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United Kingdom Atomic Energy Authority

RESEARCH GROUP

THE STORAGE AND TRANSFER OF ENERGY

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1961

U.D.C.
621.039.637

UNCLASSIFIED
APPROVED FOR PUBLICATION

CLM-P7

THE STORAGE AND TRANSFER OF ENERGY

by

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ABSTRACT

Pulsed magnetic fields require an energy store which can be switched to the load coil for the desired experimental period. At the end of this period the energy is removed from the load and either dissipated or returned to the store.

Energy may be stored in a number of ways, as electric charge in a capacitor, as magnetic energy in an inductor, as kinetic energy in a mechanical system, (e.g. fly wheel), or as chemical energy (e.g. batteries or explosives). The appropriate method of energy storage is determined by the rate of rise of magnetic field required and by the number of pulses needed before the apparatus is of no further use. The paper discusses the various forms of energy storage in the light of these experimental requirements.

The switching problems vary considerably between the different forms of energy storage. Very high rates of rise call for spark gap type switches handling high instantaneous powers, whilst the longer pulses impose unusually arduous duties on mechanical switches. Recent development work on both high and low pressure spark gaps and mechanical switches for use at voltages up to 100 kV and currents up to 200 kA will be described.

The practicability of inductor storage for energies in the region of 100 megajoules and current rise times of about 10 milliseconds has been studied. Work on the study of suitable circuits and the development of a circuit breaker to meet the onerous duty of transferring current from store to load will be reported.

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October, 1961

HL 61/6282 (C.8)

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ILLUSTRATIONS

1. Introduction

This paper studies the problem of delivering electrical energy to an experimental load circuit for short period pulses. This load circuit may be the coil of an electro-magnet or a part of the circuit of a fusion experiment. In general, this load circuit will be predominantly inductive. Since this is the more difficult problem, this is the one which will be primarily considered. The problem will be treated in three parts.

Firstly, a review of possible methods of storing electrical energy; secondly, methods of transferring the energy from the store to the load; and thirdly, examples of apparatus for performing these functions which have been developed in various laboratories.

2. The Storage of Energy$^{(1)}$

Energy may be stored in many ways - as electrical charge in a capacitor; as magnetic energy in an inductor; as kinetic energy in rotating machinery; and chemically as in, say, a battery. From such stores it is possible to obtain an electrical output relatively easily.

Other possible form of energy storage, such as a high pressure gas or liquid, have been briefly studied, and indicate considerable problems with the prime mover which is required in connection with the process of conversion from potential energy to an electrical output.

It is important to realise that no generalisations are possible concerning a most preferred method of energy storage, and particular requirements must be considered in determining the most suitable form to adopt. Figures 1 and 2 clearly indicate two of the factors which have to be taken into consideration. Probably the most important is the current rise time required in the load circuit. Figure 1 shows how the cost of energy storage varies with the size of the energy store. Electrical storage as charge in a capacitor or magnetic flux in an inductor compare unfavourably with storage as kinetic energy or in batteries.

When we consider the electrical requirements of the load, the picture is very different. Figure 2 clearly shows distinct regions in which particular forms of energy storage are most appropriate, i.e. capacitors for times below a few milliseconds; a choice between capacitors and inductors, depending upon the total stored energy for times between 1 and 100 milliseconds; and special machines or batteries for the longer times.

The reason for machine and battery costs being inversely proportional to the current rise time is that for the time scale being considered, the cost is determined primarily by the peak power required, e.g. a car battery will store, say, one third megajoule, but in one second it is only possible to remove a few hundred joules because of the internal resistance, making the cost for useable stored energy some thousand times that for the total stored.

Considering in greater detail these various methods of energy storage:-

2.1 Capacitors

The large capacitors required for energy storage were originally based on design techniques which had been established for power factor correction capacitors. As requirements grew, it was clear that such designs resulted in large, expensive capacitors, and having a life far greater than required by most pulsed experiments. Development studies directed to establishing the relationship between the various pulse duties and life have made it possible to manufacture capacitors more suited to pulse requirements, which are both cheaper and more compact. Since the stored energy density is proportional to the square of the electric stress, it is desirable to work at as high a stress as possible. To do this, it is necessary to work with a dielectric in which the corona inception voltage is raised to as high a level as possible, since it is erosion by ionisation which determines the capacitor life. This was found to be possible using dielectrics which are not suitable for normal power frequency applications. Outstanding results have been obtained using castor oil with which it is possible to obtain at least one million discharges when working at a stress as high as 2,500 volts per mil. The stress in this case is the peak-to-peak stress, a factor which it is important to bear in mind since, in an oscillatory circuit one will have to pay approximately four times as much per joule of stored energy as for a circuit in which the discharge can be made uni-directional either by critical damping or clamping at zero capcitor voltage.

The form of capacitor construction has a considerable bearing on the resultant cost. Experience has shown that the most economical form is one consisting wholly of parallel elements, the elements being of the conventional power factor capacitor type to which connections are made by inserted tabs. Element voltages of between 8 kV and 10 kV are possible before corona at the foil edges leads to a rapid reduction in life. With this form of construction, however, it is only possible to manufacture capacitors with self-resonant frequencies between 50 and 100 kc/s. For higher resonant frequencies it is necessary to adopt either the extended foil technique of construction or other arrangements for satisfactory high current, low inductance connections to the elements. For a higher working voltage it is necessary to series many elements; this is relatively straightforward, but our experience has shown that major insulation problems which arise in such a capacitor are not always sufficiently appreciated.

A serious problem that cannot be dissociated from any large capacitor energy store is that of protection against faults. The ability of a faulty capacitor to absorb energy without explosion is strictly limited, and it is necessary to introduce elements into the circuit which will limit the fault energy which may be fed into a capacitor on failure.

With low voltage capacitor banks, that is 10 to 20 kV, from which it is not required to remove the energy too rapidly, say one millisecond, the simplest protection is by series fuses. Capacitor units are paralleled to form a group having a total stored energy less than that which would explode a faulty capacitor. Each group is then connected through a suitable fuse to the main high voltage busbar.

The capacitor banks of ZETA at Harwell, and ZEUS at Los Alamos, are both protected in this way.

The fuse size is determined by the voltage which will appear across it after interruption of a fault and by I^2T, (I being the R.M.S. current for a pulse time T). These two facts show how fuse protection becomes less and less practicable on high voltage, short time capacitor banks. The higher voltage will require a longer fuse adding unacceptable inductance to the circuit, and since I^2T is approximately inversely proportional to T, a much bulkier fuse must be used, requiring a considerable amount of energy to blow it, and reducing its protective value. One reaches the case where every capacitor must have its own fuse, and the fuse cost approaches that of the capacitor. The course we have followed for the protection of fast capacitor banks is one of deliberately introducing resistance at many points in the circuit, and a protective switching system which allows simultaneous short circuits to be applied at many places should a fault occur, so diverting most of the current away from the faulty capacitor.

2.2 Inductors

With a capacitor energy store the total cost is directly proportional to the total stored energy, but with an inductive energy store this is not the case. Basically, the design of an energy store inductor is independent of the amount of stored energy required, its size and cost being determined by circuit considerations.

A first requirement is that the inductor shall deliver the majority of its energy to the load circuit and this requires that the coil time constant should be several times greater than the discharge current rise time, and using an optimised coil shape, such as the Brookes coil, the required time constant immediately determines the major dimensions of the coil. The unit cost will then be inversely proportional to the total stored energy, modified slightly at the higher stored energies by increased mechanical requirements.

When consideration is given to the means of charging the inductor, we find another significant difference as compared with capacitor energy storage. In the case of capacitors, the cost of the charging system is relatively insignificant since charging may be over a long period because of the long time constant of a capacitor. With an inductor, it is uneconomical to charge for a period more than one time constant, and this requires a high peak charging power. For this reason it is necessary to optimise the design of the combined inductor and charging system. This usually results in a coil time constant longer than the minimum required by discharge conditions. Minimum unit cost is obtained when the inductor and its power supply are of roughly equal cost.(2) Under these conditions the unit cost is inversely proportional to the 2/5ths power of the total stored energy. The inductor curves on Figures 1 and 2 assume this exponent and are extrapolations from costs obtained in the design study of a 200 MJ inductor.

2.3 Machines

A design study of various machine proposals indicated little advantage to be gained from the use of unconventional machines. We considered homopolar generators and generators driven by a prime mover with energy storage preceding the prime mover, e.g. wither a water or gas turbine. Flywheel storage with an induction motor prime mover appeared most suitable, pulse power being generated either by a large single 3,000 r.p.m. alternator feeding many parallel mercury arc rectifiers, or a multiplicity of d.c. generators, - the costs of these two arrangements being roughly comparable, but the d.c. generator scheme, such as is used on the Model C Stellarator offering greater flexibility in utilisation.

Machines specially designed for pulse duty can be made to give almost four times the nominal continuous output of the same size machine, provided the duty cycle is such that there are no thermal limitations. Figure 1 shows that flywheel storage is inexpensive, and flywheels do not contribute greatly to the cost of machines if they can be run at a speed such that maximum energy is stored in a given weight of flywheel. For practical flywheels this requires speeds greater than about 750 r.p.m.

2.4 Batteries

Batteries have often been used to provide high current pulses because of the availability of suitable surplus cells - ex-submarine or minesweeper types being ideal for such use. The new cost of a conventional type of lead-acid cell is high and compares unfavourably with other forms of energy storage. This is due to the plate needed to achieve a low resistance being too thick and containing more active material than is necessary to store the required pulse energy. To try and overcome this, work has been carried out on the forming of ambipolar plates, i.e. positive and negative material on either side of a thin lead or steel plate. Sealing such plates into the electrolyte presents problems, and I do not know any large cell which has passed the purely experimental stage.

3. Energy Transfer(3)

3.1 From capacitors

Techniques for switching a capacitor energy store to an inductive load are fairly well established. Switching can be done by devices which only have to start current flowing, spark gaps or gas filled devices being used where timing precision is required. When only a unidirectional pulse is required, it is usual to clamp the circuit at peak current by a second switch which short-circuits the load. This duty requires a switch with the characteristics of a diode since the current must start to flow with a very low reversal of capacitor voltage.

Though both atmospheric and pressurised spark gaps have been used extensively, they have considerable limitations. They offer a high standard of reliability of hold-off voltage and in triggering performance, provided the electrodes suffer no gross erosion, but due to the high current density, excessive erosion occurs with the passage of relatively few coulombs, and even with the use of tungsten alloy electrodes, it is unlikely that a high pressure spark gap will be satisfactory for more than about 10 coulombs. The high current density also results in the switch offering a very high inductance to the circuit, which can only be reduced by the operation of many spark gaps in parallel. However, to ensure satisfactory parallel operation of many spark gaps, it is necessary to isolate the gaps by cables having a transmission time greater than the trigger jitter time of an individual spark gap; this adds to the circuit inductance, a switch with 10 nsec jitter requiring an isolating cable with an inductance of 100-150 mμH.

The 'low' pressure switch (ignitron, thyratron or spark gap), (4),(5), has a much more diffuse discharge channel resulting in a lower current density and a lower inductance. The voltage working range is much greater than obtainable with high pressure switches which require variation of pressure or gap setting. This property also facilitates parallel operation with less additional circuit inductance. Due to difficulties in making a single gap switch work satisfactorily above about 20 kV, the low pressure switch has not received as much attention as have spark gaps. Now that the fundamental properties of low pressure, high current arcs are being established, and the triggering mechanism understood, it should be possible to design reliable series gap switches for high voltages.

In designing the overall circuit it is important not to omit the inevitable stray circuit impedances. Excessive inductance between the capacitors and the clamp switch will result in an unnecessarily large overswing voltage on the capacitors, and a peak current in the clamp switch which is double the peak load current. Stray capacitance across the load circuit can result in transient voltages up to double the normal working voltage, and even higher in circuits with many parallel capacitor and switch circuits when jitter is present. It is usually necessary to ensure that these effects do not lead to failure of any of the components.

3.2 From inductors

Transfer of energy from an inductive energy store to an inductive load presents far greater problems since energy transfer requires interruption of the current in the storage inductor. In an ideal circuit, this would of course, result in the appearance of an infinite voltage in zero time. It is therefore necessary to introduce a transfer impedance in parallel with the two inductors, (Figure 3). This may be either a resistor or a capacitor, the capacitor offering many advantages in efficiency of energy transfer. To transfer the whole of the stored energy from the store to the load, it is necessary for the transfer capacitor to store at least half the inductive energy. The cost of such a transfer capacitor has to be added to that of the inductor on Figure 2, making the cost of inductive energy storage less attractive. However, an improvement can be obtained by various circuit tricks, and it is possible to transfer up to 75% of the energy from the store to the load using a capacitor storing only one sixth of the store inductor energy.

The speed with which energy can be removed from an inductor is largely determined by the design of the circuit breaker. High rates of transfer requiring either excessively high currents or voltages and parallel switching is not possible. Exploding wire techniques have been used but are unlikely to be practicable for large energy stores. For current rise times of 5-10 msec it is possible to use either a compressed air circuit breaker, specially designed to obtain a rapid rise in arc resistance or a vacuum switch in which current extinction is obtained by the injection of an oscillatory current from an auxiliary circuit.

3.3 From machines

With machines the switching can usually follow conventional power engineering practice since it is possible to use field control on the machine to reduce the switched power to a reasonable level.

4. Some British Developments in Storage and Switching

A large multimegajoule capacitor bank must inevitably require long connections to the experiment. For this reason it was decided to develop a 100 kV pulse technology since at this voltage it is possible to obtain a low effective connection inductance without resorting to an unwieldy bulk of cable.

The unit capacitor size chosen was 0.5 μF, being a compromise between the requirement for a large unit to reduce the proportionate cost of the high voltage insulation and other fittings, and yet small enough to avoid excessive wastage due to individual element failures in production. These capacitors have a self resonant frequency of 500 kc/s and with a peak-to-peak voltage of 125 kV the anticipated life is about half a million discharges.

A pressurised four electrode spark gap is being developed to switch 80 of these capacitors in parallel. A switch of similar basic construction is shown in Figure 4. This switch is designed for operation at 40 kV and has been satisfactorily tested at a peak current of 130 kA, 6 coulombs per pulse for 2,500 shots without any significant deterioration in performance.

For clamp switches, satisfactory results have been obtained with mercury diodes in which the cathode is a molybdenum dish wetted by the surrounding annular mercury pool. At 40 kV such switches have passed up to 130 kA peak current and about 100 coulombs per pulse. Further developments of the internal geometry will, it is hoped, lead to a satisfactory 100 kV switch.

A design study of an inductive energy storage system concentrated attention on an inductor to store between one and two hundred megajoules, the region in which inductive storage offers considerable economy. The simplest and most economical construction is one based on the parameters of a Brookes coil. This however, leads to a coil with a very large external magnetic field which can be a considerable embarrassment to experimenters, and for this reason other forms of construction were studied which would lead to the elimination or considerable reduction of this external field. We considered ferro-magnetic shields, various forms of toroidal construction, and enclosure of the storage conductor inside a large flux cancellation coil, this latter approach proving by far the most economical.

Figure 5 is a photograph of a model showing the type of construction which could be adopted for a 200 MJ inductor. This inductor would have a diameter of $8\frac{1}{2}$ feet, and a height of 13 feet for the storage coil, and an overall diameter of 27 feet, and a height of 33 feet for the screening coil. The total weight of copper in this structure, which would have a time constant of 5 seconds, would be 102 tons, or about 150% of the weight of the unscreened coil for the same total stored energy. If the screen diameter can be made larger, then its weight may be reduced; however, a reduction to much less than 50% of the weight of the unscreened store coil leads to quite impracticably large dimensions, (Figure 6).

Development work on mechanical switchgear to be used in connection with inductive energy storage has led to the design of a special clamp switch which may be used to relieve an electronic switch when the coulombs per pulse exceed about 100. The switch is of co-axial construction and is designed to hold off a 200 kV impulse and pass a peak current of 160 kA for up to 0.1 sec. To obtain a reasonable life, it was necessary to eliminate contact bounce, and this has been done by an ingenious arrangement which uses the compressed air in the switch chamber to hold the two contact elements together.

The circuit breaker for use with a storage inductor would consist of many breaking units in series together with conventional isolators which would not have to interrupt the current. The problem could therefore be studied on a single series element, and this has led to the design of a prototype breaker which, working with air at a pressure of 300 p.s.i. will generate an arc voltage which rises at about 8 volts per μsec, and should be satisfactory for interrupting up to 80 kA in a circuit where energy transfer takes place in 5 to 10 milliseconds at a peak voltage of up to 20 kV.

A design study of energy storage machines gives some idea of the magnitude of the equipment required for charging an inductor. For a 200 MJ inductor, two schemes considered had a roughly comparable cost, (about £600,000). The first used a single 3,000 r.p.m. alternator directly coupled to a flywheel and motor, and delivered a peak output of 350 MVA to 45 6-anode mercury arc rectifier tanks. This is about the maximum peak output obtainable from a single machine because of limitations due to torsional forces in the shaft under possible fault conditions.

A similar performance could be obtained using six motor generator sets, each set consisting of three generators which would be of double lap wound construction since under pulse duty this form of construction leads to a much higher output per machine than the more conventional single lap construction.

5. Conclusions

The various possible forms of energy storage have been shown to be complementary rather than competitive, each offering certain practical and economical advantages over a range of current rise times and size of store.

To what extent is further development to reduce the cost of energy storage worthwhile? In all the systems we have considered, the energy store is essentially a buffer between the pulsed experiment and electricity from the public supply authority, and we may use this to ascertain a reasonable figure for the cost of energy storage, by equating initial capital outlay to the running costs over the anticipated life period, e.g. one joule of capacitor charged and discharged one million times would require approximately one third of a kilowatt hour, indicating a cost target of about 500 joules per £1.

Finally, an observation on the bulk of these electrical methods of storing energy. Compare them with, say, your car and its hundreds of megajoules in the tank behind; but of course, it is difficult to empty the tank in a hundredth of a second - and somewhat expensive!

Acknowledgements

I should like to thank my colleagues of the Culham Laboratory for their contribution to work I have reported, and for information on inductors, Messrs. Ferranti Limited; on machines, The English Electric Company Limited; mechanical switchgear, Messrs. A. Reyrolle & Company Limited, and mercury clamp switches, The Research Laboratories of the General Electric Company, Limited.

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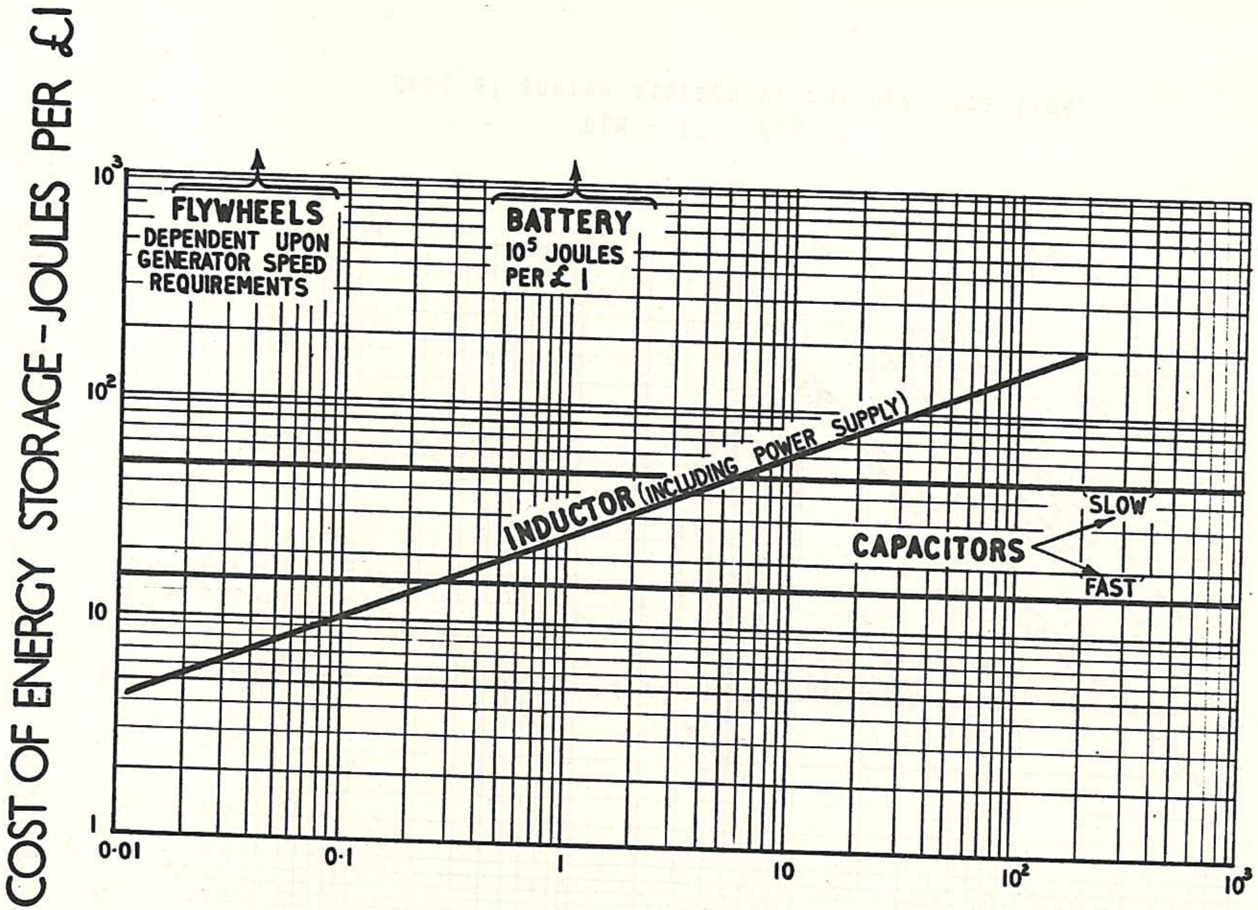
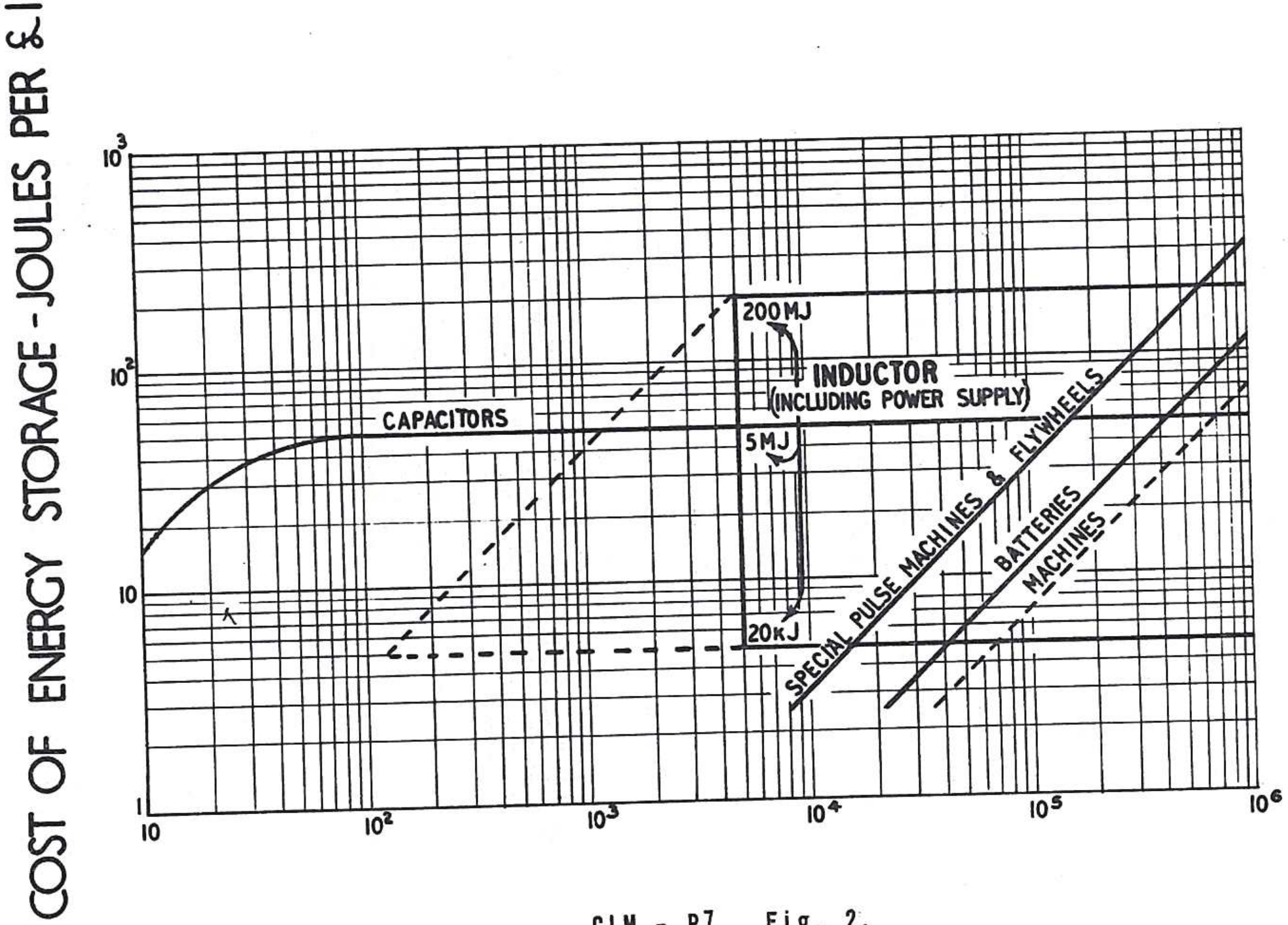
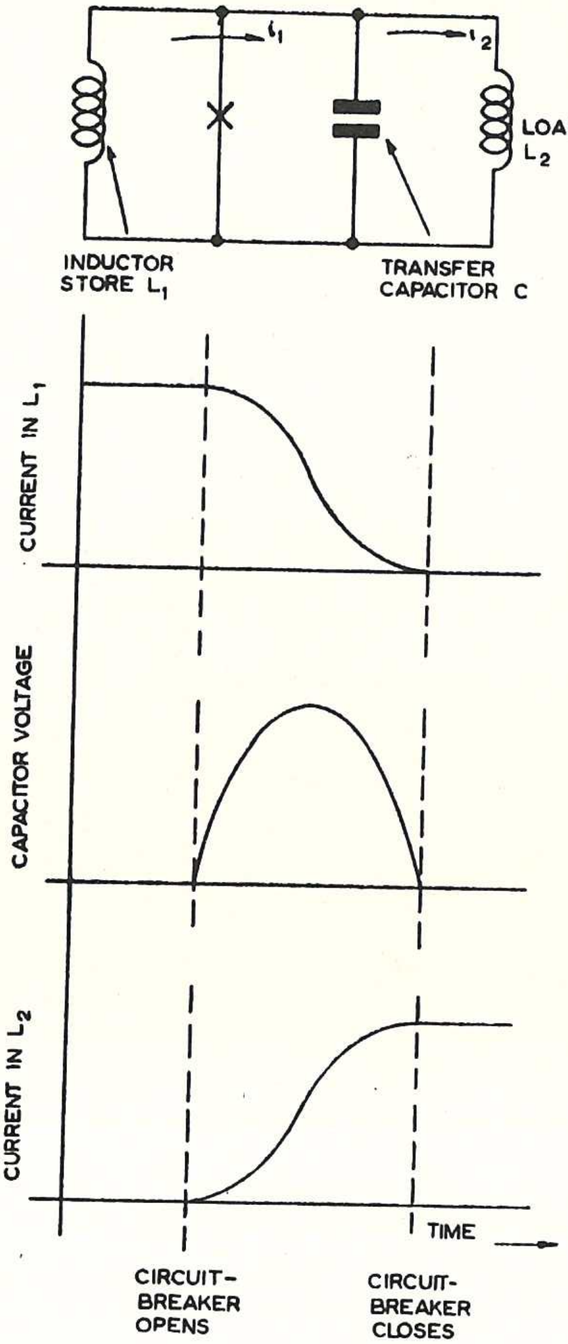


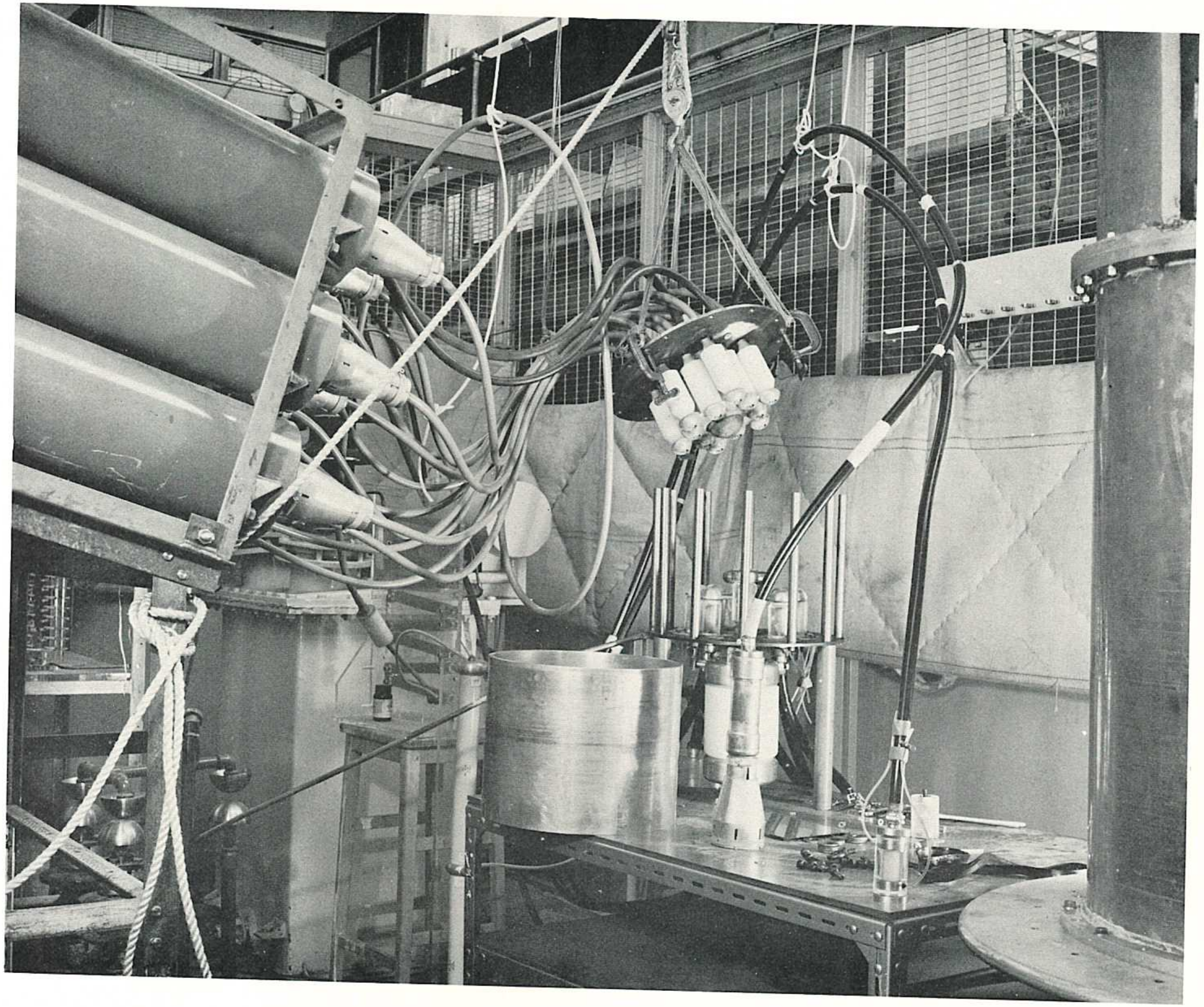
CLM - P7 Fig. 1
Cost of energy storage v. total stored energy.



CLM - P7 Fig. 2.
Cost of energy storage v. current rise time.

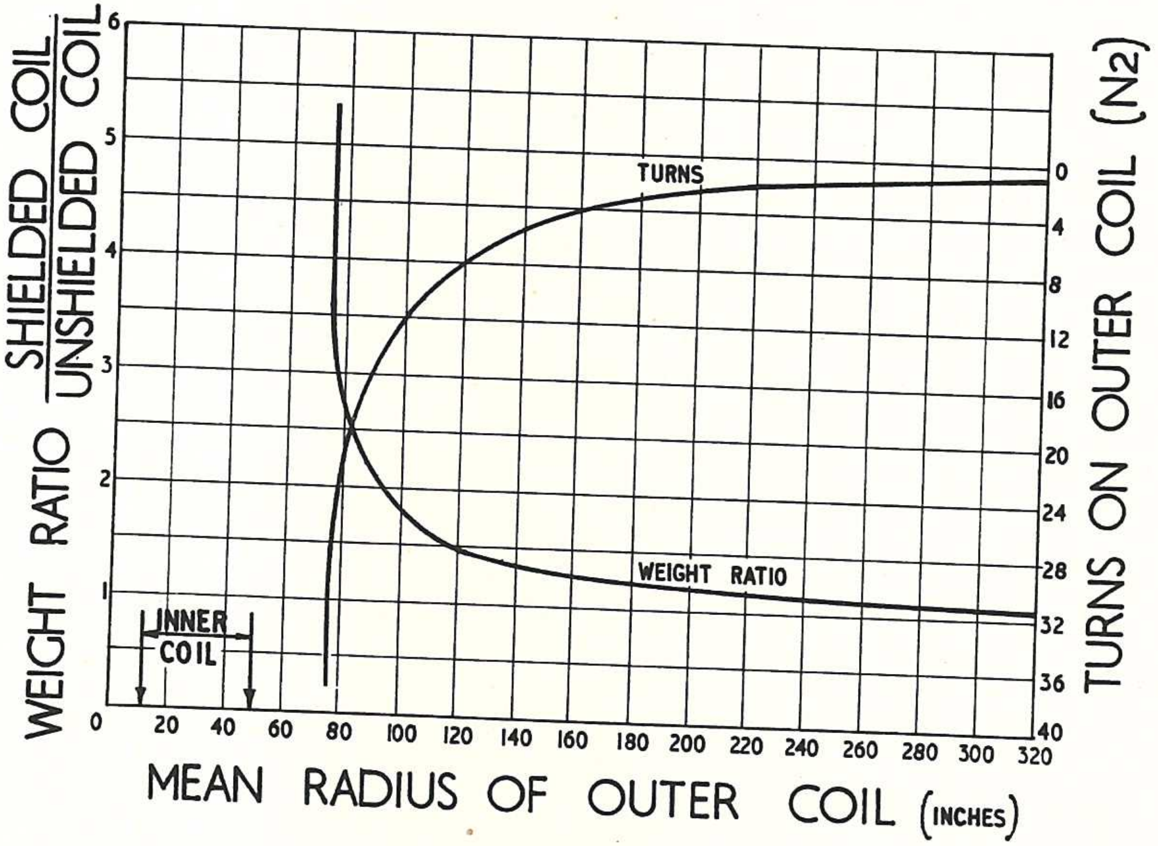


CLM - P7 Fig. 3.
Circuit for energy transfer from an inductor.

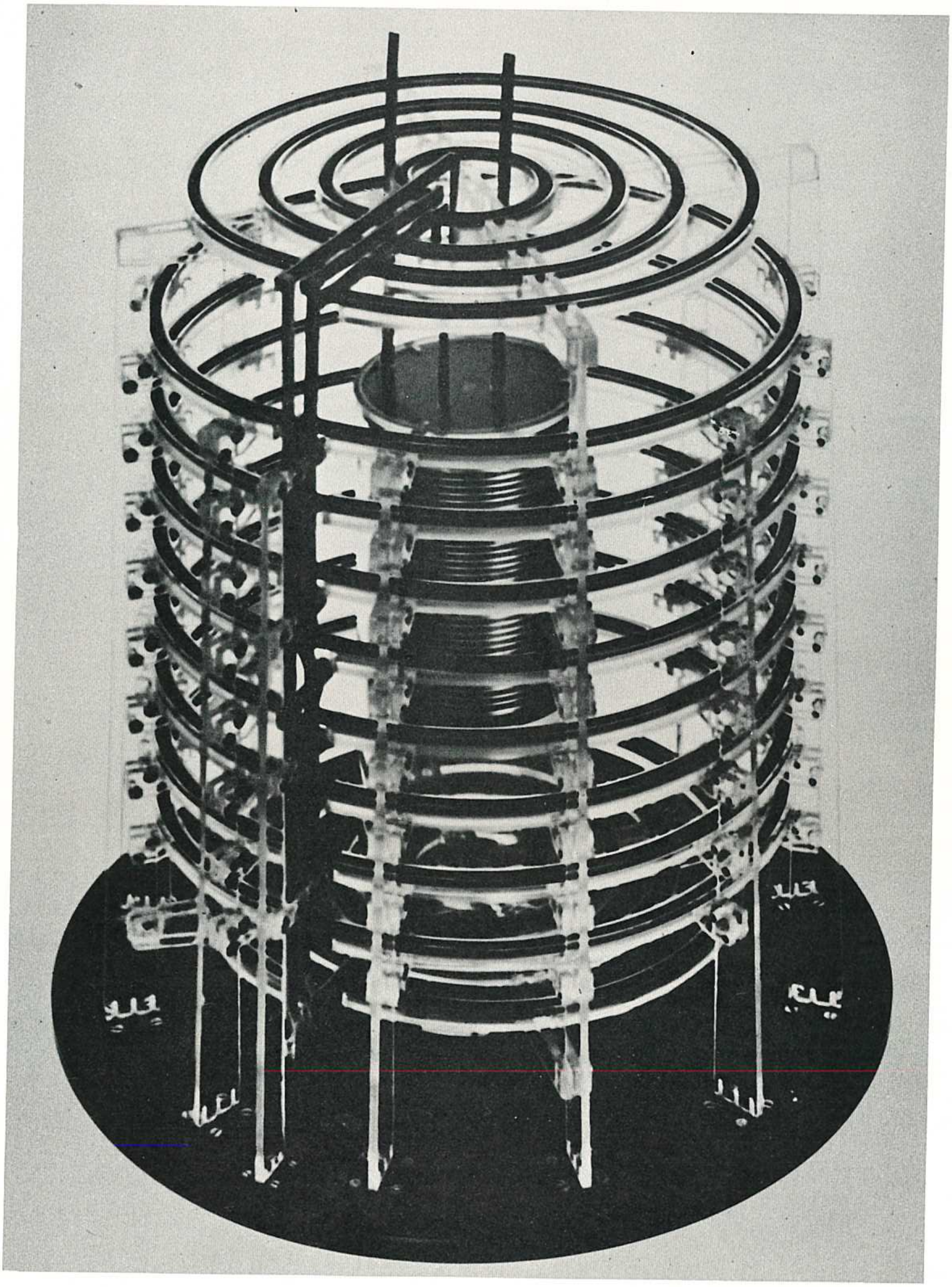


CLM - P7 Fig. 4.
40 kV four electrode spark gas.

EFFECTS OF SEPARATION BETWEEN MAIN COIL & SCREEN



CLM - P7 Fig. 5.
Model of 200 MJ inductor.



CLM - P7 Fig. 6.
Effects of separation between main coil and screen.