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HIGH POWER CLOSING SWITCHES
REVIEW OF PRESENT TECHNOLOGY

H. R. WHITTLE
P. J. ROGERS
T. E. JAMES

Culham Laboratory
Abingdon Berkshire

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HIGH POWER CLOSING SWITCHES
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H.R. WHITTLE
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A B S T R A C T

The development of closing switches for plasma physics experiments, from slow mechanically operated types and ignitrons through a range of spark gaps to solid dielectric and high speed metal-to-metal switches is outlined. Industrial applications for these switches are also mentioned.

U.K.A.E.A. Research Group,
Culham Laboratory,
Abingdon,
Berks.

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C O N T E N T S

1. INTRODUCTION

In at least two areas of modern physics (viz. plasma physics and solid state physics) largish volumes of intense magnetic fields are required for short periods for particular types of experiments. The most economic way of providing these fields is to store the necessary energy in capacitors and to transfer it into the field generating system during the experiment.

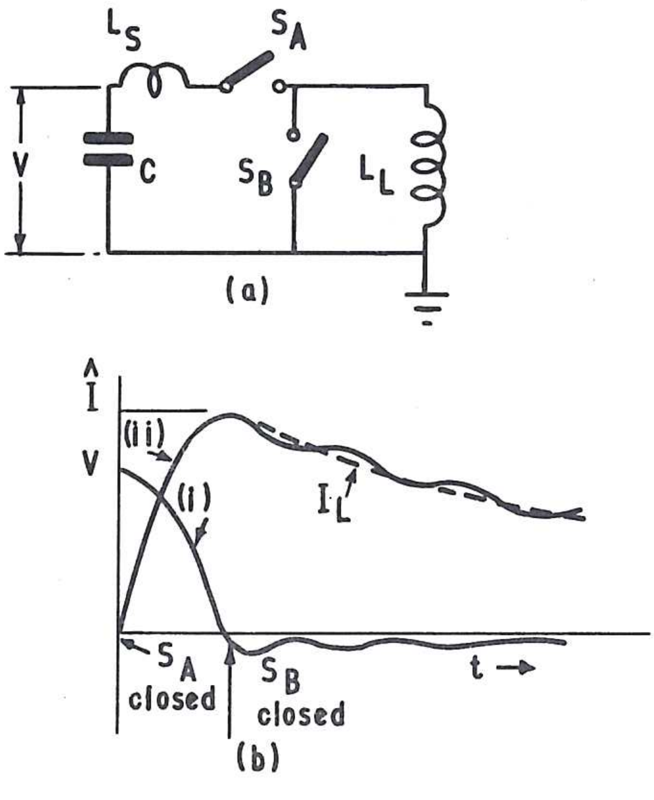
The techniques for effecting this transfer of energy have developed rapidly during the past 10-15 years. The success of the concept relies on the ability to switch very high currents in extremely short times (i.e. megamps in microseconds). This can be achieved by breaking down the insulation between two electrodes so that the current is carried in a short arc. More recently several workers have demonstrated switches which achieve metal-to-metal contact in a few microseconds.

Industrially, these techniques have direct application in high-velocity forming of metal components by the so-called 'Electro-magnetic' and 'Electro-hydraulic' processes. The latter process has been investigated also for crushing ceramic materials and rocks. Other possible uses are for point-on-wave switching during short-circuit and high-voltage impulse testing and for synthetic-circuit tests on circuit breakers. They could also, perhaps, be used as shorting switches to protect high power semiconductor components during power system faults or to prevent damage due to electrode contact during electro-chemical machining of dies and moulds.

2. SWITCHING CIRCUITS

As it is meaningless to discuss switches of any sort without considering the details of the circuits in which they are used, it is worth spending a little time studying the particular problems of applying high power closing switches.

A typical energy transfer circuit is shown in Fig.1(a). In this circuit the 'Start Switch' (S_A) is closed and when all of the energy has been transferred from the capacitor into the load inductance (i.e. at maximum current) the 'Clamp Switch' (S_B) is closed, leaving



C = Capacitor
L_S = Source Induct.
L_L = Load Induct.
S_A = Start Switch
S_B = Clamp Switch

$$I_L = \hat{I}e^{-R_c t/L_L}$$

R_c = clamp cct. resist.
I_L = load current

Fig. 1 (CLM-P 206)
Switching a typical power circuit. (a) = Circuit.
(b) = S_A and S_B closed (i) voltage (ii) current

the load current to decay exponentially as the energy is dissipated in the clamped circuit resistance (i.e. the load, the clamp switch and the appropriate interconnections) (Fig.1(b)).

In order to transfer the energy from the capacitor to the load efficiently, the inductance of the power source (capacitor, start switch and the connections to the load) must be small compared with that of the load. Sometimes it is possible to achieve this by connecting the capacitor to the load with a flat-plate transmission line incorporating properly designed low inductance switches. More often than not it is necessary to break the capacitor into sections each independently connected to the load so that the effective impedance of the source is a fraction ($\frac{1}{n}$ approx., where n = no. of sections) of that of a single section. Each section can of course be designed to have the lowest possible inductance using flat-plate transmission lines or low-inductance coaxial cables. The extent to which this latter practice has been employed may be appreciated by quoting the 40 kV, 1 MJ capacitor bank at Culham Laboratory which is subdivided into 448 separately switched sections. This bank, when connected to a single turn coil of 5 nH inductance, produced a maximum current of 15 MA rising from zero in 5 μsec.

Switches for both 'Start' and 'Clamp' duties must

(a) Reliably hold off the circuit voltage until they are 'triggered' (i.e. turned on).

(b) Withstand the very large currents and the consequent magnetic forces which are applied to them.

(c) Have a fast (usually < 1 μsec) and extremely consistent closing time over the operating range and lifetime of the switch.

(d) Have a low inductance.

For clamping duties, however, there are two further requirements which are difficult to achieve in practice.

(e) It must be possible to trigger the switch with zero voltage across its main electrodes (its normal operating condition).

(f) The equivalent contact resistance of the switch must be small so that the current does not decay too rapidly in the load circuit.

The range of circuit parameters of interest for current applications is as follows:

(1) Circuit voltage 5 - 100 kV.

(2) Peak current 50 kA - 10 MA.

(3) Load inductance 5 nH - 10 μH.

(4) Time to peak current 1 - 1000 μsec.

3. THE SWITCHES

In the historic development of energy transfer systems the first switches used were conventional mechanical shorting switches. They were, however, very inductive, slow and inconsistent in operation. They were soon replaced by ignitrons. Ignitrons are still extensively used in circuits where the working voltage is 25 kV or less, and where the maximum rate of rise of current does not exceed about 5.10^8 A sec^{-1}. In this range they are still among the cheapest and most reliable switches available.

Some attempts have been made to improve upon the performance of the basic ignitron but without much success. The most advanced of these had a mercury wetted molybdenum cathode in lieu of a mercury pool. This mercury diode was successfully tested at working voltages up to about 80 kV but it was abandoned because it was difficult to trigger reliably and its inductance was rather high.

To overcome the inherent limitations of the ignitron, 'spark gaps' of various sorts have been developed and exploited in circuits operating at up to 100 kV and with rates of rise of currents up to about 10^{13} A sec^{-1}. These so-called 'spark gaps' are triggered by initiating an arc between two electrodes. The dielectric between the electrodes can be vacuum, gas (usually air) at some pressure, or even a solid dielectric such as polyethylene. It is interesting to note that the term 'spark gap' is still applied to these switches although they bear little resemblance to their direct antecedents - the sphere gaps - which certainly predated the ignitron.

It is convenient to discuss 'spark gaps' under three headings, viz. Vacuum Gaps, Pressurised Gaps and Solid Dielectric Switches.

3.1. VACUUM GAPS

There has been little development of high power vacuum gaps because they suffer the same technical limitations as ignitrons. In addition they tend to be plagued with pollution problems due to the deposition of sputtered cathode materials at the walls and insulator surfaces. Consequently they are unreliable at 'holding off' voltages greater than 10-20 kV.

3.2. PRESSURIZED SPARK GAPS

It is possible to classify switches under this heading into three groups according to the electrode arrangements as shown in Fig.2.

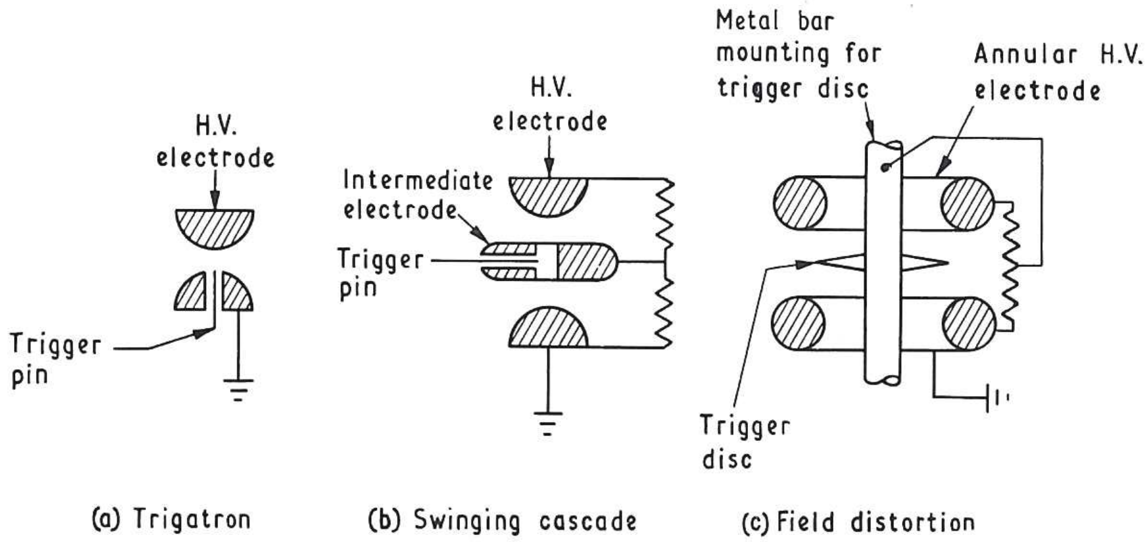


Fig. 2 Spark gaps (CLM-P 206)

The trigger circuits are not shown, but they consist of high voltage, low current circuits, switched by thyratrons or auxiliary spark gaps. Wide variations in the design of these circuits occur, depending on the type of main spark gap and the mode of operation required but a detailed discussion is beyond the scope of this article.

3.2.1. The Trigatron

The 'trigatron' is the classical triggered spark gap (see Fig.2(a)). The gap is 'irradiated' (i.e. supplied with free electrons) to start the arc in the gap by initiating a breakdown between the pin and the earth electrode. In this form the gap will only operate reliably at voltages above 70-80% of the static breakdown voltage of the gap. Also the trigger pin and its insulation are near the root of the arc on the electrode and are liable to suffer damage which leads to inconsistent operation of the switch.

The working range of this switch can be extended by increasing the magnitude of the trigger pulse until the trigger breakdown causes the voltage across the gap to exceed its static breakdown value. This operating mode is only possible when the circuit inductance is high enough to permit the necessary excursion of the triggered electrode potential.

3.2.2. Uniform Field-Irradiated Spark Gap

This is a three electrode gap (see Fig.2(b)). It is usually known as a 'swinging-cascade' gap because breakdown of the first gap by the trigger pulse 'swings' the potential of the intermediate electrode to produce breakdown of the second gap in 'cascade'.

The trigger pin arrangement (reminiscent of the trigatron) provides a source of electrons to irradiate the gap and provides very reliable triggering conditions.

3.2.3. Field-Distortion Spark Gap

By modifying the configuration of the electrode arrangements as shown in Fig.2(c) it is possible to simplify the intermediate electrode and to make a more compact and hence lower inductance switch. The operating mode is essentially the same as that of the 'swinging-cascade' switch described above, except that in this case the application of trigger voltage causes field emission from the sharp edge of the trigger disc to 'irradiate the gap.

3.2.4. The Application of Pressurized Spark Gaps

Gaps of this type working at either ambient or variable higher pressures have been widely used in plasma physics experiments. They have a wide operating range and are extremely reliable. In practice the main design problems are those associated with keeping the switch small and compact (to reduce its inductance), controlling the position of the arc and consequently the erosion of the electrodes and avoiding contamination of insulator surfaces.

Both the swinging-cascade gap and the field-distortion gap have been used for clamp switch duties. This requires them to be operated in a 'simultaneous breakdown' mode, because there is no voltage across the switch to break down the second gap. For this purpose it is necessary to balance carefully the trigger input impedances relative to each main electrode and to provide a very sharp fronted trigger pulse.

3.3. SOLID DIELECTRIC SWITCHES

The arrangement of a solid dielectric switch is shown in Fig.3. In these switches it is possible to work with very small electrode spacings without compromising the reliability of the switch in terms of its voltage 'hold off' and consequently they can be designed in very low inductance configurations. The dielectric is replaced after each 'closure' so that by controlling the location of the arc each time it is possible to distribute electrode erosion over fairly large surfaces. The switch is triggered by initiating an auxiliary arc discharge in the trigger insulation. The consequent flow of current in the trigger

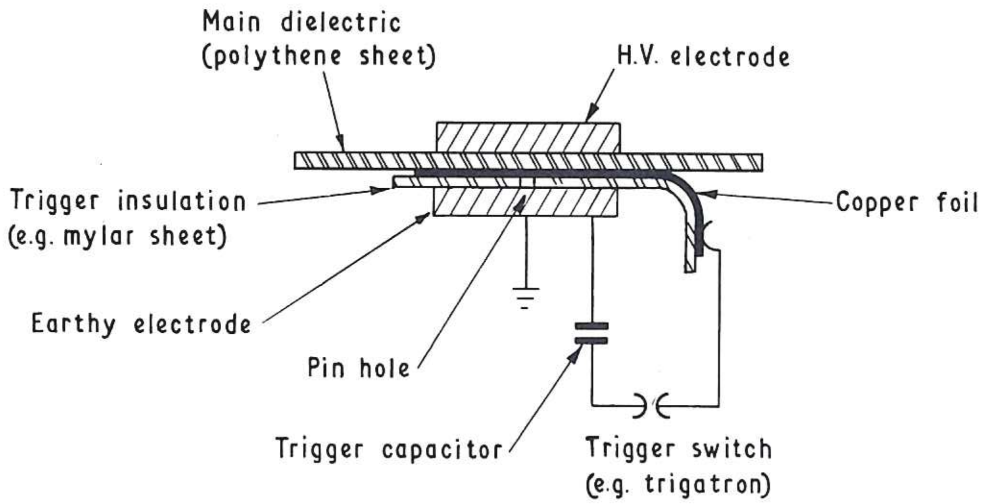


Fig. 3 Solid dielectric switch (CLM-P 206)

circuit leads to the physical rupture of the main dielectric. The position of the breakdown is predetermined by a pin hole in the trigger insulation at the desired location. Very heavy current switches have holes in the electrodes (connected to an exhaust system) to relieve the switch of the high pressures generated by combustion in the arc.

4. FAST MECHANICAL SWITCHES

In all of switches discussed above the energy loss in the arc is a serious problem when used for clamping duties. As a result there has been revival of interest in switches which have metal-to-metal contact and which, for want of a better name, we call mechanical switches. Recently two different mechanical switches have been developed, viz. the Rivet Switch and the Exploding Foil Switch. The contact resistance of these switches is typically a few microhms as compared with a few milliohms equivalent contact resistance of an arcing switch (i.e. the quotient of the arc voltage and the switch current).

4.1. RIVET SWITCH

The rivet switch is closed by driving a soft copper rivet through the solid dielectric so as to firmly rivet the replaceable electrodes together (see Fig.4). The rivet is driven by an electro-magnetic hammer.

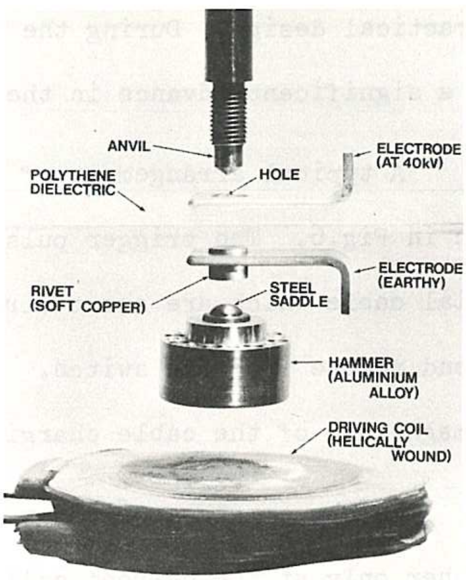


Fig.4 Rivet switch (CLM-P 206)

4.2. EXPLODING FOIL SWITCH

The configuration of this switch is shown in Fig.5. A metal foil is exploded (i.e. fused by an auxiliary capacitor) at the point F, so distorting the upper electrode that it shears through the main dielectric and makes contact in the groove of the lower electrode.

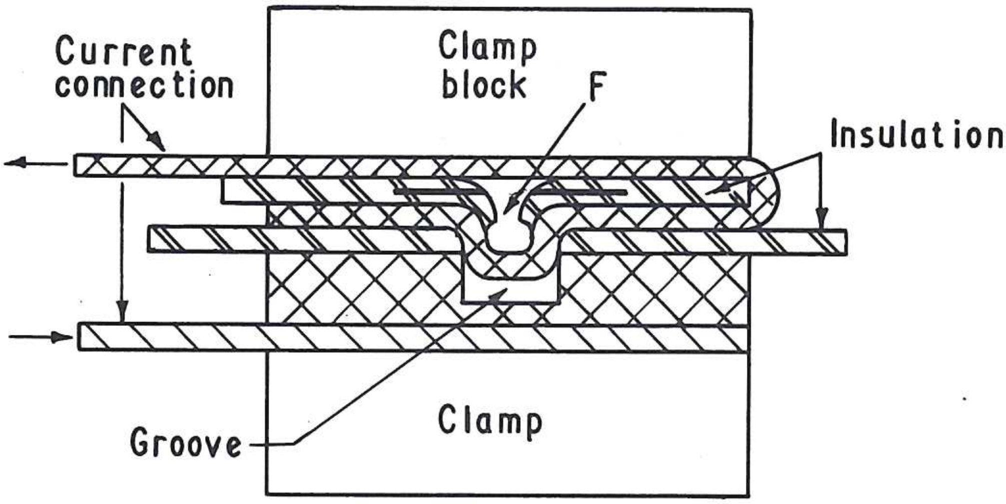


Fig. 5 Exploding foil switch (CLM-P 206)

5. MULTIPLE SWITCH ARRANGEMENTS

In a brief review such as this it is not possible to discuss all the details of the various techniques. Brief mention has been made of various triggering arrangements and some of the difficulties of practical design. During the past three years (or so) there has been a significant advance in the techniques for paralleling switches.

A typical arrangement of a multi-switch capacitor bank is shown in Fig.6. The trigger pulses are derived from lengths of charged coaxial cable which are short-circuited by a single master spark gap at the end remote from the switch. In this way trigger pulses of twice the magnitude of the cable charging voltage are obtained at the switch.

In the arrangement shown in Fig.6 the main cables are connected together only at the current collector plates on the load coil. Each

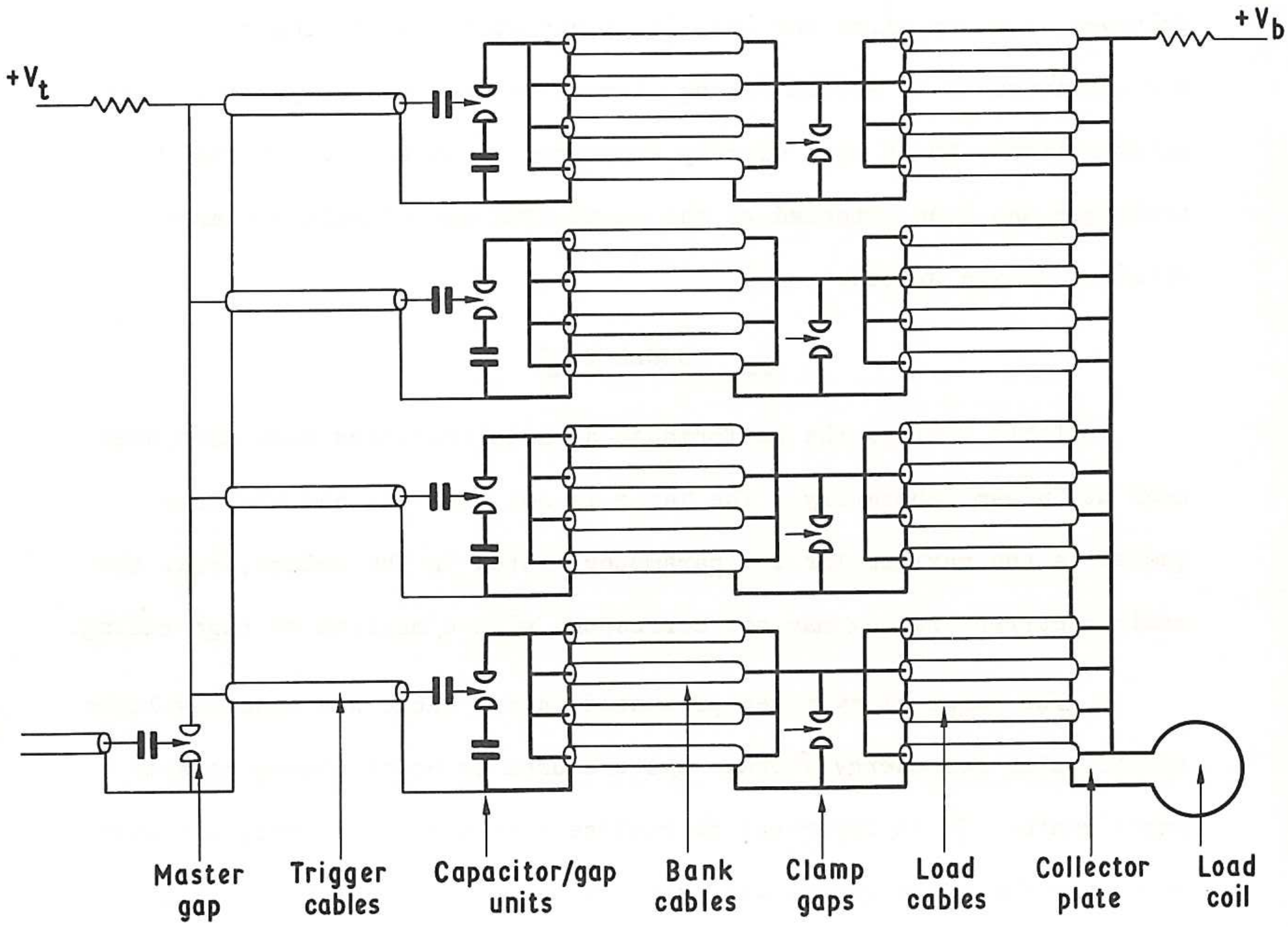


Fig. 6 Basic circuits of low inductance capacitor bank (CLM-P 206)

'Start' switch then is electrically isolated from its neighbour by the transit times of the connecting cables. Until recently, it has been deliberate design policy to maintain this time separation in the belief that it was necessary for the reliable triggering of all the switches, i.e. to allow for individual variations in firing times. Now improvements in switch firing characteristics and trigger circuits allow switches to be more closely connected in parallel. In fact the technique has been extended to the successful use of multiple arcs within a single switch.

6. CONCLUSIONS

Table I lists the performance data for switches that have been used at Culham Laboratory. The Table is not complete and the data quoted is the maximum for the parameter listed in the column, i.e. the maximum current rating may not correspond with a maximum voltage rating.

The range of switches presented in the table has been developed specifically for energy storage systems used to power plasma physics experiments. It is important to realise that these switches, although developed for experimental use, are not bits of string and sealing-wax but properly engineered components for high-energy storage systems. By the nature of their application they must operate with consistency and precision, withstand high mechanical loads, and meet high standards of reliability and safety under both normal and fault conditions.

In the case of pressurized spark gaps, steady development over the past 10 years or so has led to the introduction of the field-distortion configurations improved electrode materials and refined triggering circuits. These switches now operate reliably at high ratings for many thousands of discharges without adjustment or other

TABLE I - MAXIMUM PERFORMANCE OF VARIOUS SWITCHES

NOTE: The maximum values are not necessarily achieved simultaneously in one specific switch unit

Switch Type		Voltage kV	Peak Current kA	Coulombs	Closing time µsec	Jitter* nsec	Inductance nH
LOW PRESSURE SWITCHES	Ignitron	20	100	400	1.0	10	100
	Mercury diode	75	300	130	1.0 ?	10 ?	100
	Vacuum switch	30	2,000	20	0.2	20	5
PRESSURIZED SPARK GAPS	Uniform-field irradiated	40-100	500	7	0.05	5	40
	Atmospheric field-distortion	40	300	250	0.05	5	50
	Pressurized field-distortion	60	500	7	0.02	2	15
	Multiple-arc field-distortion	60	1,000	10	0.02	1	5
SOLID DIELECTRIC	Single arc solid dielectric	40-100	2,000	200	1.0	200	10
	Multiple-arc (current trigger)	40-100	2,000	2,000	1.0	200	5
	Multiple-arc (over-volted)	25	15,000	100	0.005	1	1
MECHANICAL SWITCHES	Rivet switch	40	600	2,500	50.0	1,000	20
	Exploding foil switch	40-100	2,000	2,000	3.0	100	5

* Jitter: maximum variation from the mean closing time.

maintenance. The existing or slightly modified versions may well find industrial applications as outlined in the introduction.

Solid dielectric switches (both electrically and mechanically disrupted types) suffer the disadvantage that components must be replaced after each operation. However, they are simple to make and their performance in terms of peak current carrying capacity, low inductance and voltage hold off puts them in a class apart and above any other type of switch. Thus, they may be particularly suitable for use in high power test circuits or as protective short-circuiting switches.

As a tail-piece to this review it is worth noting that the advances in switching which we have been discussing have been paralleled by an equally spectacular advance in the design of pulse capacitors and heavy coaxial cables, i.e. the other major components in energy-storage systems. In these fields the U.K. electrical industry has made significant contributions.

7. REFERENCES

A bibliography of references (CUL-808) is available from the Librarian, U.K.A.E.A., Culham Laboratory, Abingdon, Berks.