# ARCING PHENOMENA IN HRC FUSES UNDER VARYING TEST CONDITIONS.

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1.0 INTRODUCTION The use of several ribbon type fuse elements in parallel in an HRC fuselink to give adequate current rating and short circuit performance is normal design practice. However, knowledge of the manner in which such elements share the duty of circuit interruption and of the way in which arcing currents commutate between elements is far from complete. A better understanding of such phenomena would be of use to the fuse designer; it could also help the applications engineer who may wish to deduce the nature of a fault condition in service by studying the relevant blown fuse.

It is now well known that when a fuselink with several parallel elements interrupts a low value of fault current, this current flows during the arcing period in only one element at a time and that each element in turn burns back to the requisite length for extinction. This phenomena (1) was previously investigated and described by the author when the action of a model 'fuse' under low and moderate fault current conditions was monitored by a multi-channel oscillograph and high speed cine camera (2).

The present paper extends this work to cover the interruption of high values of prospective current so that a more complete picture may be obtained of current sharing between elements during arcing at most practical values of fault current. The work is of recent origin and is still continuing. Hence only tentative conclusions are possible at this stage based upon the data analysed up to this time.

2.0 TEST METHOD The aim of the experiments was to observe the pattern of arcing in a model fuse at varying current densities. Observation was to be carried out electrically by monitoring the individual current in each fuse element on an oscillograph and optically using high speed cine cameras. A similar technique was used to that employed earlier for observing commutation of arcs under low overcurrent conditions. However, experience dictated the use of several refinements of the earlier method to cater for the much higher test currents employed. Fig.1 shows the test arrangement in simplified form. A shallow test box constructed of asbestos board was filled with granulated quartz of the type used for filling HRC fuses. Four silver ribbon type fuse elements were stretched across the top of the box and secured to terminals at each end. A very thin layer of sand (later omitted) was sprinkled on top of the elements and a sheet of glass laid on top of the sand. Neoprene gaskets provided gas tight seals around the edges of the box and a thick perspex 'lid' was clamped down over the glass plate and rubber seals to complete the assembly. A filler hole at one end of the box allowed additional quartz to be introduced and compacted by vibration after assembly was complete. The box was mounted horizontally and the cameras viewed its transparent top from a distance of 2-3 metres via a mirror mounted at an angle of 45° above the box.

A schematic diagram of the test circuit is given in Fig.2 Limitation of laboratory supply facilities dictated the choice of 700 volts r.m.s. for the test voltage. The prospective test current was set to the required value by means of adjustable series resistance and reactance, with minimum values of 'R' being used so as to obtain the lowest values of power factor for each setting.

In general, power factors of less than 0.3 were obtained. The maximum available prospective current was 3200 amps. It was not possible to control the switching with respect to the point on voltage wave hence several shots with random switching were necessary at each current setting to give an adequate picture of events. A six channel electro-magnetic oscillograph provided individual current traces from each of the four fuse elements and also provided a record of total fuse current and arc voltage.

The fuse elements in the test box were of a type representative of modern practice. The emphasis of the investigations being directed towards high voltage fuse operation (since the earlier work had concentrated on the low overcurrent problems of h.v.fuses), therefore scaled down versions of a type in present use for fuses rated at 3.3kv were employed. The elements were 6.35 mm wide by 0.019 mm thick and had seven series reduced sections of $2.9 \times 10^{-4}$ $cm^2$. The reduced sections were spaced widely apart (25cm) to obviate any chance of the arcs merging during operation. The four elements connected in parallel in the fuse test box were deemed to have a nominal current rating of 35 amps (by inference from the current which such elements would carry when built into a real fuse).

3.0 <u>CAMERA EQUIPMENT</u> In the earlier low overcurrent tests a cine camera running at 4000 frames per second gave an adequate record of the arcing commutation which took place during the comparatively long (10-500 milliseconds) arcing periods involved. The present tests at higher prospective currents required much greater camera speeds in order to record the extremely rapid variations in the initial pattern of arc build up. A cine camera running at 9000 frames per second was used for all the tests to give a relatively crude picture of the complete arcing period. This was supplemented for later tests by a cine camera run in 'streak mode'. In this camera the film was run continuously without an intermittent motion at a speed of 55 metres/second. The streak mode camera was placed at an angle to the array of fuse elements in the test box so that each of the 28 individual arcs at the element reduced sections appeared as a separate streak of light on the film (see Fig.4). Careful analysis of the dimensions and positions of each of these streaks enabled a complete picture to be built up of the growth and decay of the associated arc in the fuse element itself. An electronic camera was also used to supplement the information for certain tests. This gave a matrix of frames on polaroid film of a selected portion of the arcing period, the interval between frames being 1 microsecond. The cine cameras were fitted with a triggering device which closed the supply to the test fuse when the cameras reached the required speed. The electronic camera was itself triggered by a photo electric cell which caused scanning to commence once the first arc appeared.

4.0 TEST PROCEDURE In previous work, commutation of arcs between fuse elements had been explored over the range 1.7 to 6.0 times fuse rated current corresponding to pre-arcing reduced section current densities of 0.525 to 1.9kA/mm$^2$ per element. In the present work the range 12-90 times rated current was explored corresponding to element reduced section current densities of 3.75 to 26.7 kA/mm$^2$. At each current setting (see table 1) several tests were carried out to cover different switching angles and to ensure that adequate cine and oscillographic records were obtained. After each test the elements and fulgurite adhering to the glass cover plate were removed and photographed for later analysis (Fig.3).

During the course of the tests it was found possible to mount the elements directly on the underside of the glass cover omitting the thin covering layer of sand. This gave improved cine records without noticeably affecting the initial pattern of arc build up (although it is likely that the glass did have some effect on the later phases of the arcing period).

Table 1 - SUMMARY OF TEST SCHEDULE

| No. of Tests. | Prospective Current | Pre-Arcing Current Density | Camera Records |
|---|---|---|---|
| 6 | 450A | 3.75kA/mm$^2$ | A |
| 6 | 600A | 5.0 " | A |
| 33 | 750A | 6.25 " | A + B |
| 15 | 3200A | 26.7 " | A + B + C |

A: Conventional cine camera run at 9000 F.P.S.

B: Streak mode camera run at 55 metres/second

C: Electronic camera at $10^6$ frames second.

5.0 TEST DATA ANALYSIS

5.1 Tests at 450A These tests simulated a fault current of about 12.5 times the fuse current rating. From previous work it was known that, at up to 6 times rated current, the total arcing current was carried by each parallel element in turn, with no discernable overlap as the current switched from one element to another until all arc were extinguished.

In the present tests at 12.5 times rated current there was evidence of a transitional phase (Figs. 6c and 7). In a typical case arcing commenced at some reduced sections in two elements simultaneously. The current then switched consecutively to a third element and finally to the fourth element which cleared the circuit. The last element to clear, arced for a much greater proportion of the total arcing time than the others and so was responsible for the major part of the arc energy dissipated. In most tests two and sometimes even three elements were arcing simultaneously during some portions of the arcing period. The total period during which arc build up and commutation took place was of the order of 3 milliseconds, hence the 9000 F.P.S. cine camera was able to provide an adequate record of events unaided.

5.2 Tests at 600A These tests simulated a fault current of about 17 times fuse rated current. From Figs. 6d and 7 it will be seen that arcing took place in all elements more or less simultaneously. However, there was great disparity in the degree of arcing in the different elements and there were corresponding disparities in the sharing of current between elements at any given instant. This appeared in some measure due to the unequal rate of build up of series arcs in each element; once all 28 arcs had ignited, current sharing tended to equalise and all elements cleared simultaneously at the natural current zero.

5.3 Tests at 750A These tests simulated a fault current of about 21 times rated current. The current density of 6.25kA/mm$^2$ was a close approximation to that required for the maximum arc energy test (test duty 2) in most recognised fuse test specifications and on those tests where the closing angle happened to be between 0$^\circ$ and 20$^\circ$ after voltage zero a close agreement with the requirements of TD2 in IEC 282-1 was obtained.

The conventional cine camera was no longer fast enough to record the initial arc build up and so the streak mode camera was employed as a useful adjunct (Fig.5). The initial portion of each streak mode film was analysed to produce an arcing pattern diagram (Fig.6) and this in conjunction with the conventional film provided a complete record of the arcing period.

As is seen in Fig.6a and 7, arcing commenced in all four elements practically simultaneously. There was a rapid build up of the number of series arcs in all elements with little evidence of unequal current sharing. All 28 arcs were initiated in a period of about 140 microseconds from which point in time all four elements burned back equally to extinguish simultaneously at the natural current zero.

5.4 Tests at 3200A These tests simulated a fault current of 90 times rated current. From Figs 6b and 7 it is seen that although operation was generally similar to the 750A case the arc build-up period was much reduced - typically only about 80 microseconds. Burn back and arc extinction were correspondingly more rapid with the fuse current falling to zero well before the natural zero pause. It will also be noted that, as expected, the fuse exhibited 'cut-off' the peak current being well below the prospective value.

Some attempt was made to expand a portion of the initial arcing period to allow closer examination. The electronic camera used for this purpose provided 12 frames spaced 1 microsecond apart (unfortunately not reproducible here). They confirmed an impression gained from the streak mode films that individual arcs fluctuated rapidly in intensity (at least optically) over periods as short as 5-10 microseconds and that these fluctuations were completely random and unrelated to any given current path. The fluctuations in arc intensity could not be related to any discernible variations in the oscillographic traces.

5.5 Effect of Closing Angle It could be inferred from a study of the test data that the pattern of arcing is more closely related to the pre-arcing time than to the allied function of current density. Where the pre-arcing time was greatly extended due to closing the circuit onto a minor loop of current, considerable differences in arcing patterns were sometimes apparent; the general effect being to produce the kind of unstable element-to-element arcing pattern normally peculiar to tests at low current densities. Insufficient data has so far been obtained to confirm or quantify this aspect of the investigation. However, Table 2 summarises the pattern which appears to emerge from the tests done so far. The table suggests that arcing will be consecutive from element to element for pre-arcing times greater than 1000 microseconds and that it will generally be concurrent in all elements at once for pre-arcing times less than 500 microseconds.

Table 2

| Pre-arcing Time | Tests giving 'Consecutive' Arcing | Tests giving 'Concurrent' Arcing |
|---|---|---|
| 1 millisecond or more | 15 | - |
| 500-1000 microseconds | 3 | 8 |
| Less than 500 microseconds | - | 22 |

(Remainder of tests not relevant to above table).

6.0 CONCLUSIONS

6.1 At fault currents between 6 and 12 times fuse rated current a fuse of the type tested will operate in a mixture of consecutive (arcs in one element at a time) and concurrent (arcs in several elements at the same time) modes. The last element to clear will usually do so on its own and will have much heavier fulgurites than the others.

At fault currents in the region 12-20 times rated current, arcing will be concurrent but still very uneven as between one element and another. At fault currents above 20 times rated current, arcing will be wholly concurrent and will be similar in severity for all parallel elements. The period during which arcs are formed at each reduced section of the elements is very short compared with the total arcing time. Typically 140 microseconds at 21 times rated current falling to 80 microseconds at 90 times rated current.

6.2 Pre-arcing time appears to be a prime factor in determining arcing patterns. The longer the pre-arcing time the greater the likelihood of element-to-element commutative type arcing. Hence for a given level of fault current the arcing pattern of the fuse may vary depending upon the instant of closing the circuit with respect to voltage zero.

6.3 While it is recognised that the results of this investigation can only apply, strictly, to the element type and test conditions specified it is thought likely that the results are valid in practice. The extent to which this is the case will be investigated in future work.

ACKNOWLEDGEMENT AND REFERENCES

(1) Mikelucky H.W. I.E.E.E. Transactions Vol. PAS-84 No.12.

(2) Rosen P. Symposium on Switching Arc Phenomena 1973, Lodz, Poland.

Acknowledgements: Electricity Research Council.
GEC English Electric Co., Ltd.,

# FUSE ELEMENT TESTING BOX

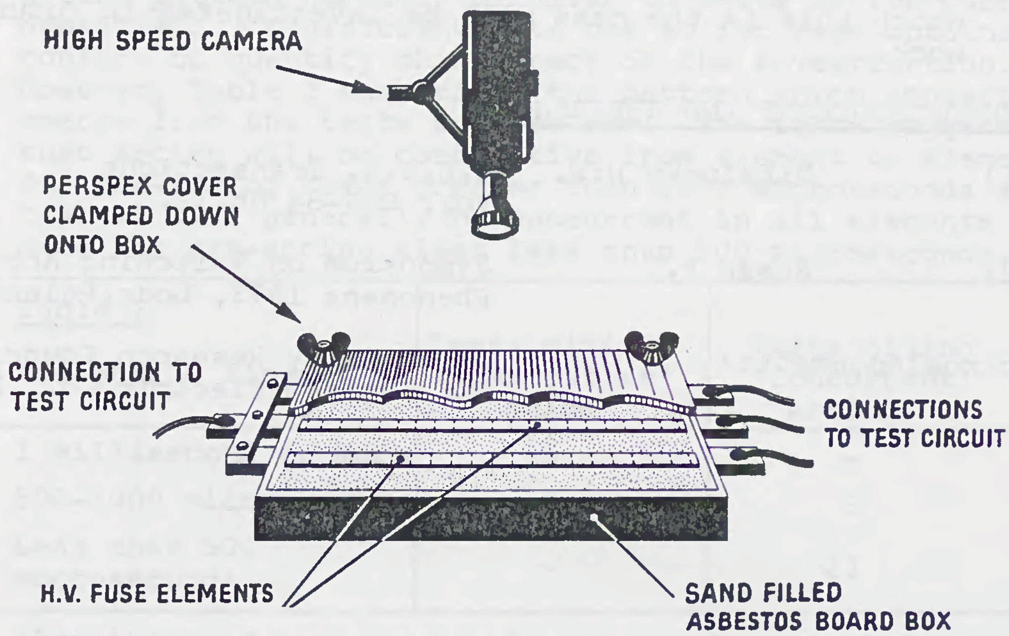



FIG.1.

# BASIC TEST CIRCUIT

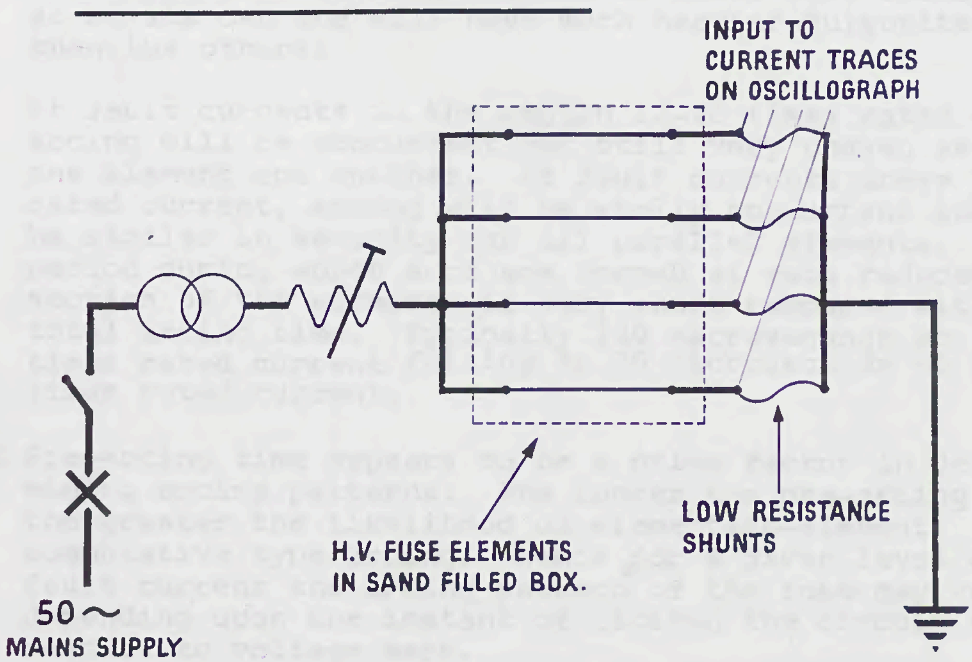



FIG.2.

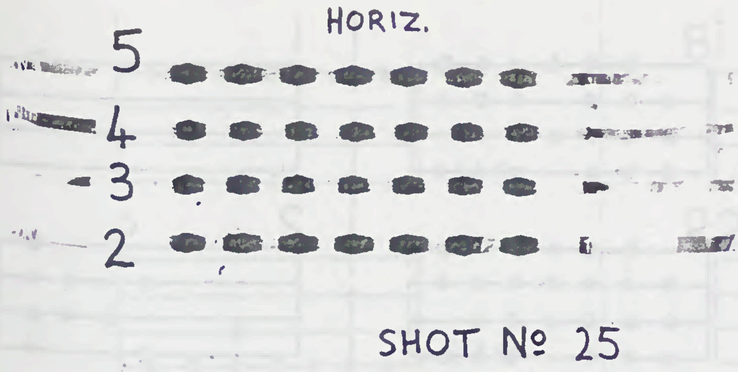



FIG.3.

Set of elements after 750A test showing fulgurites.

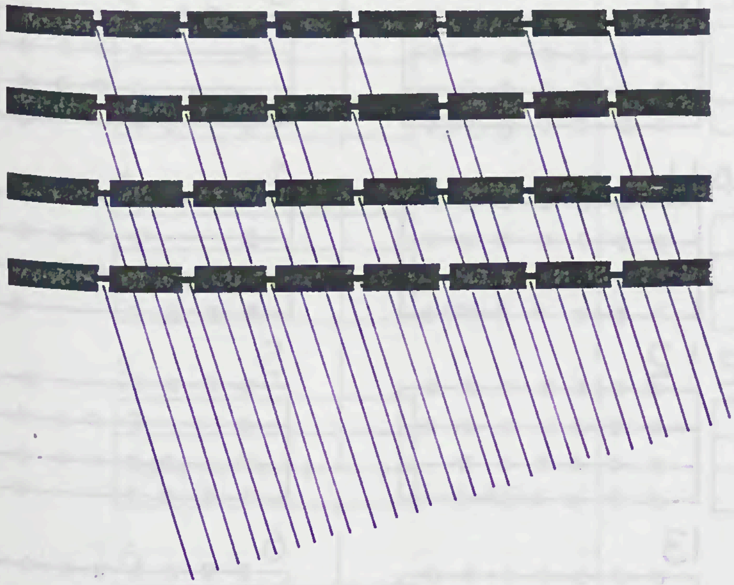


FIG.4.

Diagram showing how streak mode camera scans elements to pick up individual arcs.

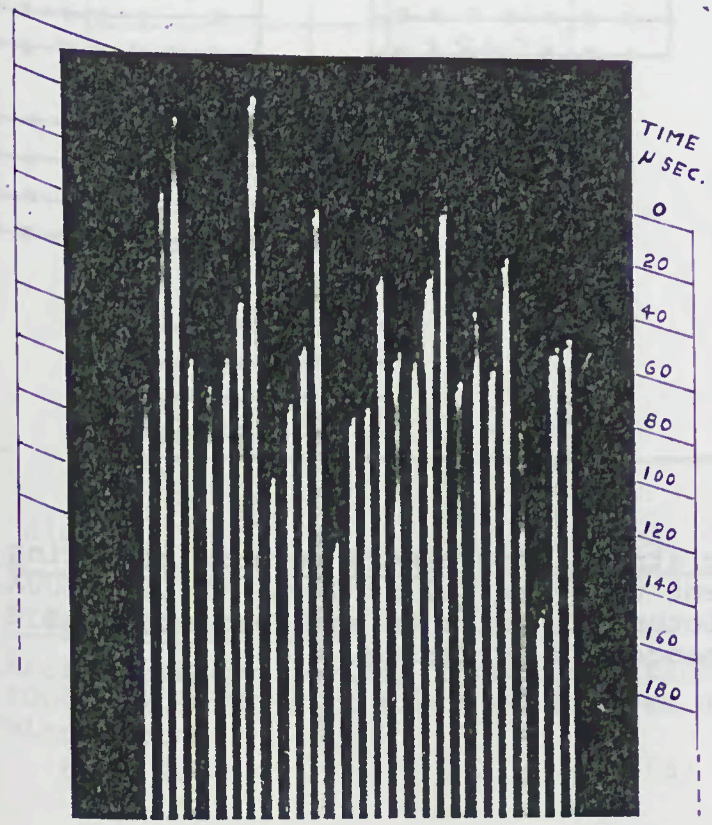
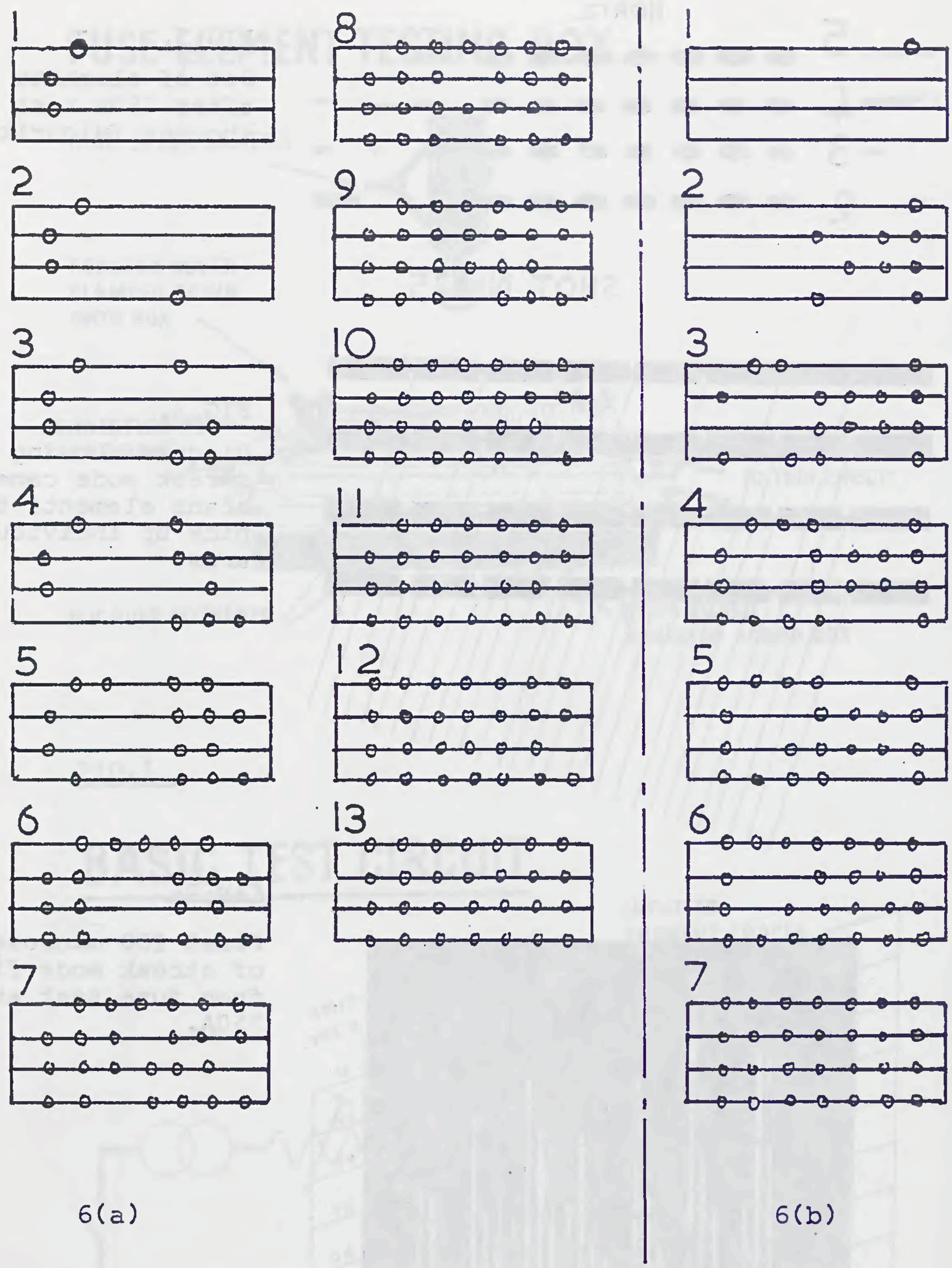



FIG.5.

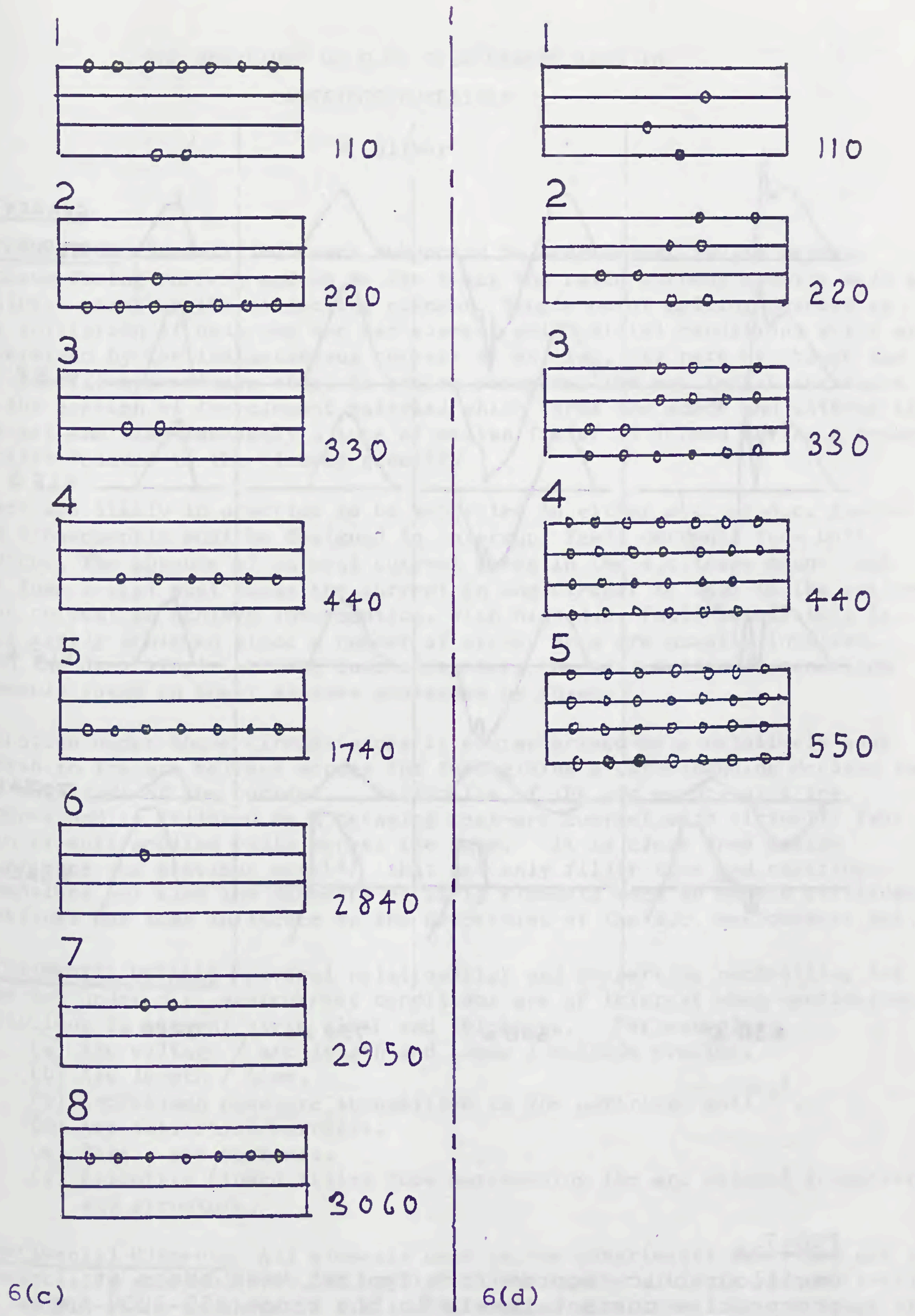
First 200 microseconds of streak mode film from fuse test at 750A.




6(a) 6(b)

FIG.6

Reconstruction from streak mode camera records of arcing pattern in 4 element test box (a) at 750A, (b) at 3200A. In each case the picture is built up at 10 microsecond intervals from commencement of arcing.




6(c) 6(d)

FIG.6. (Continued)

Arcing pattern derived from conventional cine film run at 9000 F.P.S. No's to right of figures denote elapsed time in microseconds.

6(c) 450A 6(d) 600A

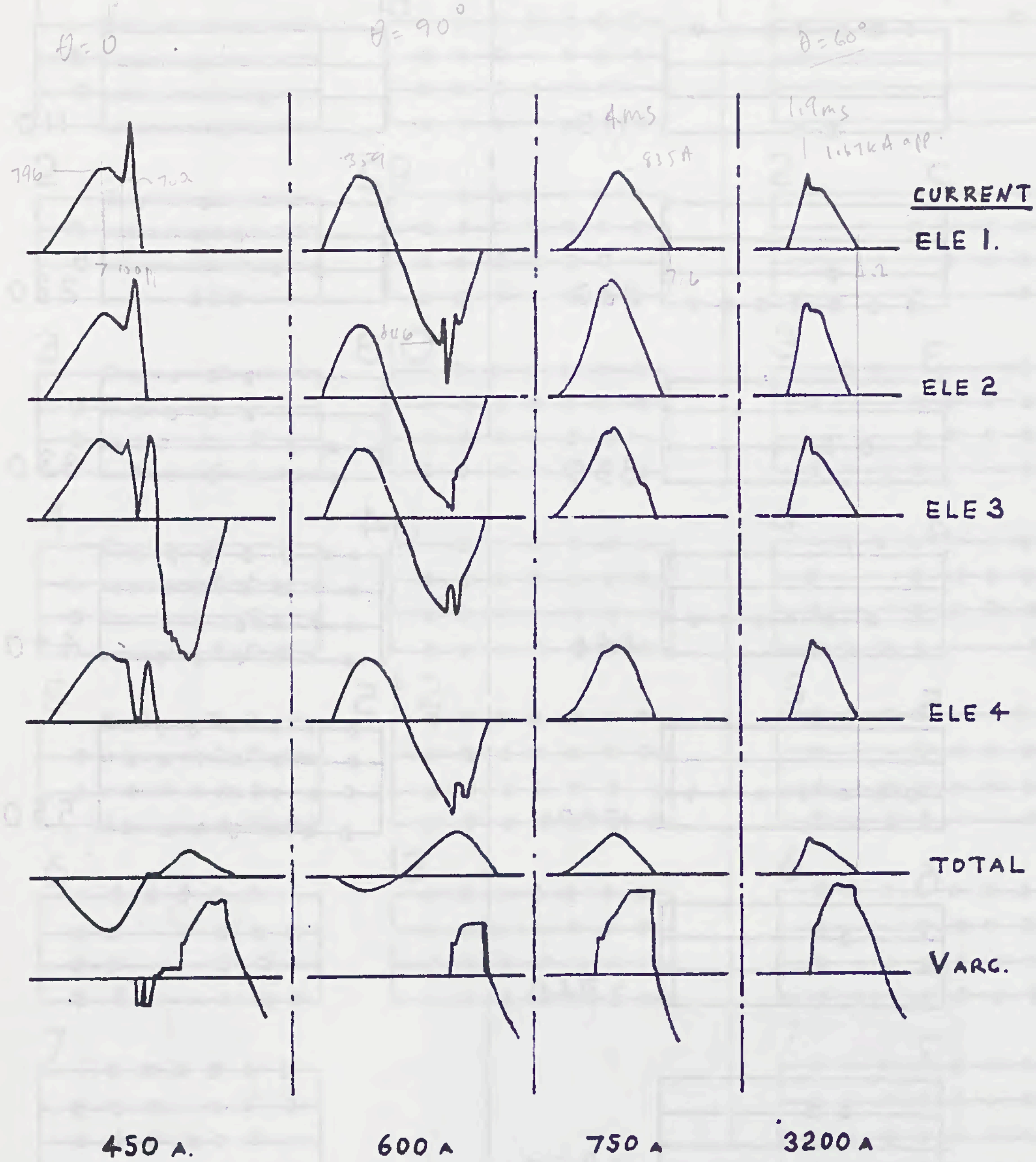



FIG.7..

Oscillographic records from typical test shots at prospective current levels in the range 450-3200 Amps.