN AND LOAD CONDITIONS

The following comments deal with features of the design which were tested for the first time by this incident. Firstly, the locking cone[3] which prevents the rotor fixing screw undoing if the shaft turns on the rotor was called into use. In the case of the top rotor, the rapid deceleration could have induced the shaft and slip-ring to turn on the rotor in the direction to undo the screw. The locking cone was designed to tighten in this direction. Subsequently, when the bearing seized, the rotor slipped on the shaft in a direction which would have tightened the screw and slackened the locking cone. Apparently the screw did not move in this direction since the locking cone was firmly clamped and gave some trouble before it could be removed when dismantling the generator.

Secondly, the bearings were subjected to 1.5 times the emergency load on which the design was based, and although they yielded under this stress, they did not break. Further, the yielding and damage was spread through most of the items concerned with the integrity of the bearings, showing that the design was adequately consistent throughout.

Thirdly, the water lubrication for the air bearings worked perfectly. The power absorbed in the water was inconveniently low and the lower rotor continued to turn for longer than expected.

Fourthly, the transient high pressure in the lubricating oil, caused by the impact load on the thrust bearings, caused the overload protection to the motor driving the oil pumps to open and stop the pumps. When the system is complete, the drop in pressure caused by the pumps stopping will start a third pump driven by a diesel engine. On this occasion the diesel-driven pump was not ready for connection to the system. Under these circumstances, it would have been an advantage if the motor overload cut-out had been by-passed.

6. INITIATION OF ARCS IN THE ELECTROLYTIC SWITCH

On the two occasions when arcs occurred in the electrolytic switch, the first indication of the fault was an unusual change in the current. The second occasion led to the overload of the generator. The switch, or some improved alternative, is essential for many experiments using the homopolar generator. It will therefore be necessary to investigate its failure in detail. A number of comments can be made at this stage as a starting point for such a study.

The switch had operated satisfactorily for more than 140 pulses before the operating cycle was speeded up, and 14 more with the faster operation. After the first fault, only three further pulses preceded the second failure. Although fourteen fast-cycle pulses are a lot to reveal an incipient fault, the increased speed could be the cause of the change in the way the electrolyte streaming off the electrodes carried the current and subsequent breakdown of the air gap. There are several ways this could have occurred:

Firstly, the tank may have jammed on one side, tilted, and caused a concentration of current in the streams of electrolyte from a few plates in the north-west block of electrodes, where the arc occurred. If these streams had become hotter, their resistivity would have decreased, and a cumulative increase in current could have caused local boiling, giving a rapid increase in resistance.

Simple calculations on the basis of uniformly distributed streams of electrolyte carrying equal currents indicate that the temperature rose only 10 to 20°C during the interrupt sequence. Some non-uniform initial conditions could be assumed and a computer programmed to calculate the subsequent development. However, a start will first be made by observing a section of the switch interrupting the same current density as has been used and slow motion pictures will be obtained of the way the electrolyte streams form*.

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*After writing these comments, the operation of a section of the switch has been tested[(2)]. The abrupt reduction of current could be reproduced when the streams of

(Contd.)

Secondly, the plates may have dried between pulses so that air could get between rust flakes and the electrode surface. If this air was still trapped in some areas by the electrolyte, it would cause a current concentration in the wetted areas and again might cause a failure as suggested above.

Thirdly, the effect may have been the same as that observed by Marshall[4] during tests on small electrolytic resistors. These tests showed a sharp reduction in the current between electrodes when the voltage was raised above a critical value. If this effect occurred during the recent operation, it is difficult to understand why it did not occur on the 12th November immediately after the electrolyte conductivity was increased to 0.1 ohm^{-1} per cm cube. Sixty-one pulses were taken between this date and 27th November. If this effect was actually responsible for the sharp decrease in the current, it does not in itself explain why the arc developed somewhat later, unless it also led to some electrolyte splashing up to the point where the arc started.

7. THE TERMINATION OF CURRENT PULSES FROM THE GENERATOR

Although the homopolar generator and its bus bars can have an extremely low internal inductance, some configurations of the generator that have been used, result in higher values of inductance and these set a limit to the rate of decrease of current permissible if high voltages are to be avoided on the bus bars.

The inductance of the fully connected generator is less than 10^{-7}H and the bus bar connected with the half-bars on the outside could be as low as 5×10^{-8}H to the electrolytic switch.

When the generator is connected using only 12 brush units on the rotor rims and no half-bars in the bus bars, the total inductance to the arc could be about 10^{-6}H; most of this is due to the electrolytic switch. Under these circumstances, when a voltage limit of 2 Kv is set, the maximum rate of decrease of currents is such that 1,200 volts can be induced in addition to the steady 800 volts from the generator.

Therefore $$10^{-6} \times \left(\frac{di}{dt}\right)_{max} < 1200$$

or $$\left(\frac{di}{dt}\right)_{max} < 1200 \text{ A per } \mu \text{ sec}$$

(The maximum value of di/dt required for the recent experiments was 5 A per μ sec.)

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electrolyte from the plates were inadequate to carry the current until the current was terminated gradually. This arose when the plates were not immersed far enough to collect a sufficient volume of electrolyte. It would also be dependent upon the wetting of the plates so that although the immersion was sufficient on the 27th and 28th November, 1968, the faster reversal of travel on these days would have reduced the time allowed for full wetting of the rust on the plates.

The value of 1,200 volts, is the steady state value when di/dt = 1200 A per μ sec. If reflections from discontinuities in the bus bar and switch system are small, the voltage will increase from its initial value at the rate dV/dt = Zo di/dt for the first 2.6×10^{-7} sec. In this case, Zo $\approx$ 1 ohm and the voltage would change by 300 V before the effect of the reflection from the generator end modified the rate of change. The steady value of 1,200 V would be present when the transients on the system decay, if the current were still changing at the same rate.

Experiments using exploding wires enclosed in pressure jackets to extinguish the arcs by means of the shock wave reflected from the jacket have been reported by McFarlane(6). There the arc was carrying a peak current of 10^5A at 10,000 volts, and the arc was extinguished in 3 μ sec.

Similarly enclosed exploding wires were tested in our laboratory with 250 V across them. They carried 35,000 A and induced a voltage of 1,700 volts across a 10 μ H choke when the wire ruptured. In this case

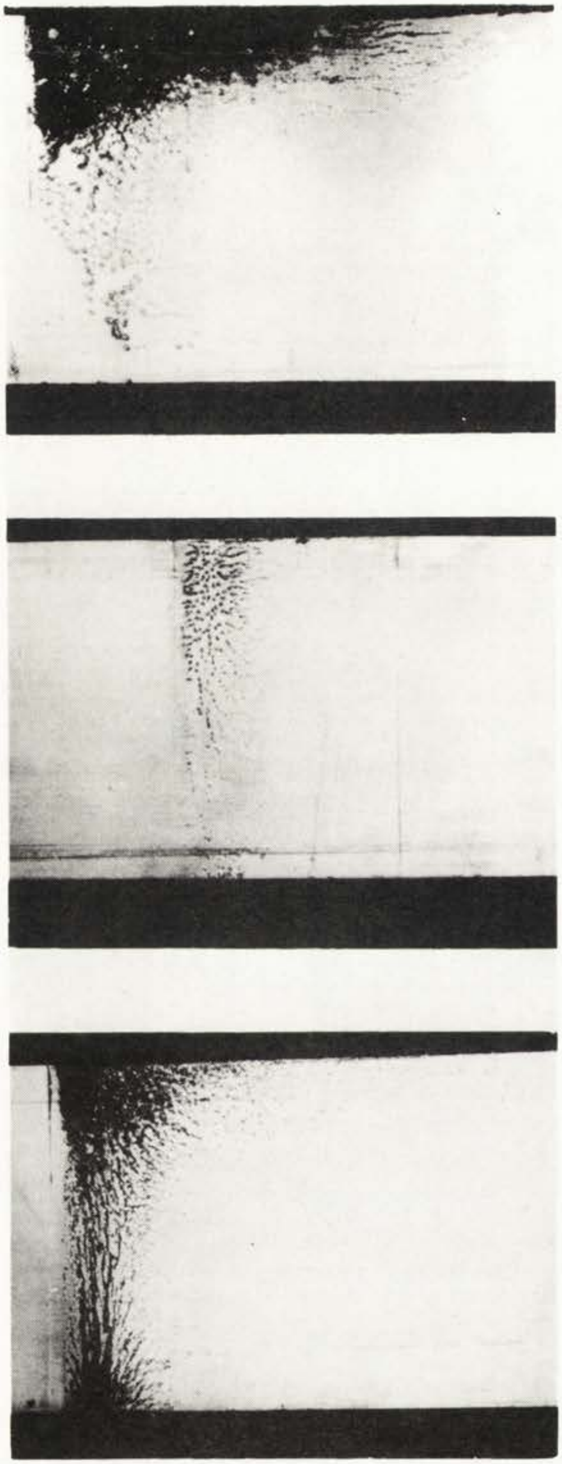
$$di/dt = 170 \text{ A per } \mu \text{ sec.}$$

No voltage surge could be observed across the 10 μH choke when the fuse was not enclosed in the pressure jacket. Thus, assuming the voltage was less than 50 V, an arc of 35,000 A between the fuse holder terminals must have taken longer than 7×10^{-3}sec. to blow out, at a uniform rate. It has not been possible to extinguish arcs in air at these voltages and currents in less than 300 μ sec. even when the arc was in a transverse magnetic field produced by the arc current flowing in a solenoid around the arc. It is clear that in these experiments we have not been able to reach the limit on the rate of change of current set by the generator and the bus bars. If the bus bars and brush units are all in circuit, one of the largest inductances would be the electrolytic switch. The total inductance may be kept as low as 2×10^{-7}H, in which case the maximum allowable rate of decrease of current would be 6,000 A per μ sec. If an inductive store is used and is charged to 10^6A, the shortest permissible break time would be 160 μ sec. This is a little too slow but usable for a store which is to deliver its energy in 10^{-3}sec., as required for the flash tubes of a Q-switched laser. It is too long for other applications, and in these cases the current would have to be diverted from charging the inductance into a shunt resistance for the time required to stop it.

Methods of limiting transient voltages should be adopted with all loads on the generator. The simplest, all embracing method of doing this would be to fill the spaces between the bus bars with a lossy dielectric which could prevent a transient ringing for more than a few cycles. If the dielectric strength and constant of the material are greater than those of air, an increase in the high frequency voltage rating of the bus bars can be achieved, along with a reduction in the characteristic impedance.

A suitable material is sold under the trade name of "Miscolite" - an asbestos board used for switch board panels; it was found more lossy at 1 MHz than any other

Initiation of arcs
in S.W. bus bars.



Open end.

Intermediate
clamp.

Upper clamp
below clamp
at which most
powerful arc
occurred.

Figure 6 Showing how arcs developed from some initiating discharges but not from others.

convenient material tested and is readily available at a low price. The four vertical bus bar runs have been filled with Miscolite at a cost of about $1,000. Further insurance against breakdown across the ends of the Miscolite was achieved by covering each bar with a layer of PVC sleeving overlapping the bakelite spacers at the joints. This type of insulation could be added into the horizontal runs of bus bars at a later date, if considered necessary.

A further precaution against transients and voltage build-up, which must be observed in future, is to never leave a length of unused bus bar connected to the generator terminals.

8. BREAKDOWN AND ARCS IN THE BUS BARS

After the arc developed in the electrolytic switch, there were a number of places in the flash tube circuit where air insulation broke down, but it had not done so when the current was flowing normally through the electrolyte. Examples are: across the terminals of the bow switch, from the input terminal of the bow switch to the output of the series resistor Rs, a gap of about 4", and across the bus bars at the top of the arc chamber and on the south-west run to the high field magnet laboratory.

The bus bars were insulated to work at 1,000 V d.c. They had previously been tested to 2 kV over some of their length and 1 kV on other sections. A test voltage of 800 V was applied while the generator was being run up in the four disc mode. Tests on the insulators show that the bus bars would break down at about 10,000 V d.c. due to tracking across the surface of the bakelite spacers in the corner clamps, and 12-13,000 V d.c. across the surface of the ½" spacers on the vertical runs. However, it is well known (see Terman[5], page 123) that the dielectric strength of air is somewhat less at radio-frequencies than for d.c. and low frequencies. It is also well known that pulse voltages lasting a micro-second or less do not cause break-down across surfaces, in dielectrics, or in gases, at values well in excess of the steady value that would cause such breakdown[7]. It is very likely that a peak voltage of 3,000 volts at one MHz on top of 500 volts d.c. would cause the ½" air gap in the vertical bus bars to arc over, while a 10,000 volt pulse lasting one micro-second, on top of the steady 500 volts would not cause break-down. There seemed to be evidence that break-down due to radio-frequency voltage had occurred. The appearance was confirmed by an experienced welder (Mr. W. O'Neill) when he commented without being asked, that the marks left by the arcs in the south-west bars were similar to those produced by the argon arc welder when the "Pilot-Arc" was used to start it, and the welding arc was swept across the surface of the aluminium. The marks show that many hundreds of small discharges occurred, some, but not all of which led to heavy d.c. arcs (see Figure 6).

Literature on early radio transmitters working at about 10-100 kHz speak of the difficulty of generating higher frequencies using the negative dynamic-resistance characteristic of arcs. However, some months ago we observed that frequency

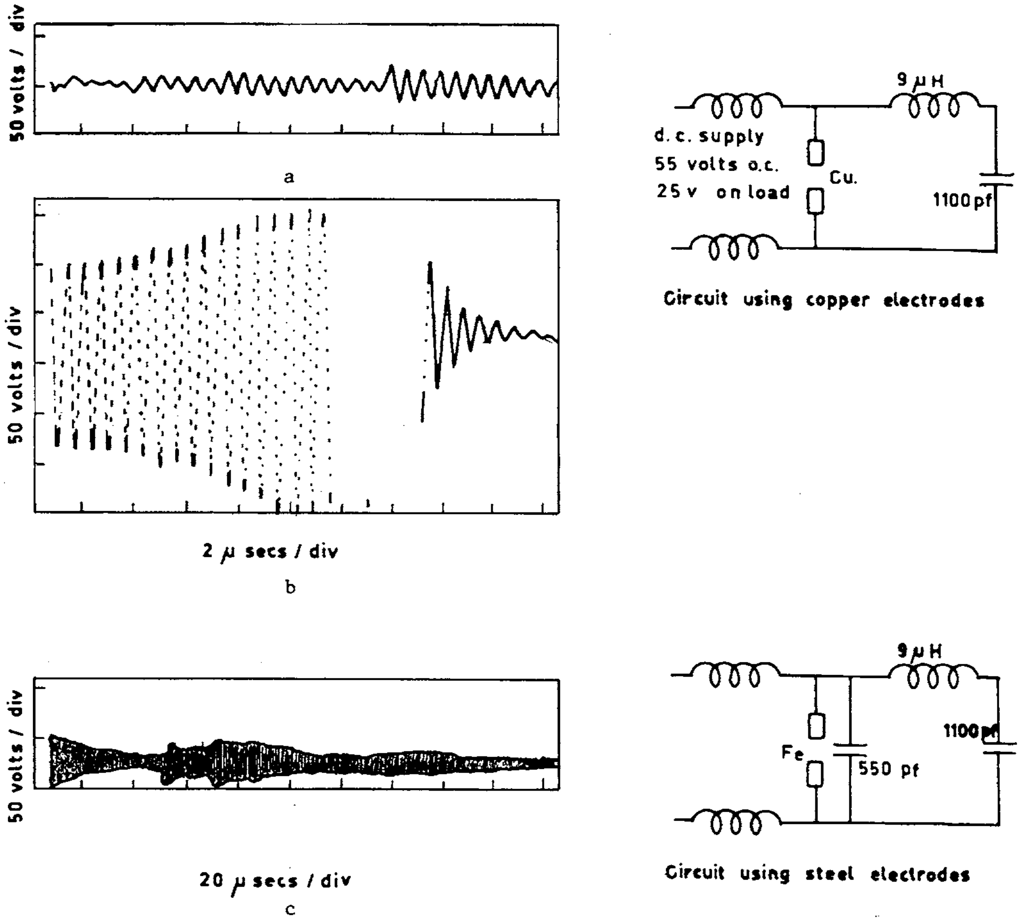


Figure 8 Tracings of oscillograms showing changes in the amplitude of 1.5 MHz oscillations in a resonant circuit. The voltage measured across the capacitor shows:

(a) Increases occurring as a series of in-phase transients.

(b) An example of a continuous increase to a large amplitude, followed by sudden quenching.

(c) The fluctuations of amplitude over a period of 200 μsec.

(a) and (b) were recorded while using copper electrodes, and (c) using steel electrodes.

components as high as 1 MHz were present in the current through arcs under certain conditions. The degree to which a circuit tuned to 1.5 MHz could be driven, was checked using the circuit shown in Figure 7.

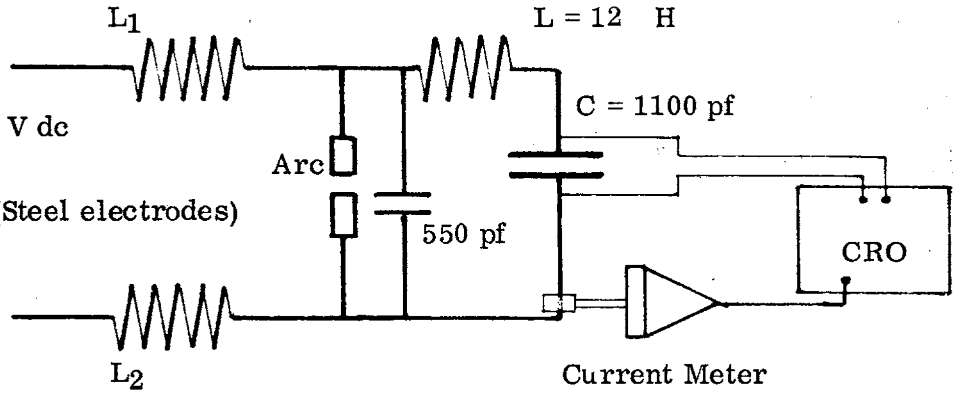
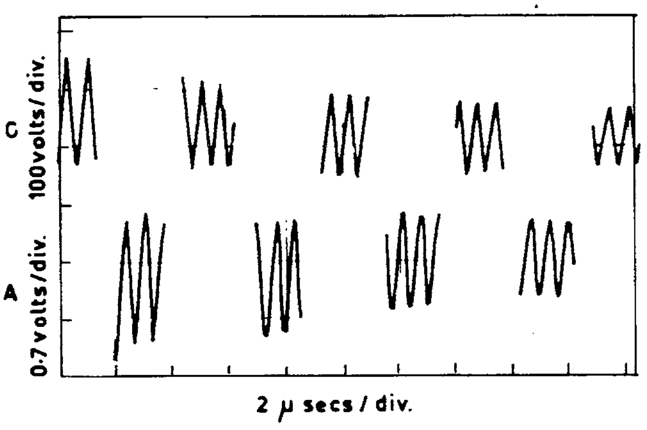


Figure 7 The circuit used to demonstrate the excitation of a tuned circuit by an arc.

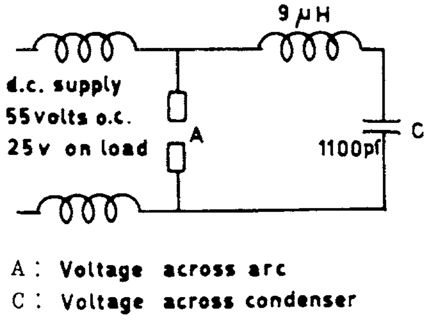
When the arc was burning with some molten steel on the surface of the electrodes, the tuned circuit carried a high current at the resonant frequency. No attempt was made to optimise any parameters of the circuit. The current in the circuit was measured as well as the voltage across the condenser, as a check on the calibration of the observations.

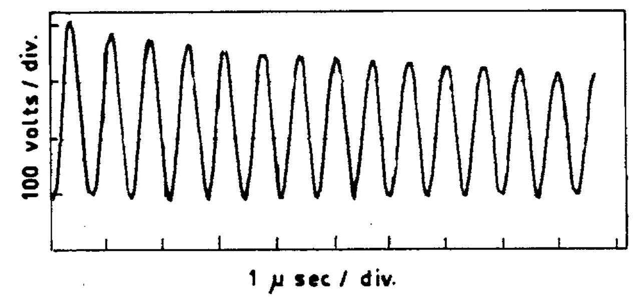
The highest excitation of the circuit was transitory but values as high as 200 volts peak amplitude across the condenser were observed (see Figure 8b which shows a record of a case when the voltage was greater than 150 V peak). The decay of amplitude was at most as great as that due to the losses in L and C and on occasions less, indicating that the resistance of the arc was very low and in some cases negative, at a frequency of 1.5 MHz. The oscillations recorded in Figure 9 occurred repeatedly when the electrodes were set to produce drops of molten steel which fell across the arc gap. In this case, a momentary interruption of the current through the arc could cause C to charge to a high value due to the voltage developed across the chokes L1 and L2. If the arc then became a very low resistance, the circuit would have continued to ring with a decay due to the losses in L and C. If the arc was in a transient state in which it could present a negative resistance, the oscillation could increase in amplitude as some records show (see Figure 8).

The bus bars of the homopolar generator form a low-loss system with many possible resonant modes. Two of the lowest frequency modes were checked to see the ratio between the voltage on the open end of the south-west riser and the voltage applied between the electrodes of the electrolytic switch, where the arc occurred.



a





b

Figure 9 (a) The radio-frequency voltage across the arc, A, observed alternately with the voltage across the capacitor C.

(b) The typical decay of a transient oscillation in the resonant circuit including the arc.

The generator ends of the north-west and south-east risers were connected via a thin wire which would have had an inductance comparable with the generator itself.

The bus bars were left unterminated in the arc cubicle for the first measurement, in which case the circuit was as shown in Figure 10.

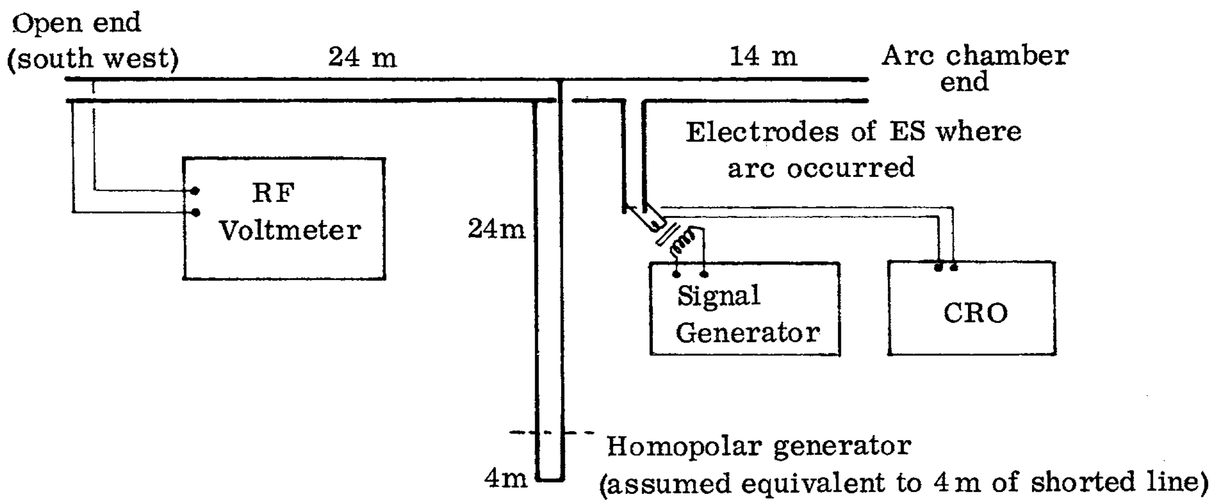


Figure 10 Current used to measure frequencies at which the bus bar system resonates and standing wave patterns occur.

Three resonances with antinodes at the south-west end were observed in the frequency range 0.6 MHz to 2.8 MHz. The dominant one was at 1.5 MHz where a 3.6 fold increase in voltage was observed. The normalised readings over the frequency range are shown in Figure 11. For each of these resonant frequencies, the 14 M length of open bus bars from the switch was less than a quarter wave length long, and therefore was equivalent to a capacitor coupling into a line about 52 M long, open at one end and shorted at the generator end. Frequencies at which the impedance looking into the feed point was inductive and which resonated with the loaded line, gave rise to standing waves with high voltages at the open end. The measurements show the frequencies at which such resonances do occur.

Other sharper and more discrete resonances occurred when the bus bars were shorted at the arc chamber end. In this case the dominant mode was a frequency of 1 MHz: at this frequency the voltage at the open end was 8.8 times that applied to the electrodes (the normalised measurements are plotted in Figure 12). When the short circuit was replaced by a non-inductive resistance of 0.5 ohm the resonance at 1 MHz was heavily damped, as shown in Figure 13, while a termination of 2.5 ohms, was too high to match the characteristic impedance - see Figure 14. The peak in the response at 2.1 MHz was present in all measurements and was due to

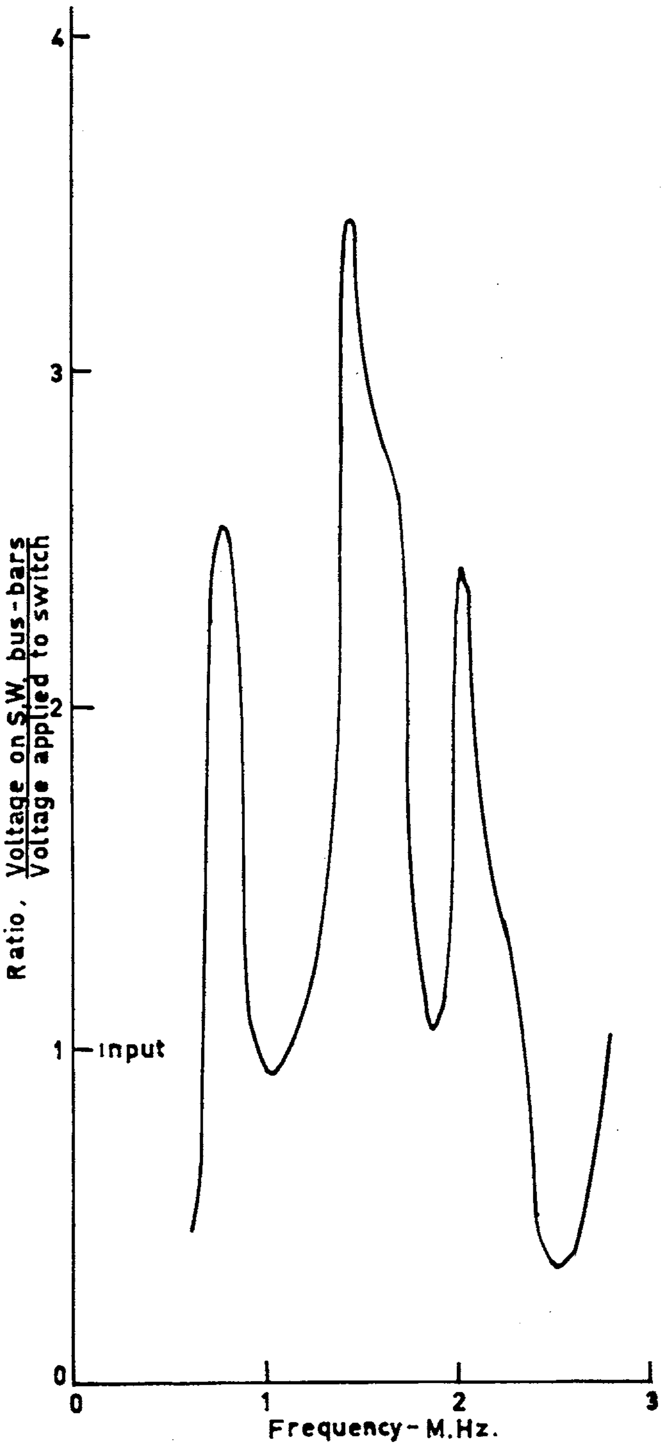


Figure 11 Three resonances of the bus bar system with an open circuit at the arc enclosure end.

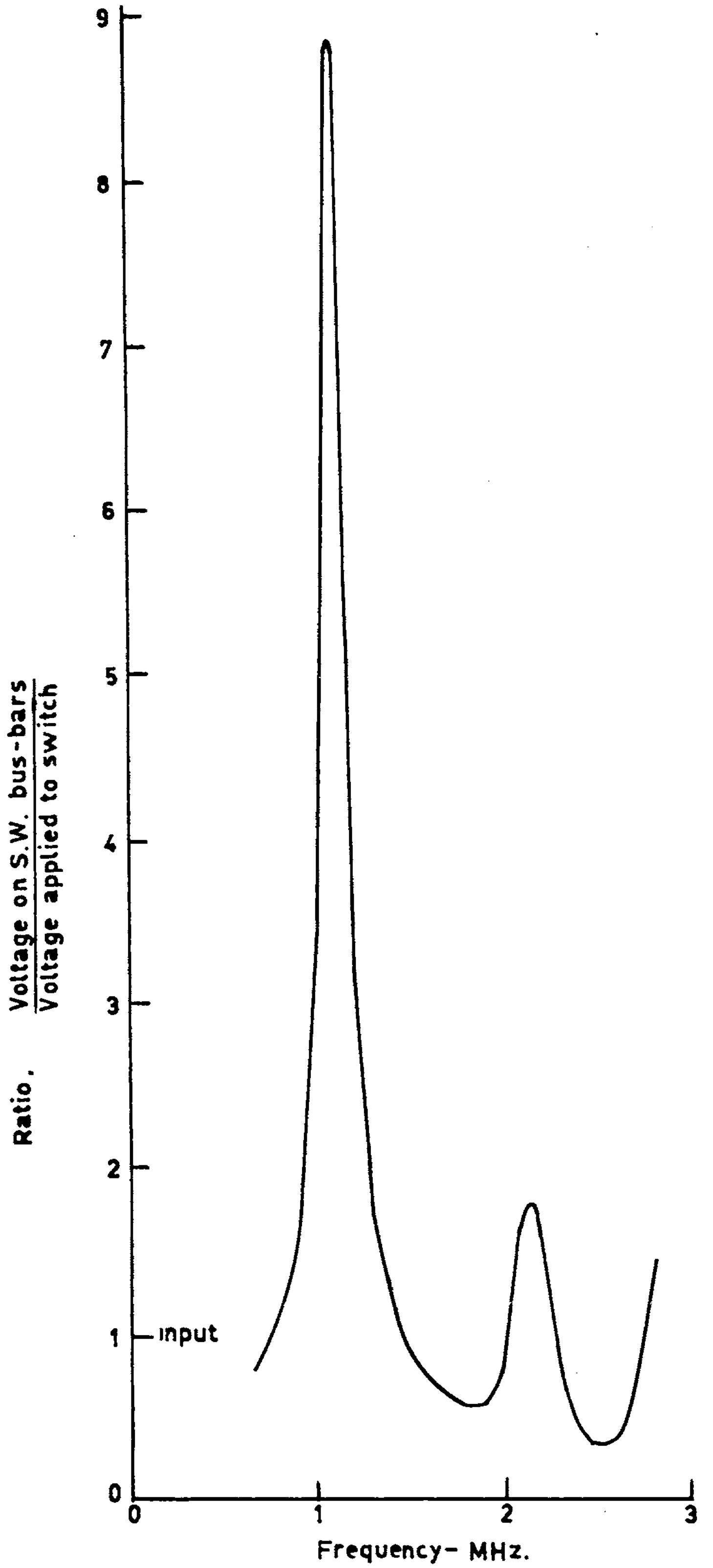


Figure 12 The dominant resonance at 1.1 MHz which occurs on the bus bar system when shorted at the arc enclosure end.

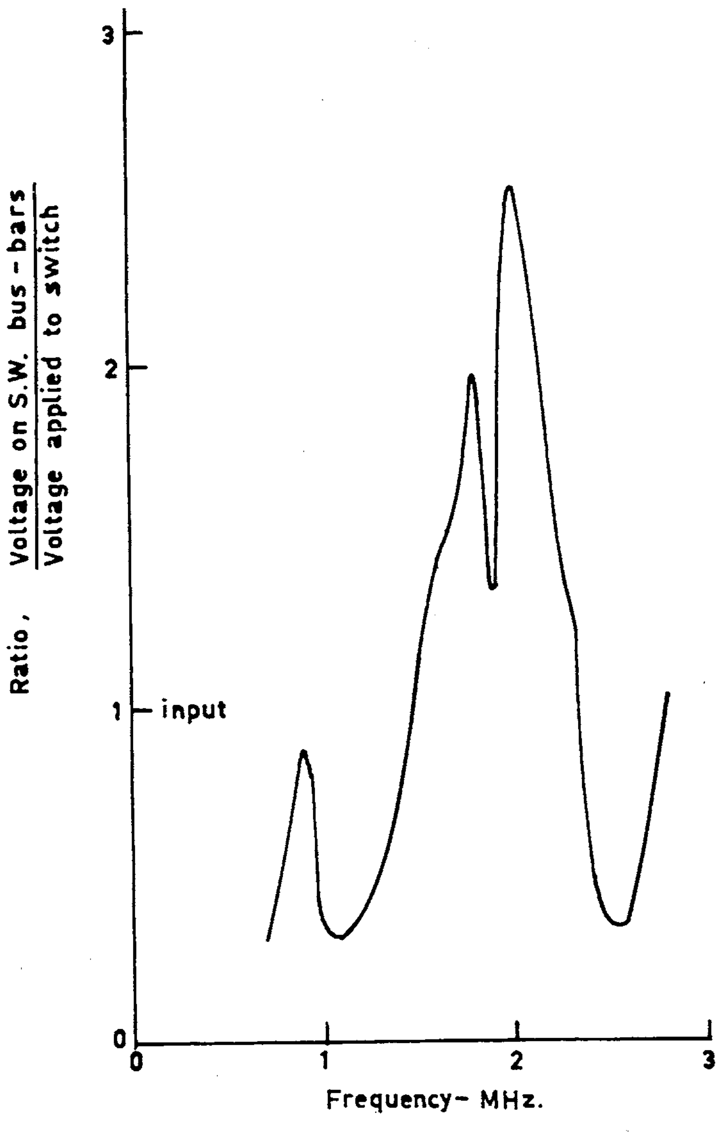


Figure 13 Resonances observed when the bus bars to arc enclosure were terminated with 0.5 ohms. This resonance is associated with the electrolytic switch electrodes. The main bus bar standing wave has been damped out.

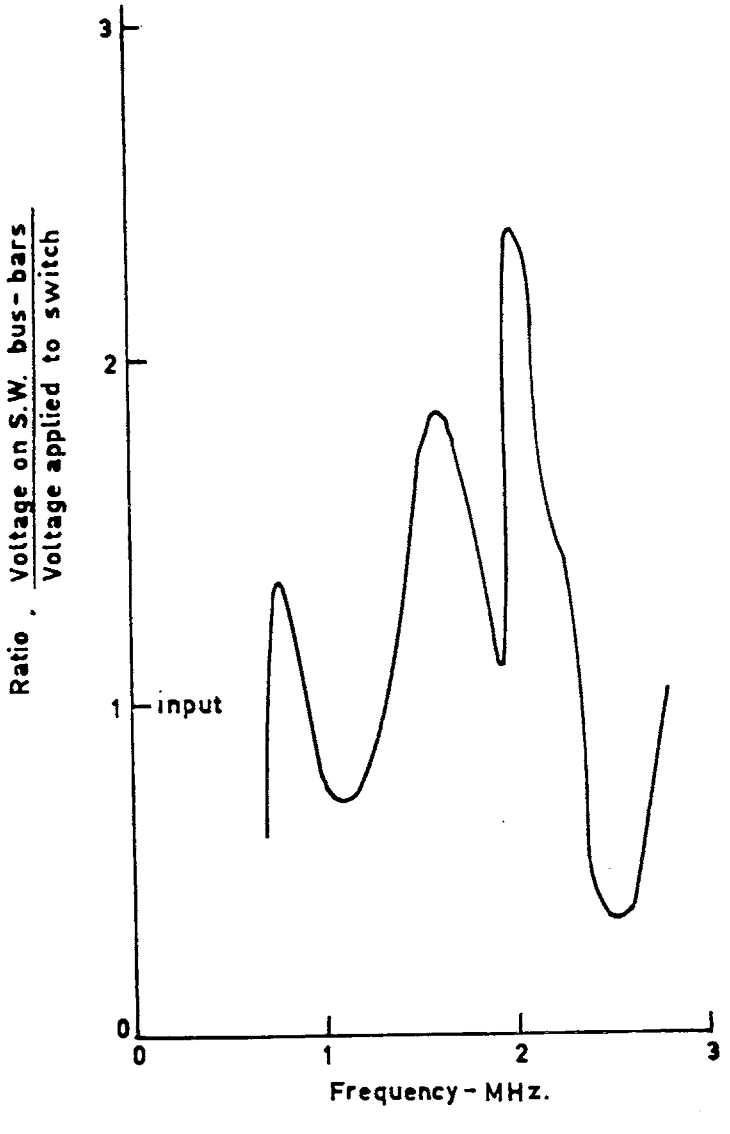


Figure 14 Resonances observed when the bus bars to the arc enclosure were terminated with 2.5 ohms. In this case the open circuit standing wave pattern with a maximum voltage at 1.5 MHz is not completely damped.

a resonance within the electrodes of the electrolytic switch itself, but it was not investigated further.

During the measurements with the bus bar shorted at the arc chamber end, the 14 M length of bus bar was considerably shorter than a quarter wave length for the resonance at 1 MHz and would therefore have presented an inductive impedance at the switch. The resonance would then occur when the impedance at the tapping to the main bus bar was capacitative.

The measurements were not made to give a quantitive assessment of the bus bar resonance with any particular configuration, but only to demonstrate the multiplicity and frequency range of possible standing wave patterns on the bus bars.

The measurements plotted in Figures 13 and 14 show that a terminating resistor of 1.0 ohm at an open end can be used to suppress a resonance if a short circuit does not develop across it. Such a resistor would have to be designed to absorb 640 kW during a pulse, at 800 V. It would however only halve a single voltage transient due to a rapid change in the current in the bus bars.

The observations on the bus bars and on the model are indicative of a mechanism whereby an arc, at an appropriate location in a high-Q system with resonant frequencies in the region of a MHz , can maintain oscillations on the system and produce high voltages localised to limited regions along the length of the system.

In the case of the homopolar generator on the 28th November, an arc had developed in the electrolytic switch and from time 0.14 to 0.52 sec., Figure 5, a second arc was burning between the bus bars at the arc chamber end. During this period, a standing wave could have developed and decayed several times on the main bus bar system, and many of the small arc marks on the bus bar may have been made at this time. When the current dropped at time 0.52 sec., the arc in the test load was still conducting, and although the d.c. current was low, it could still be coupling radio-frequency power to the bus bars and generator terminals. The bus bars appear to have flashed over, either in the $\frac{1}{2}$" gap between the bars in the south-west riser, or the 1" gap where an arc had already been in the arc experiment cubicle. This arc caused the damage to the homopolar generator.

Returning to the period from time 0.52 sec. to 0.58 sec., trace 9 of Figure 5 shows no current was flowing via the electrolytic switch to the arc enclosure, and trace 10 indicates about 300 A flowed through the bus bars. Such a current could flow only through some leakage path in the bus bars. It is suggested that it was via ionised air initially produced between the bus bars on the south-west riser, by high radiofrequency voltages generated between time 0.14 sec. and 0.52 sec. The 300 A current apparently maintained a steady ionization until the cathode areas became hot enough to change to an arc mode. If this occurred at time 0.58 A, the current could have risen to several hundred thousand amperes and caused the initial damage to the sliding brushes. The amount of aluminium burnt from the south-west riser indicates that the arc passed 10-15,000 coulombs, and since it probably lasted less than 0.1 sec. the peak value must have been in excess of 100,000 A.

9. CONCLUSIONS

For this work the homopolar generator was used for the first time with the four rotor discs in series. It was shown that this made it possible to run xenon flash lamps at 800 V at high power, for longer periods than can be achieved when the power is taken from storage condensers. When the lamps were mounted close together, the magnetic field from one did not affect the discharge in the other.

The many successful pulses taken before the arc occurred in the electrolytic switch demonstrated that this switch could be used for voltages up to 800 V, if the electrodes were immersed and withdrawn in such a way as to produce suitable streams of electrolyte. However, because there is a danger that such streams may not always occur, this method of operating the generator into a low-power load will not be repeated.

This was the first occasion on which the water lubrication of the air bearings was used to take power from the rotors. The stability of the bearings using water was verified by this run and the friction observed drew attention to an error in earlier calculations of the retardation. The corrected calculations agree with the observed value.

The arcs within the bus bars drew attention to their radio frequency characteristics. The bus bars are low-loss transmission lines and an unloaded section can produce a high voltage if suitably excited at a resonant frequency.

Subsidiary experiments have shown that a d.c. arc can excite a resonant circuit, tuned to a frequency as high as 1 MHz, and can generate a peak voltage of more than thirty times the voltage applied to the arc. Thus an arc can be dangerous when supplied with power via low-loss bus bars which can resonate at a frequency less than several Mhz. Thus a long length of unloaded bus bar connected to the generator can introduce a hazard which can be simply avoided in future.

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EP-RR 2	Carden, P.O.	Limitations of Rate of Rise of Pulse Current Imposed by Skin Effect in Rotors	Sept., 1962	April, 1967
EP-RR.3	Marshall, R.A.	The Design of Brushes for the Canberra Homopolar Generator	Jan., 1964	April, 1967
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No.	Author	Title	First Published	Re-issued
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