materials are studied which require correction for absorption or angular errors, a linear correction may be sufficient.[8] If a linear correction is required, one more potentiometer may be added to the gear train and used with, or as, the range or sensitivity control in the strip chart recorder. For this purpose a recorder with continuously adjustable range is convenient. An equivalent method was used by Geisler[11] who scans rings of constant α rather than a continuous spiral and therefore applies corrections in steps.

If somewhat greater resolution of detail is desired another intensity level can be added by using the spare positions provided on the alarm switch and chopper cam assembly. A convenient code to use for the added contour is a double dot, two closely spaced dots, followed by the normal separation space.

Probably no simple automatic technique for plotting can be made applicable to all research problems involved in the preferred orientations encountered in different materials. There are two systematic limitations to automatic plotting with this apparatus. First, the intensity levels which define the orientation contours must be preset. If the settings are not appropriate to display the orientation clearly they must be corrected and the x-ray scan repeated, or the diagram could be manually plotted from the strip chart record. The second limitation is that diagrams with more than four or five intensity levels are not feasible. It then becomes difficult to distinguish easily where the intensity code changes between different patterns of dots and where it changes from dashes to solid line.

The advantages offered by this plotter are in reducing the time and work required to prepare a pole figure by eliminating the hand plotting of data read from films or strip charts. The specimen preparation and machine time are the same as for conventional recorder techniques and a strip chart record is produced simultaneously for each specimen. In some of the areas where pole figures are being introduced, for example in the plastics technology, the orientations are not complicated, pole figures are fairly simple, and many are needed due to the lack of product uniformity. For such applications an automatic pole figure plotter should be useful.

ACKNOWLEDGMENTS

The author is indebted to G. I. Addis and E. Flowers for design of the circuit and to E. Flowers for construction of the apparatus.

THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 36, NUMBER 7 JULY 1965

Method of Producing a Fast Current Rise from Energy Storage Capacitors[*]

H. C. Early and F. J. Martin
Department of Electrical Engineering, The University of Michigan, Ann Arbor, Michigan

(Received 1 February 1965; and in final form, 15 March 1965)

A rate of current rise of the order of 10^{13} A sec^{-1} can be produced by inexpensive capacitors used in conjunction with a special, low inductance fuse and spark gap. The capacitors are discharged through the fuse until the current reaches a near maximum value at which time the current is transferred from the fuse into a load inductance of about 1 nH. The spark gap isolates the load until the moment of current transfer.

INTRODUCTION

THE maximum *di/dt* of a conventional capacitor bank is equal to the ratio of the capacitor voltage to the total inductance of the discharge circuit. Attempts to increase *di/dt* by using higher voltage capacitors yield little benefit (above about 20 kV) because the higher voltage apparatus requires more insulation spacing, and the circuit inductance is correspondingly increased. Circuit inductance can be decreased by using a large number of parallel capacitors, switches, and connecting leads. However, reducing the circuit inductance to a few nanohenries by paralleling multiple circuits involves an elaborate and expensive installation.

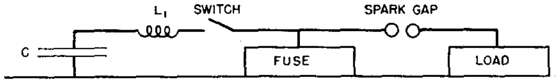

FIG. 1. Equivalent circuit.

The fuse-spark gap system described here provides the equivalent of a very low source inductance during the interval when the current is transferring from the fuse to the load. This system was designed for experiments with a hypervelocity gun having an inductance of approximately 1 nH. The peak current is typically 500 000 A.

PRINCIPLE OF OPERATION

Figure 1 illustrates the operation of the pulse sharpening system. The inductance L_1 represents the total stray inductance associated with the capacitor and the initiating

---

[*] This work was supported by the Langley Research Center of the National Aeronautics and Space Administration by Grant NsG 640.

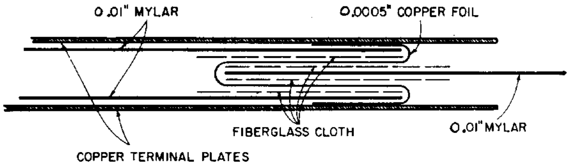

FIG. 2. Cross section of fast opening fuse having very low inductance. Vertical dimensions are exaggerated.

switch. The spark gap is designed to break down at a predetermined voltage.

In operation, the closing of the switch causes the current to build up in the circuit through the fuse. When this current approaches a maximum value, the fuse melts and the fuse voltage increases abruptly until the spark gap breaks down and transfers the current from the fuse into the shunting load. The rate of current transfer into the load is limited only by the inductance of the fuse, spark-gap, and load, and the inductance represented by L_1 is not of major significance. Hence, the energy storage system does not need to be designed for minimum inductance. The fuse, spark gap, and load are the only circuit elements where minimal inductance is required, and this inductance is minimized by constructing these elements from wide, flat, closely spaced conductors.

FUSE DESIGN

The optimum fuse for this application has minimal inductance and has a low resistance during the period when the capacitor current is rising. Then, the fuse voltage should rise abruptly to a high value while the current is transferring into the load.

A very fast rate of rise in fuse voltage (approximately 5×10^{10} V/sec) was achieved by making the fuse of 0.013 mm copper foil sandwiched between layers of glass cloth and clamped under very heavy pressure. As the fuse melts, the vapor pressure of the copper forces the liquid metal into the mesh between the filaments of the glass cloth. There is a fast rise in fuse voltage, but the formation of an arc plasma is prevented by the high clamping pressure and the insulating effect of the glass cloth. The fuse current drops to zero before arcing occurs. There is no gaseous electrical conduction involved in the fuse action.

Low inductance is achieved by folding the sandwich of glass cloth and copper foil and then clamping it between heavy copper plates which serve as the terminal connections as shown in Fig. 2. This figure also shows sheets of Mylar insulation which are added for extra dielectric strength. A clamping pressure of the order of 350 kg/cm^2 is applied by means of a hydraulic jack.

SPARK GAP DESIGN

The spark gap is necessary in order to isolate the load until the fuse voltage has reached a maximum value. The spark gap is designed to break down at a voltage approximately $1\frac{1}{2}$ times the dc voltage on the capacitor bank. Because of the stray inductance associated with the capacitors, the sudden interruption of the current through the fuse causes the fuse voltage to rise sufficiently high to cause breakdown of the spark gap.

A first approach to the design of a very low inductance spark gap is to clamp a sheet of Mylar, or other sheet insulation, between parallel copper plates. When a rising voltage causes the Mylar to rupture, the circuit is closed. Such a crude spark gap has limitations which necessitate extra refinements. For instance, its breakdown voltage is erratic, and the Mylar ruptures at an unpredictable location at the edge of the metal plates. This edge breakdown results in a "blow out arc" with excessive voltage drop. On the other hand, if the Mylar rupture is not near the edge of the plates, the arc current vaporizes Mylar and copper in a confined space and a very high gas pressure is generated. This high gas pressure causes a voltage drop of several kilovolts, wasting a substantial amount of energy and decreasing the rate of current transfer to the load.

In order to ensure that the Mylar breakdown will occur at the desired location in the center of the plates, three sheets of Mylar are used to form a sandwich as illustrated in Fig. 3. The thin sheet of 0.038 mm Mylar, which is the one that ruptures, is protected on both sides with thicker sheets of 0.25 mm Mylar. The thicker Mylar sheets have holes at the location where the thin sheet is to rupture. With a fast rising voltage, the thin sheet of 0.038 mm Mylar will puncture at approximately 30 kV.

The gas pressure can be reduced by a venting arrangement through the upper copper plate. A number of closely spaced 3 mm diam holes near the center of the plate allow the gas to escape. The arc erosion causes damage to these venting holes, and it is convenient to use an expendable insert containing the venting holes so as to avoid replacing the entire plate after each operation.

TYPICAL OPERATING CONDITIONS

The assembled apparatus is sketched in Fig. 4. The spark gap sandwich is on top of the folded fuse sandwich,

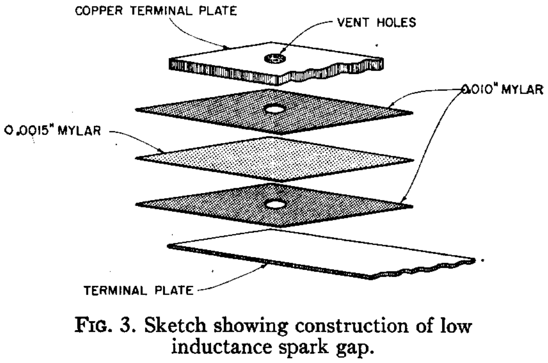

FIG. 3. Sketch showing construction of low inductance spark gap.

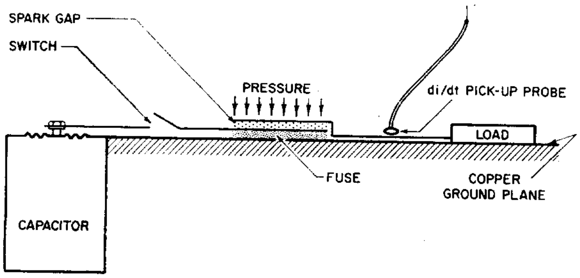

Fig. 4. Sketch of components mounted on ground plane. Copper sheet connecting to load is 10 cm wide and insulated from ground plane by 0.25 mm Mylar sheet.

and the assembly is compressed by a hydraulic jack. The copper foil in the fuse is 6.5 cm wide and 7 cm in length with one fold in the center. The total calculated inductance of the fuse, spark gap, and load is 2 nH.

A manually operated switch is used for initiating the discharge of the four 20 kV, 14 μF capacitors. This switch operates at atmospheric pressure. In order to obtain consistent operation, the switch is designed to avoid prebreakdown corona and to avoid magnetic blowout forces on the arc column.

For testing the design of the fuse and spark gap, it is convenient to use a load of folded Nichrome sheet. A typical "dummy" load has a resistance of 0.004 Ω and an inductance of 1 nH. Figure 5 is a current trace of the load current for a test with a dummy load. The current trace was taken with a *di*/*dt* pickup probe and integrating circuit. During the first 1.7 μsec the load current remains at zero, while the fuse current builds up to 400 000 A. At 1.7 μsec the current starts to transfer, and the load current jumps to 400 000 A.

The rate of current rise is too rapid to measure with the instrumentation that is available. A calculated maximum rate, based on the V/L ratio of approximately 1.5×10^{13} A sec^{-1}, needs to be corrected for the voltage drop in the spark gap and the resistive voltage drop in the conductors. The voltage across the spark gap is 1–2 kV, after the first few nanoseconds following breakdown. This voltage is small compared to the 30 kV that is causing the current to transfer. Although the conductor resistance is much larger than the dc value, because of the shallow skin depth of the current, this voltage loss is also small compared to 30 kV.

A recording of the voltage across the fuse, taken with a Tektronix 545 oscilloscope and Tektronix voltage probe, is shown in Fig. 6. The peak of the voltage spike corresponds to the breakdown of the spark gap.

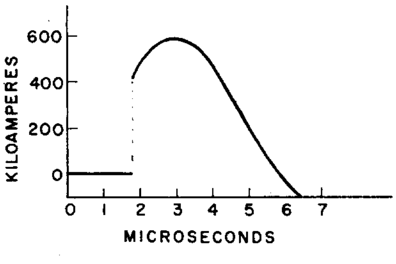

Fig. 5. Load current into test load of folded Nichrome sheet.

When the load consists of an exploding foil hypervelocity gun, the load voltage jumps to about 15 kV as soon as the arc in the gun is initiated. This high load voltage places a more stringent requirement on the fuse than in the case of the dummy load of Nichrome sheet, since the fuse is required to withstand a high voltage for a longer interval.

MEGAMPERE CURRENTS

The question has arisen concerning the possibility of designing fuses and spark gaps for operation at current levels in the multimegampere range. The present fuse design could be scaled up for heavier currents if multiple parallel fuses or an equivalent wider fuse were used. However, the magnetic forces in the vicinity of the spark gap would presumably cause problems. Multiple parallel spark gaps could be used if they could be made to break down simultaneously. A triggering system on each spark gap would appear to be necessary.

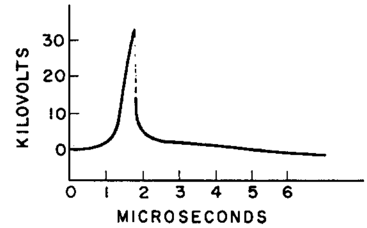

Fig. 6. Voltage across fuse when operating with test load.

ALTERNATIVE TECHNIQUES FOR OBTAINING VERY FAST CURRENT RISE

Comparable rates of current rise by other methods are reported in the literature. One system[1] uses a parallel plate, Mylar dielectric capacitor of 0.004 μF which is rapidly pulse charged to 300–400 kV. The energy stored is approximately 250 J, and the peak discharge current is 5×10^4 A. Another system[2] uses 15 Marx generators in parallel which produce an output voltage of 320 kV and deliver approximately 1100 J to a matched load. A third system,[3] with a much higher energy storage and peak current capability, uses 10 000 μF of 20 kV capacitors that are discharged by 390 spark gap switches.

ACKNOWLEDGMENTS

W. N. Lawrence and J. W. Robinson contributed valuable assistance in the development of this apparatus.

---

[1] I. M. Vitkovitsky *et al.*, *Exploding Wires*, edited by W. G. Chace and H. K. Moore (Plenum Press, Inc., New York, 1962), Vol. II, p. 94.

[2] J. K. Trolan *et al.*, *Exploding Wires*, edited by W. G. Chace and H. K. Moore (Plenum Press, Inc., New York, 1965), Vol. III, p. 361.

[3] A. C. Kolb *et al.*, "A High Energy Magnetic Compression Experiment," *Nuclear Fusion*, 1962 Supplement (Conference Proceedings, Salzburg, Austria, September, 1961), Part II, p. 553.