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PRECAUTIONS TAKEN ON A HIGH TENSION
ELECTRICAL INSTALLATION -

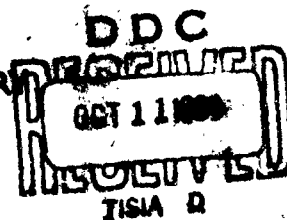
AN ESSAY ON SAFETY

BY
A.G.H. TROUGHTON

JUNE 1963

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PRECAUTIONS TAKEN ON A HIGH TENSION ELECTRICAL INSTALLATION -

AN ESSAY ON SAFETY

by

A. G. H. Troughton

ABSTRACT

The problem of devising adequate safeguards for an high voltage system grows rapidly as the complexity of the system increases. The philosophy and practice of rendering a system safe is discussed and its application to a complex system described in detail.

INTRODUCTION

Rendering an isolable high tension unit electrically safe seldom presents any difficulties, but an extensive system may present a severe problem. While every case must be considered on its own merits the principles involved do not vary, for example it is always necessary to ensure that interlocks will fail safe.

For this reason it was considered worthwhile to describe the application of these principles to a specific example of an electrical system capable of delivering lethal shocks.

2. RULES AND PRECEDENTS

In non-experimental work the regulations usually observed are the I.E.E. Regulations [1] and the Electricity Regulations of the Factories Act [2]. The former has no legal status although it is certainly accepted as a code of good practice.

Experimental work is formally exempted from the Factories Act but it is expected that its rules should be adhered to wherever possible. There is, in addition, a common law responsibility to provide safe working conditions although this does not entail going to extreme lengths to protect personnel from remote dangers.

The effect of these immunities from regulations is to place the responsibility for the safety of experiments firmly on the scientist. Usually he requires assistance, and establishments using much high voltage equipment issue their own supplementary regulations. Such compilations are the A.W.R.E. Instructions 41/48, [3] which are in the process of being superseded by Instruction /62 [4] and A.E.R.E. Instruction SC.5/1900 [5]. These have the useful property of telling the experimentalist what he can do rather than what is to be avoided.

Finally there is 'Electrical Accidents and their Causes' published by the M.L.N.I. Factories Inspectorate which provides graphic illustrations of actual incidents [6]. These provide an insight into the way accidents occur and, one hopes, give some practice in discrimination between possible and likely accidents.

3. GENERAL PRINCIPLES

All equipment over 500 V associated with a stored energy of 1 J or over 5 kV with an output of more than 5 W is dangerous, although the hazard arises mainly from secondary causes, e.g. falling. When these values are raised to 20 J and 50 W respectively the equipment is lethal in its own right.

When an experimental arrangement has been declared dangerous it is necessary to make it responsible to one man. The Aldermaston system is to designate a suitable person and make him directly responsible after the Superintendent; such people as the establishment Safety Officer acting in a purely advisory capacity. The duty of the designated officer is to certify operators as fully trained or adequately supervised, that people are aware of the hazards existing, and that such unskilled persons as cleaners work in designated areas only when instructed. It is understood that a man should never work alone on lethal apparatus. The second man should be sufficiently skilled to be

useful in an emergency and a labourer or a person under twenty-one is not acceptable. The apparatus will normally be interlocked, and it is only common sense to demand that the ownership of the operating key is well defined.

Before starting work it is essential to ensure that the working area is clear. A warning klaxon sounded a short time before switching on is recommended, supplemented by inspection of the area. Turning on should activate red warning lights.

Assuming an accident occurs it must be possible to turn off the equipment positively and safely. Apart from permanent legible notices to delineate the designated areas it is necessary to mark all essential controls to indicate function. Crash switches should also be placed in all working areas.

It is obviously unwise to permit unassociated work to be carried on in the designated area and most codes of practice stress good house-keeping, i.e. eliminating trailing wires, etc.

Devices containing capacitors should be contained in a cabinet fitted with gate switches, either Castell mechanical or electro-mechanical, arranged to fail safe and be reasonably tamper proof. These should cut off the supply and discharge the condensers on opening the door. Cables connecting such cabinets should themselves be interlocked. Where automatic discharging is not possible an earthing rod is acceptable but the best practice is to use the rod to supplement automatic devices.

Interlocks themselves raise many problems. It is clearly impossible to produce a completely tamper-proof interlock, and A.E.R.E. go so far as to say any interlocking system depends on co-operation by the staff. While interlocks are acceptable for routine operation, servicing etc. usually requires an overriding facility. Time locks, no-volt release and dead man's handle-type switches are palliatives rather than answers to this question. Other half-measures are exhortations to keep one hand in the pocket or use insulating mats or gloves.

Efficient earthing is essential and with pulse operation earth loops must be obviated. Very large voltages may then appear between adjacent earths and this introduces problems of its own and one solution is to render the area 'earth free'. [7].

Finally, associated hazards must be considered, bursting condensers or the generation of X-rays.

Most codes of practice also stipulate regular inspection.

4. EXPERIMENTAL ARRANGEMENT

The original experimental arrangement envisaged a mechanically interlocked room containing all the hazardous apparatus, and a mechanical interlock was in fact installed. However, an override was necessary to permit adjustments to be made and this, together with the growth in complexity of the rig, made the safeness of the system doubtful. The following is a brief description of the system at this point which must be included to allow subsequent sections to be appreciated.

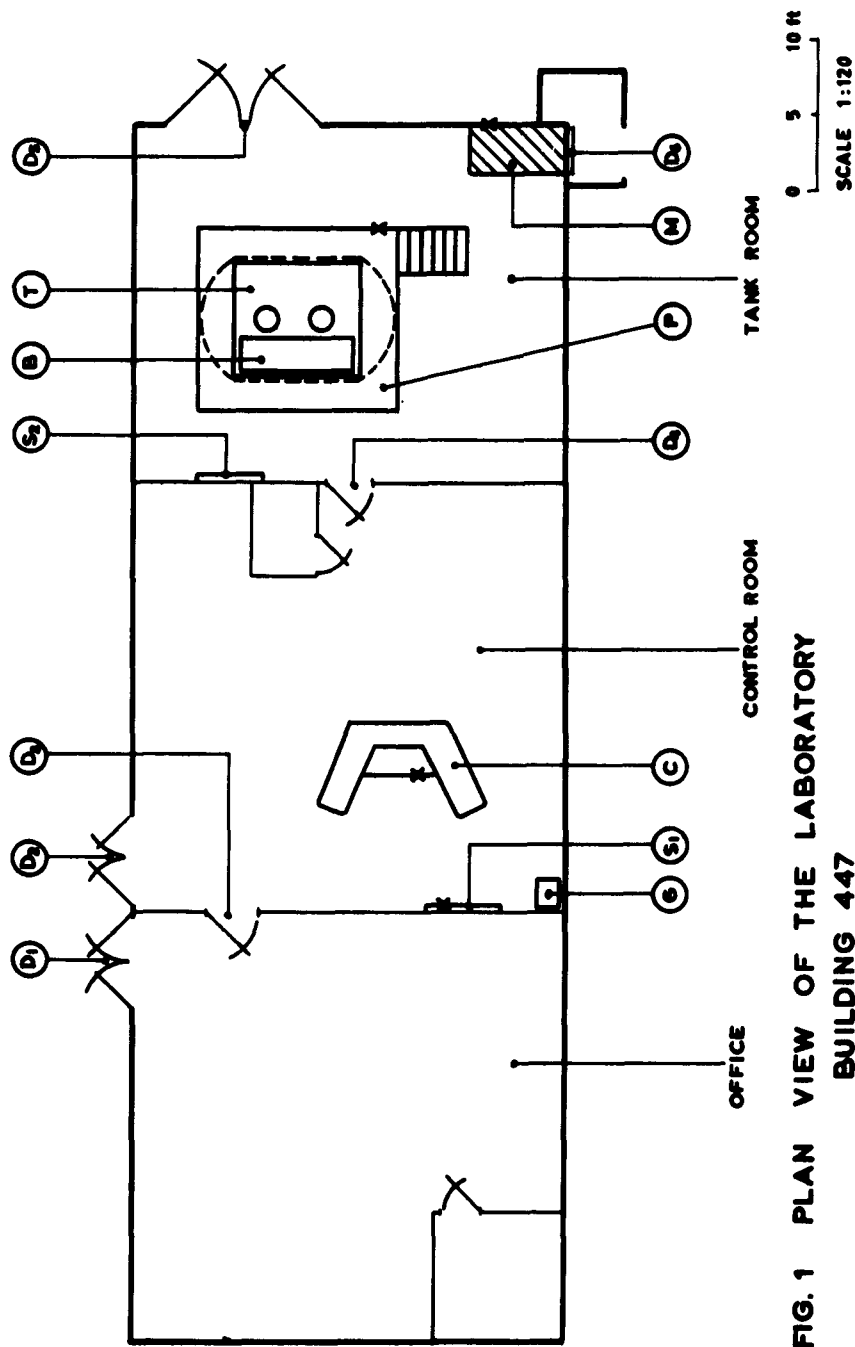


FIG. 1 PLAN VIEW OF THE LABORATORY
BUILDING 447

The apparatus was designed to generate underwater electric sparks in the energy range 1 to 100 J within a seven-foot diameter steel vessel pressurised up to 150 lb/in², the electrical energy being stored in a condenser bank placed above the pressure vessel. Provision was made for measuring the potential across the spark gap using a voltage divider and current through the circuit using a transformer. In the original and unsafe form the main earth was connected to the shielded box containing the condenser bank and the pressure vessel, metal scaffolding catwalk, and gantry supporting the overhead lifting tackle were earthed individually to a single point on this; an arrangement necessary to eliminate inductive loops. Apart from electrical measurements photographic records of the spark were to be taken using a spark light source but the cameras have been adapted for remote operation and the flash source is readily isolated.

The associated measuring instruments and other control gear are situated in the next room and under normal operating conditions it should not be necessary to go into the room containing the pressure vessel.

The arrangement is shown in Fig. 1. The control desk is at C and the tank at T. S₁ and S₂ are electrical distribution panels for the two sets of apparatus, S₁ possessing duplicate controls overriding S₂. The doorway D₄ was fitted with a Castell interlock system, which provided for overriding at S₂ for fault-finding. The E.H.T. generator was placed at G.

The most significant feature of the room containing the condenser bank (B) to the Safety Officer is its dampness. Most tank operations, such as filling, result in water being spilt on the floor and tank platform.

5. THE CIRCUITS TO BE SAFEGUARDED

The main hazard was presented by the condenser bank placed above T in figure 1. If all the elements were paralleled and charged to full voltage an energy of 600 J would be available at 25 kV.

On switching the circuit given in figure 2 the condensers are discharged through the spark gap and as water is a conducting medium there is no means of isolating the steel pressure vessel. If a thyatron unit is used as a switch the whole unit will momentarily attain the condenser bank voltage.

The main condenser bank is charged from the generator G and the voltage measured with electrostatic meters in console C which are connected directly to the condenser bank.

To eliminate earth loops the earth connections are made to a single point as shown in figure 3. Although the circuit diagram in figure 3 suggests the circulatory current should not give rise to any potential variations at the earth connection it is found in practice that large voltage charges occur, however well the system is earthed (see appendix). It follows that large potential differences normally appear between the various branches, A, B, C etc., and these may well be larger under fault conditions.

An alternative experimental arrangement replaces the condenser

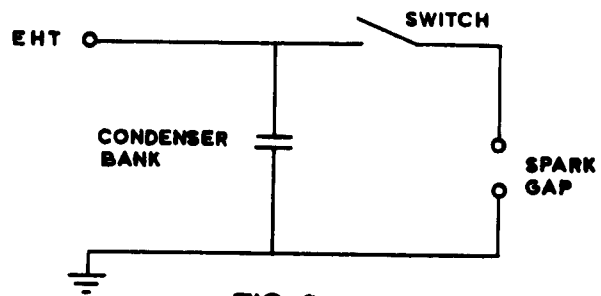


FIG. 2

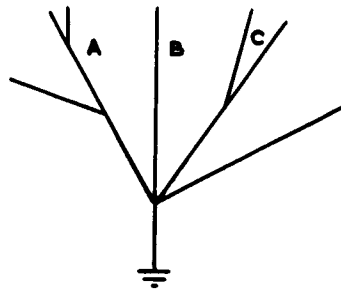


FIG. 3

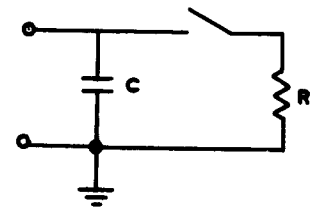


FIG. 4

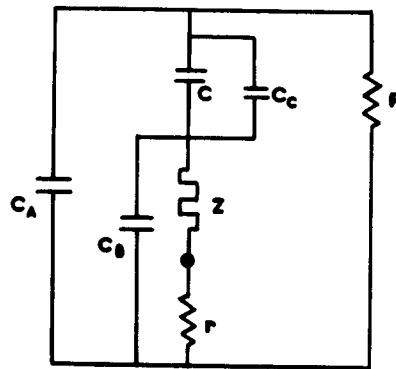


FIG. 5

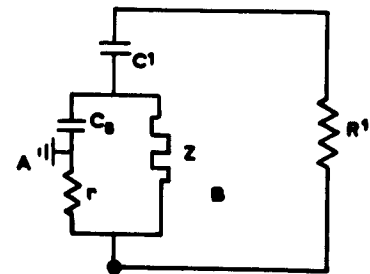
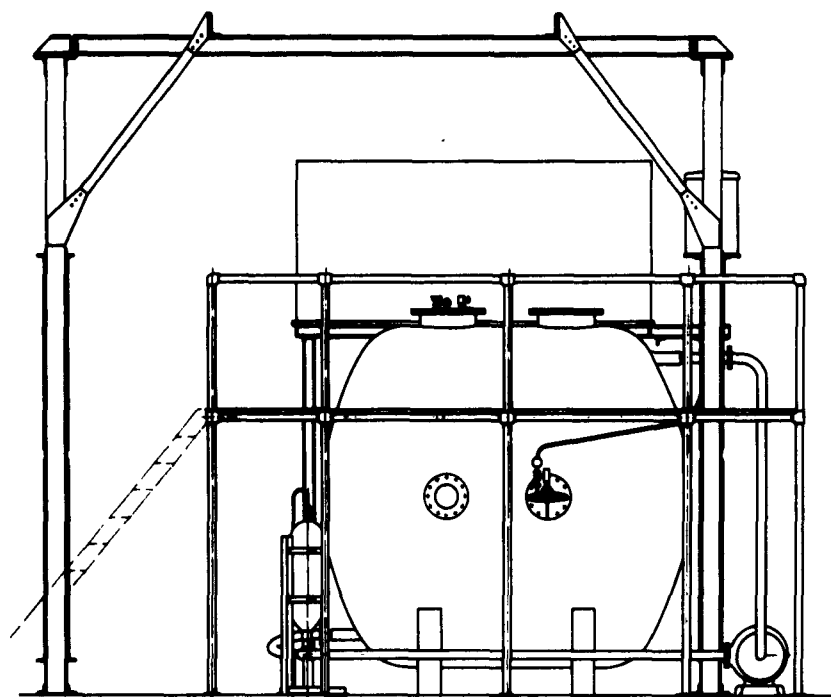
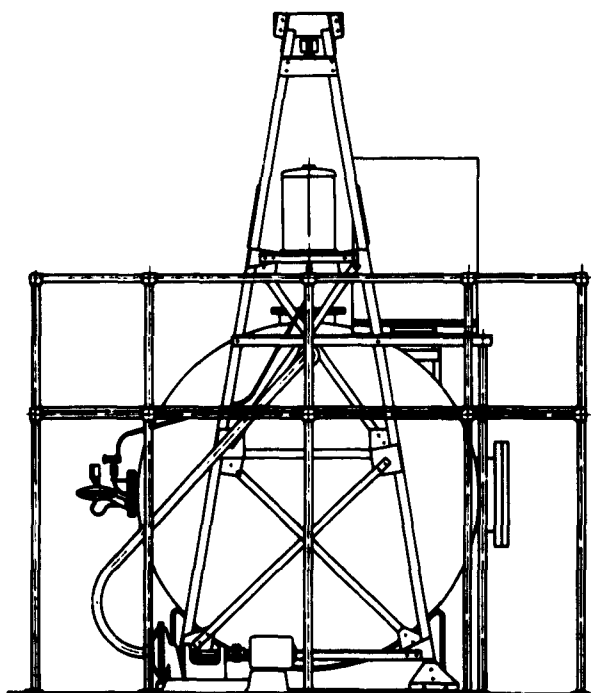


FIG. 6

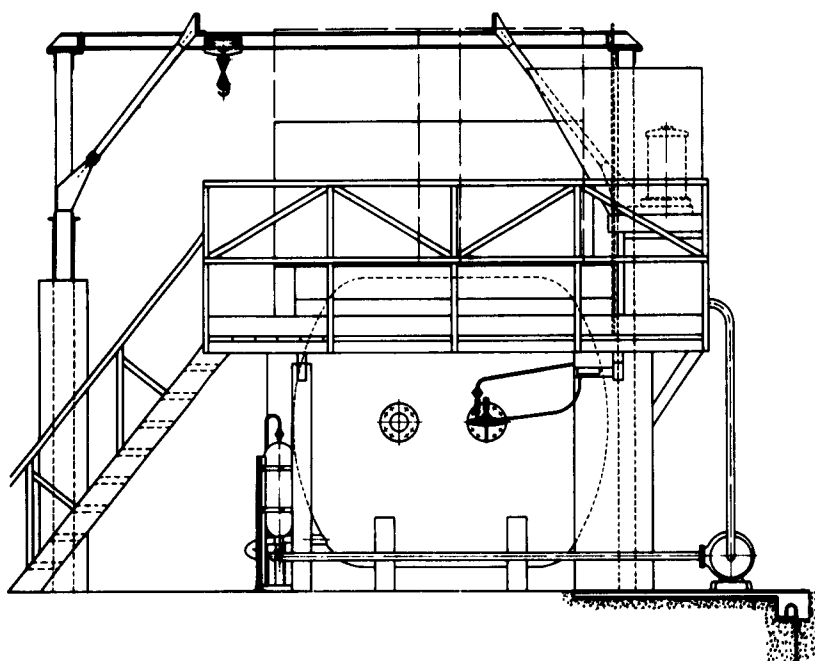


(a)

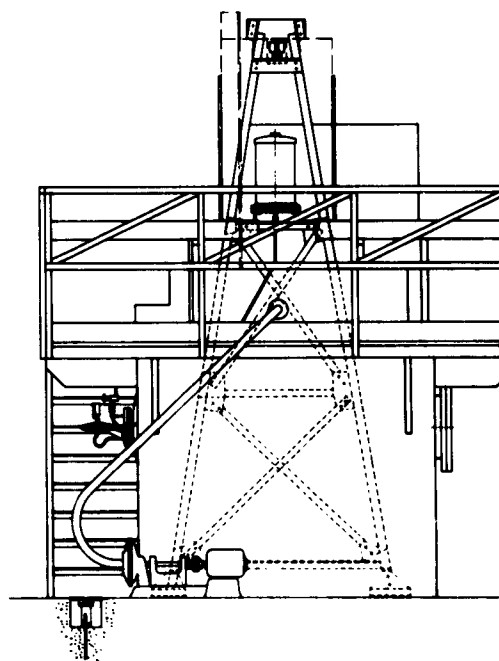


(b)

FIG.7 ORIGINAL ARRANGEMENT OF APPARATUS



(a)



(b)

FIG. E MODIFIED ARRANGEMENT OF APPARATUS

bank and E.H.T. generator by a Marx-Goodlet impulse generator capable of delivering 10 J, 75 kV pulses. The supply voltages and the energy available in the control room are very much lower than in the previous case but the earth pulses are more severe.

Apart from the main discharge there are a number of trigger generators with their associated power supplies. Each of these supplies is capable of delivering 25 W at 5 kV and they are used to charge the condensers to a maximum 100 J. This energy was available at the E.H.T. input panel, the contacts being accessible with the plug removed. The output of the trigger units was derived from a pulse generator which would normally give up to 20 kV peak voltage output.

6. APPLICATION

Before attempting to apply the principles outlined in section 3 it is as well to consider the requirements peculiar to this establishment. The standing regulations [8] permit the experimenter to dispense with all mechanical safety devices if he sees fit. However, there is no tradition of lethal high voltage work and apparently no curb on the peregrinations of window cleaners and other maintenance personnel; for this reason a fully interlocked system was specified.

While accepting that interlocks require the sympathetic co-operation of staff, laboratory tradition still demanded a design of interlock easier to use than misuse. As a simplification the restricted area was divided into two positions: the control desk room in which all potential sources of danger were protected by tamper-proof interlocks; and the tank room, normally protected by a Castell mechanical interlock, where overrides gave access to a room in which devices were fully interlocked though of less sophisticated design. The justification for this was that access to the door interlock keys was to be restricted and access to the tank room under potentially dangerous conditions limited to qualified personnel.

All the solutions to the override problem quoted are rather unwieldy and the override key was made to operate a klaxon with 1 in 10 duty cycle so that it would be impossible to be unaware that the overriding facility was being used.

The I.E.E. recommendation that outlets of different phase should be separated by at least ten feet was disregarded. Apart from distributing the load equally between the phases it was necessary to use all phases to eliminate mains pick-up. Outlets for all three phases appeared on both distribution boards and in the console. To offset this adequate labelling and coding was employed.

7. SAFETY PRECAUTIONS IN TANK ROOM

Probably the greatest danger in the tank room is associated with the large potential differences which may arise between adjacent earths. To eliminate earth loops the earth connections are made as in figure 3 and under normal working conditions large currents may flow, and in the worst cases large potentials appear across cables which are connected together a few inches nearer earth. Under unspecified fault conditions a large porportion of the stored energy may be available in this way.

The original apparatus shown in figure 7 had the main earth at

the top of the copper box with the gantry, catwalk and tank system earthed independently to this point.

To ensure that it was not possible to touch adjacent earths inadvertently the scaffolding catwalk was removed and replaced by a wooden one. Cross bars were introduced into this to make it impossible for an unconscious person to roll or fall from platform to floor. The copper tank was isolated from its metal bearer below by paxolin sheet and from the ports in the pressure vessel by $\frac{3}{8}$ in. perspex sheet.

The gantry raised a problem as it was not possible to isolate it effectively from the floor in wet conditions and the overhead girder of the gantry could not be shielded without drastically reducing the head room. For this reason the top girder of the gantry was electrically isolated from the rest.

Metal frameworks in easy reach of each other and also actual earth lines were then boxed in with framed plywood. 15 kV grade rubber matting was laid on the catwalk, a higher specification being superfluous as most of the conductivity in the frequently wet conditions is along the surface. Similar matting was also placed on working areas. Figures 8A and 8B show these modifications.

The copper box contained the main condenser bank and as it was desirable to see the contents during setting up, perspex doors interchangeable with the interlocked upper doors were fitted rather than introduce overrides. Two separate sets of switches were installed. Short circuit switches of the type shown in figure 9 were placed in parallel with the condenser bank and double ganged microswitches as described in section 9 were used to switch off the E.H.T. supplies and sound a siren when the door was opened with the mains on. Neither of these switches was made tamper-proof as this was difficult mechanically and, when the E.H.T. generator was on, access to the copper box was restricted to selected key-holding personnel. Also in the copper box was a large gravity-operated relay coupled with the Castell interlock system which was arranged to short-circuit the condenser bank in the deactivated position (fig. 10). A microswitch mounted on the relay was used to switch off the E.H.T. generator in the safe position to prevent large short circuit currents from being established.

The test vessel was pressurised by an hydraulic accumulator and the specification called for a control tap at the console. To provide effective isolation the copper tube used for the pipeline was broken at the wall between control and tank room and a rubber tube inserted, the pipeline elsewhere sheathed in Portex tubing. The pressurising gas, nitrogen, is not likely to provide a conducting path.

As the system stands the spark gap may be withdrawn from the tank without tripping any interlocks. In order that the operator should be in no doubt that the device was safe a high voltage switch was placed immediately above the top tank ports which was to be used to short circuit the condenser bank and turn off the E.H.T. units. A perspex cover on this switch allowed the action to be seen (fig. 11).

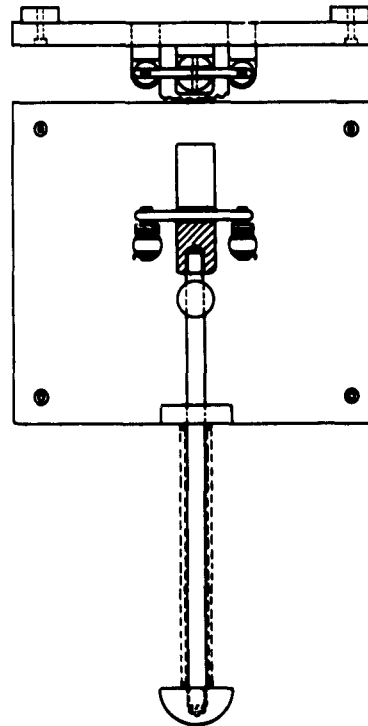


FIG.9 COPPER BOX INTERLOCK SWITCH

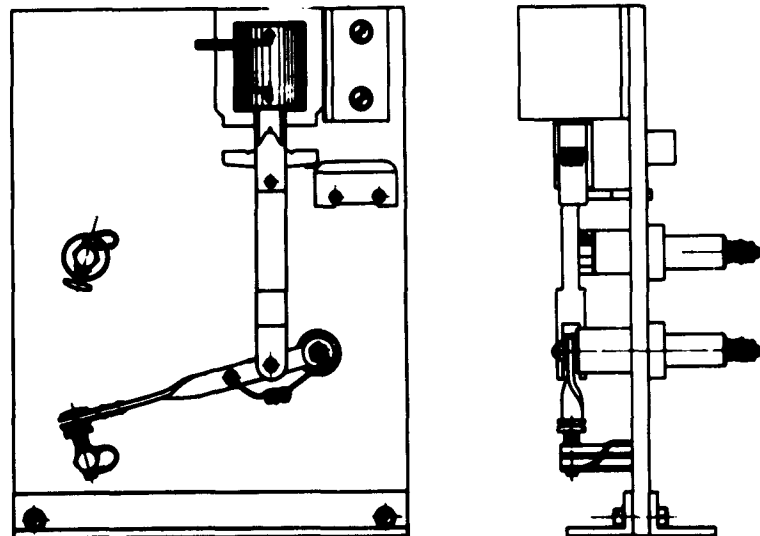


FIG.10 GRAVITY OPERATED RELAY

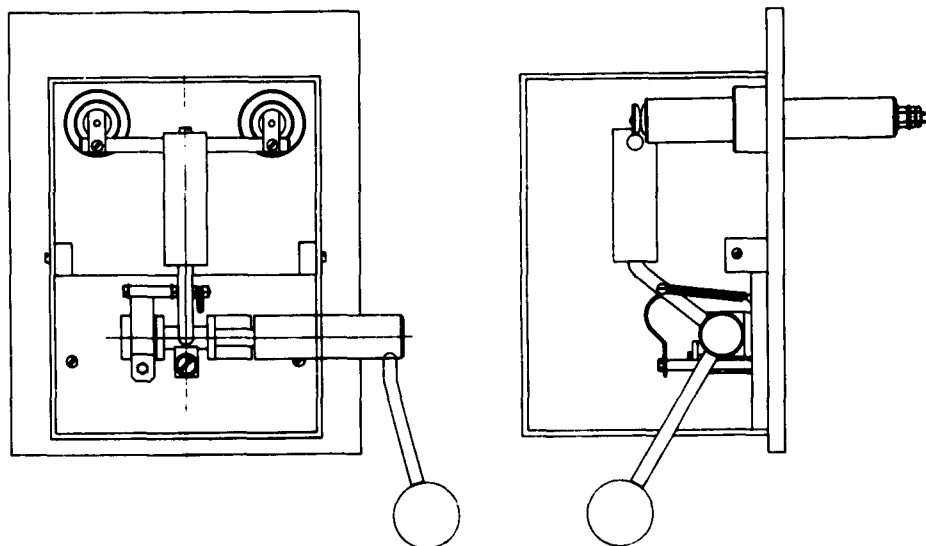


FIG. 11 PERSPEX COVERED SAFETY SWITCH

Crash switches were placed in a safe area at M and at the top of the catwalk stairs. The safe area was covered with insulating rubber matting.

The whole room was protected by a Castell mechanical interlock on the door which controlled the E.H.T. breaker and the heavy gravity operated relay placed as described above. The interlock switch for normal operation being at S_1 , with the override switch at S_2 . The override switch was double gang, operating a klaxon at a duty cycle of one in ten, so that it would be impossible for the override to be left on without being aware of the fact. The electrical arrangement is shown in figure 12.

To summarise, with the door interlock overridden access to the tank room could be attained with all supplies on. The interlocks controlled the E.H.T. circuit breaker and condenser bank discharging devices only. The interlocks were rudimentary and intended only to protect experienced personnel during essential equipment testing and maintenance.

8. THE CONTROL ROOM

The E.H.T. generator was placed in the control room for convenience at G in figure 1. Fixed above this was a resistor chain consisting of twenty Morganite tubular resistors rated at 100 W each contained in a box (fig. 13). If any of the condenser discharging devices in the large copper box at B jammed this bank would take 6 kW before the overload trip engaged, and so the mains dropper was fitted with blowers. The resistor chain was completely enclosed by a box and the metal portions earthed. It was arranged that in the event of any resistor disintegrating there was no electrical path to any earth or mains. The lid to this box was fitted with an interlocked hinge as described in section 9.

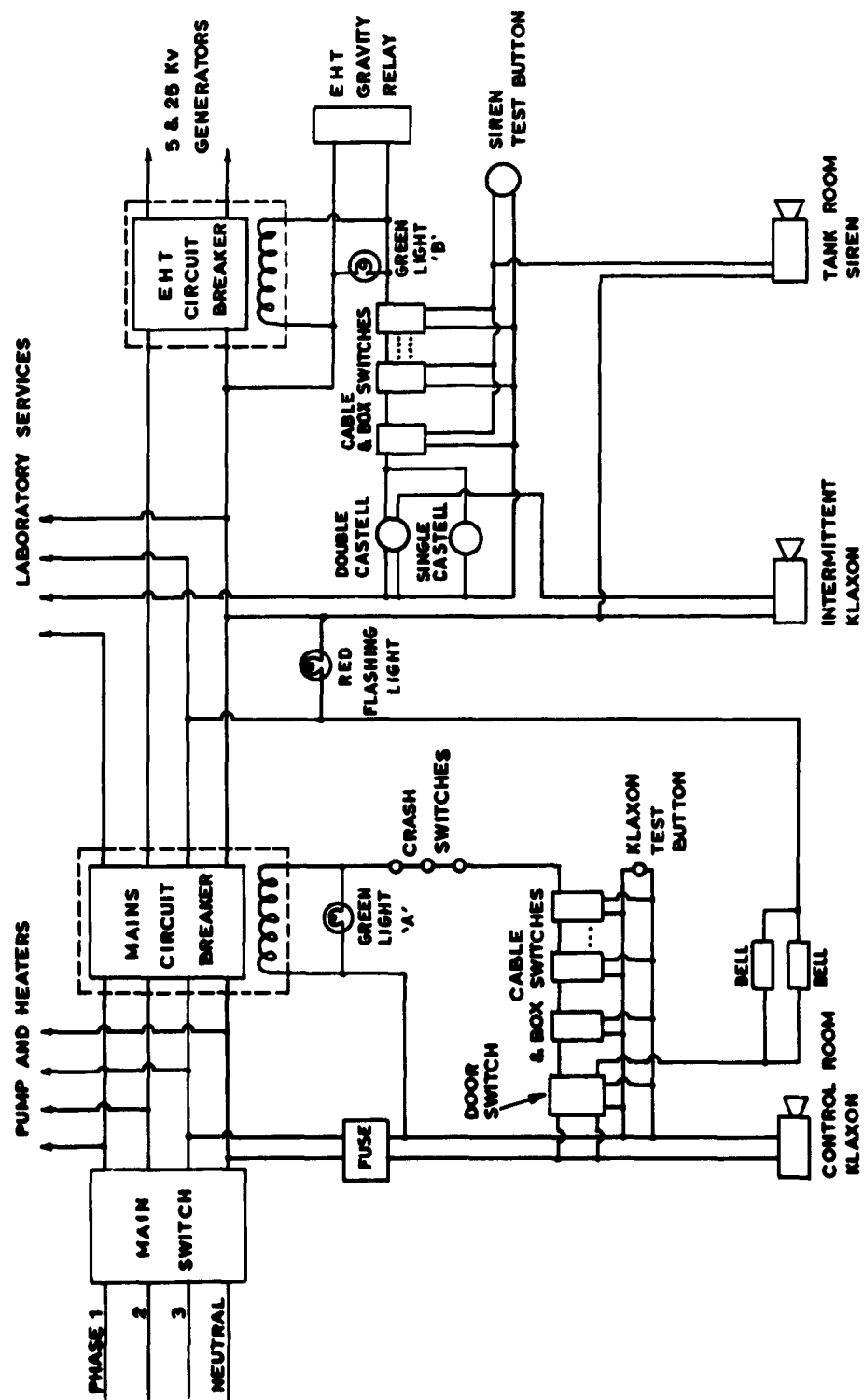


FIG.12 BLOCK DIAGRAM OF THE INTERLOCK SYSTEM

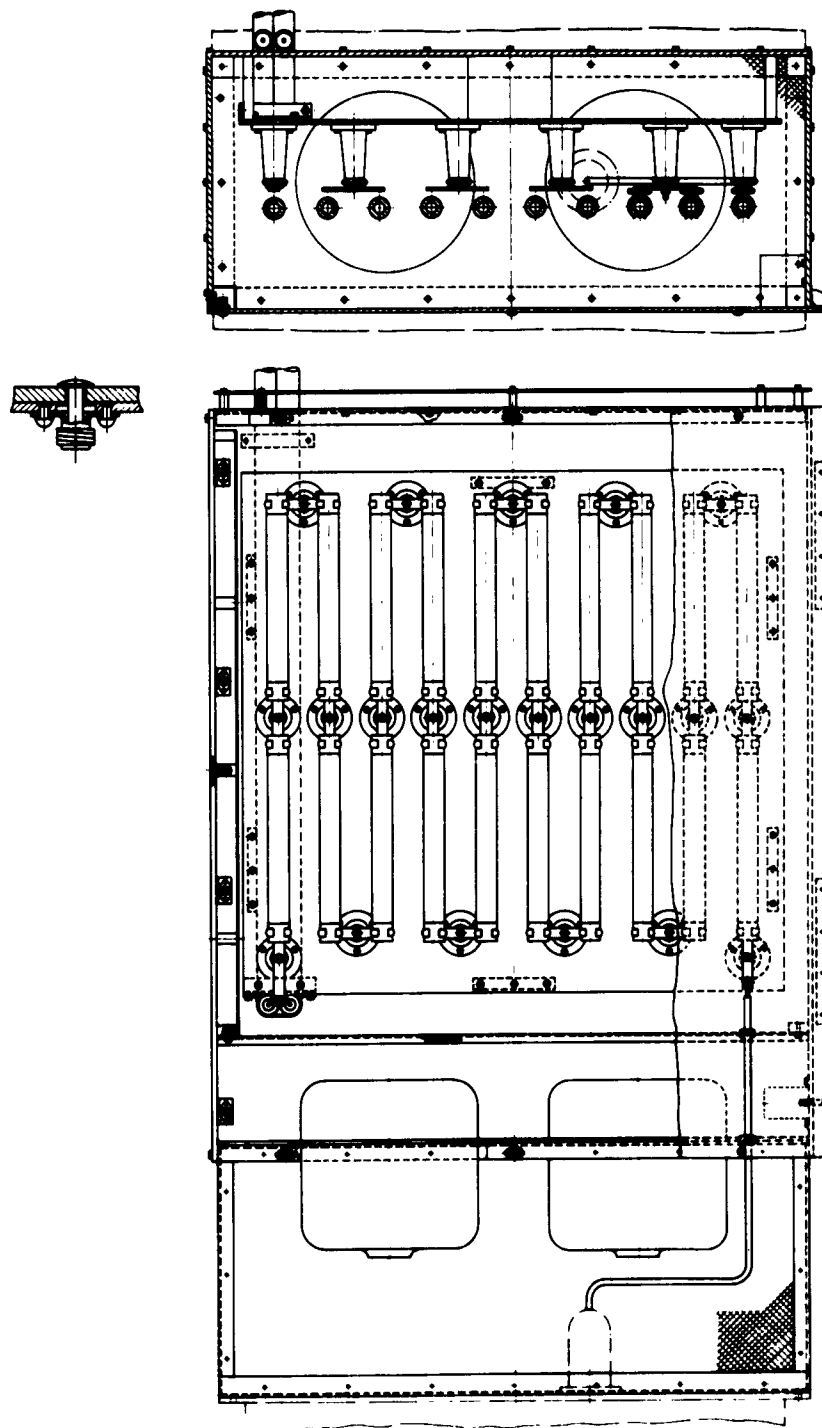


FIG. 13 EHT DROPPER UNIT

Two leads ran from the dropper, one to the console and measuring devices, the other to the copper box in the tank room. The maximum voltage to be carried was 25 kV, D.C. but as there was an almost certain probability of a rapid change in voltage the line UR17, rated at 22 kV for pulse operation was specified.

Inside the console the cable entered a distribution box (fig. 14). This contained three relays. The E.H.T. line was connected through the actuating coil of the first and, if a current greater than 10 mA was passed, actuated the mains breaker (fig. 15). The second and third served to switch in or out of the circuit two low range scalamp voltmeters, a high range scalamp meter remaining always in circuit. These relays were of the type shown in figure 10. The relay box and scalamp boxes were interlocked with hinge switches, the latter being hinged on top and in front (fig. 16).

The small E.H.T. units, trigger units and cables posed a more difficult problem. The experiment called for two E.H.T. units, two trigger units and two cables. Prudence and past experience demanded a spare trigger unit and cable. This eliminates the fitting of permanent cables immediately and suggests plugs and sockets.

Two points arise: the plugs must be interlocked, and there was the possibility that the wrong cable would be connected at the tank room end. To overcome all objections the following scheme was used:

- (1) The two E.H.T. units were placed in a box with an interlocked hinge (fig. 17).
- (2) The E.H.T. mains supply was arranged to come from the trigger units, special mains plugs being provided to ensure the wrong supply was not being used.
- (3) The trigger unit was fitted with an automatic discharging relay to operate on switching the mains off.
- (4) The trigger unit was fitted with hinge interlocks on the servicing access panel.
- (5) The E.H.T. input plugs and the pulse output plugs were interlocked (fig. 18).
- (6) The pulse cables were interlocked into the copper box at D.
- (7) Dummy interlocks were provided at both ends for the spare pulse cable.
- (8) The control room interlocks were placed in series with the mains breaker and the tank room interlocks with the E.H.T. breaker.

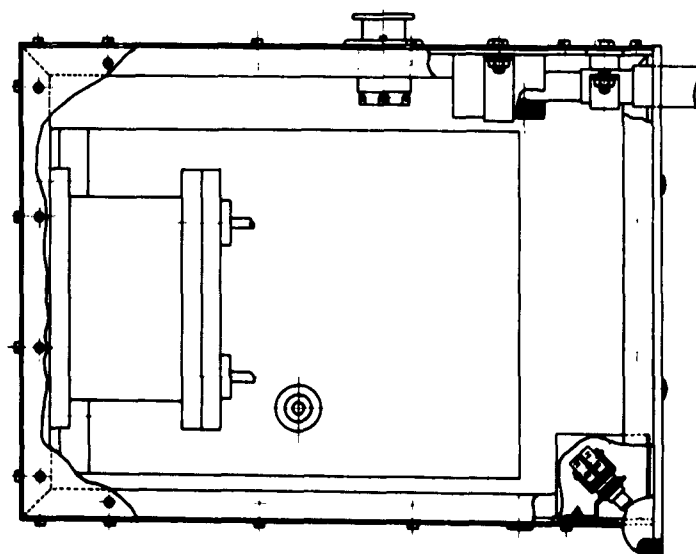
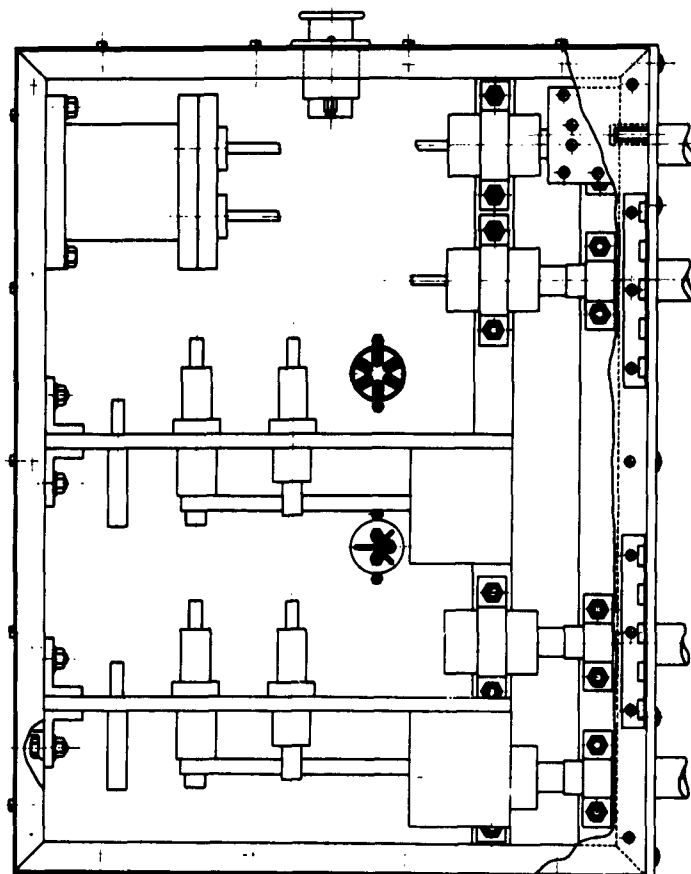


FIG.14 EHT RELAY BOX

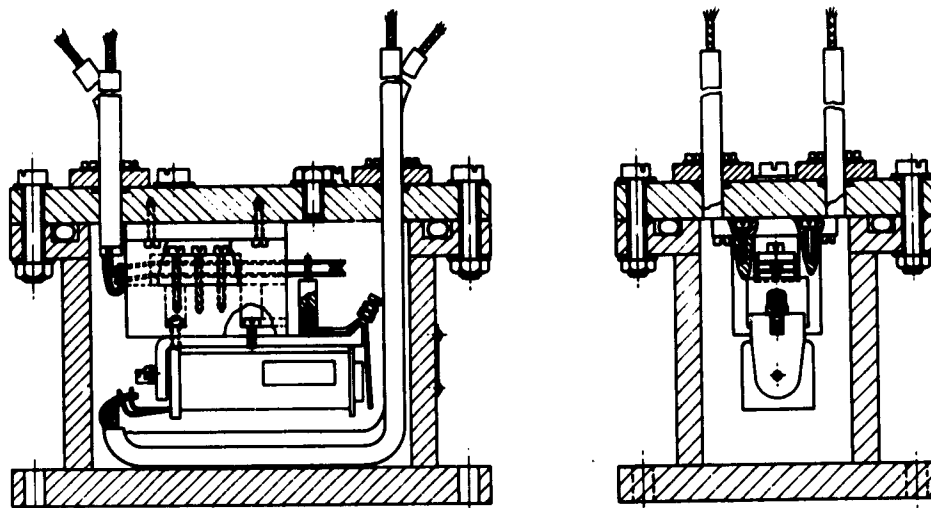


FIG.15 LEAK DETECTING RELAY

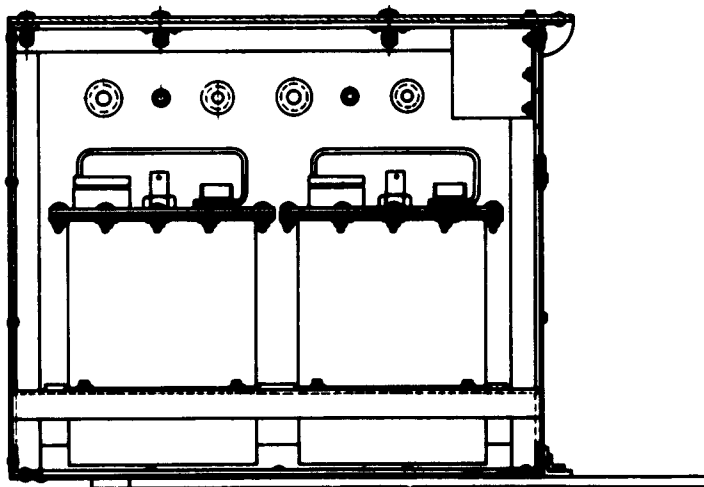


FIG. 17 5kV GENERATOR BOX

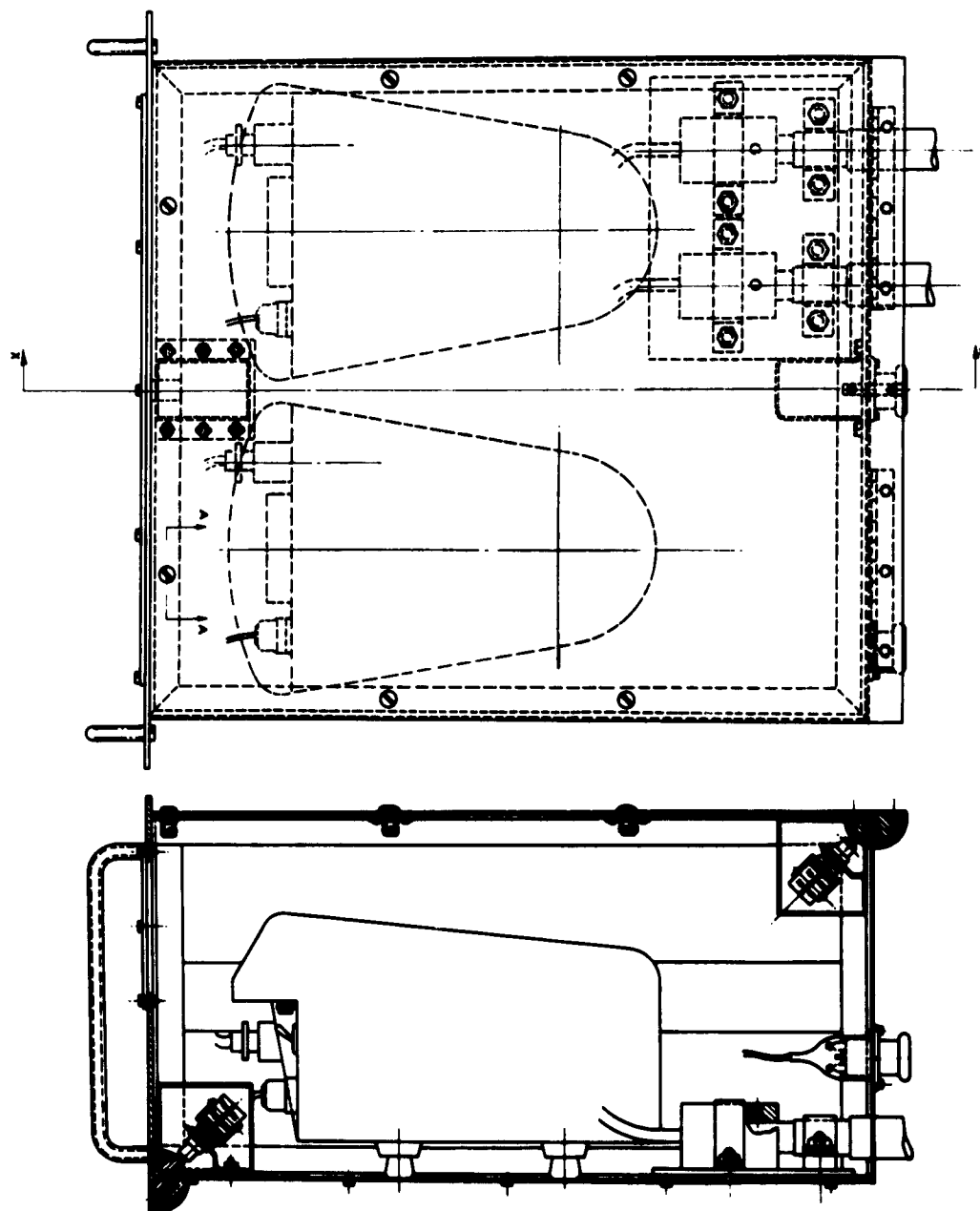


FIG.16 SCA-LAMP

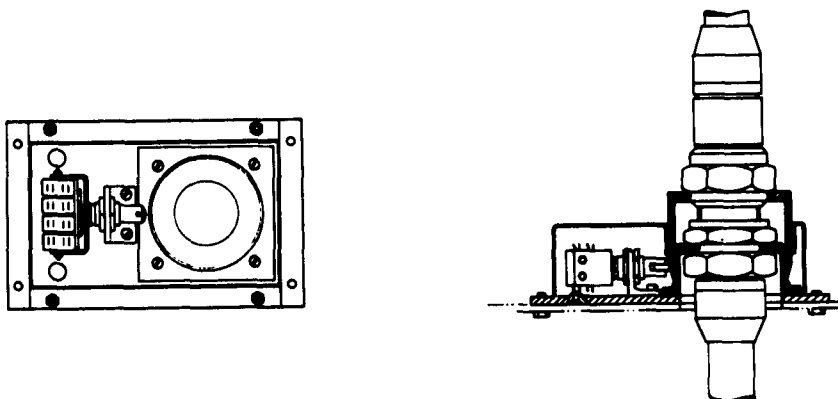


FIG.18 DOOR HINGE WITH MICROSWITCHES

The control room door was fitted with a hinge interlock operating the main contact breaker (fig. 19). This gave immediate access in case of accident and at the same time rendered all circuits safe. To prevent abuse warning bells were placed outside the door and in the tank room which operated when the mains switch was closed with the door open. Warning notices, a red light and intercommunication facilities with the control room were provided outside the door. The latter was made completely separate from the main system. Crash safety switches were fitted at control board and console.

To summarise, the control facilities have been separated from the working portion of the apparatus, partly in the interests of safety, and placed in an interlock protected room.

The facilities in the control room have been protected by nominally tamper-proof interlocks for which no overriding facilities have been provided and all of which control the mains breaker. As this controls the circuit breaker on the E.H.T. units a very substantial degree of protection is provided.

9. TYPES OF INTERLOCK USED

Apart from the standard Castell mechanical interlock, three types of interlock were used, all electrical. The most widely employed was the hinge switch based on a microswitch. A microswitch has a limited life and an automatic fault detecting system was devised. Assuming that the only form of damage is mechanical, i.e., contacts welding or a broken spring, the system shown in figure 20 is intrinsically safe.

This switch comprises two 2-pole changeover microswitches ganged mechanically. The mains is carried by the top pair of contacts which are normally closed. If both switches are not in the same state a continuous path is available through the centre contacts and this is used to operate a klaxon (fig. 21). The lowest pair of contacts is unused except in the door switch where it operates the bell circuit.

The mechanical arrangement of one of the hinge switches is shown in figure 19. The design makes tampering difficult. For example, to

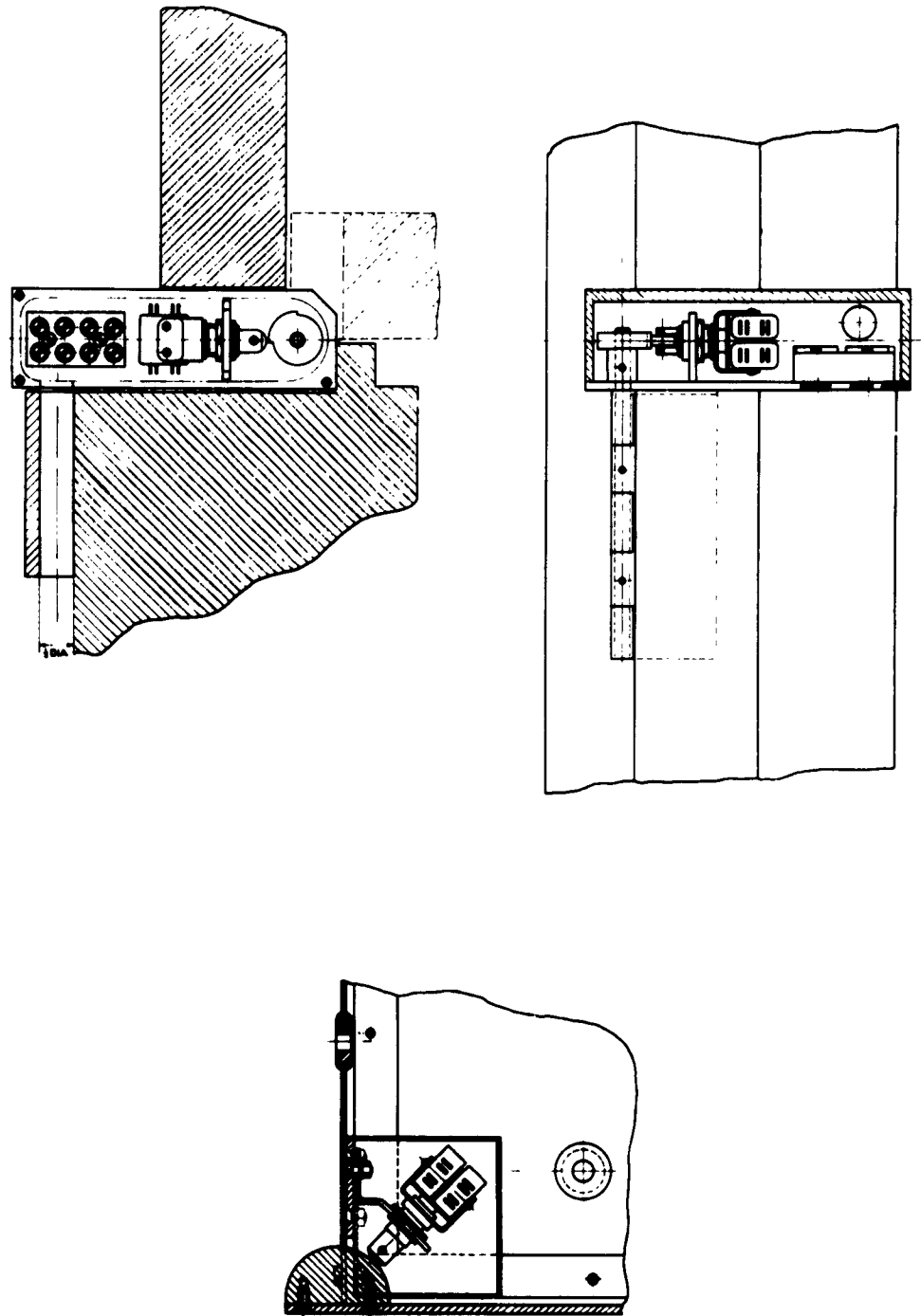


FIG. 20 CAM OPERATED — HINGE INTERLOCK



OR

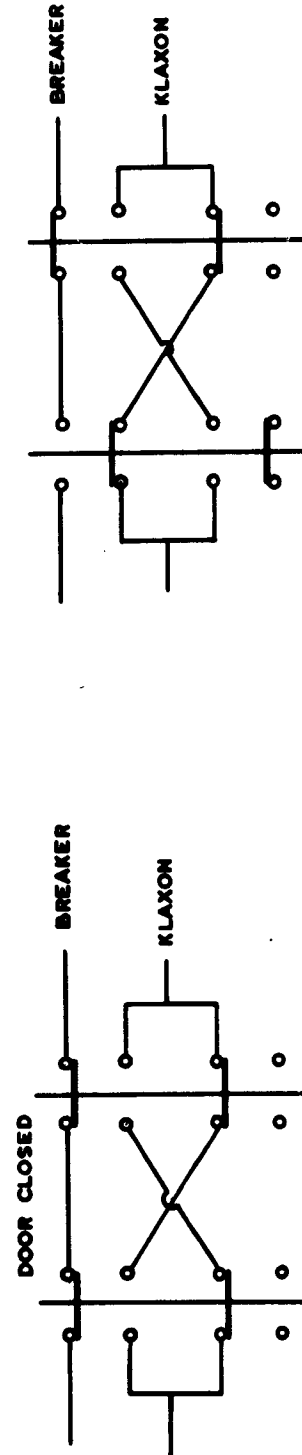
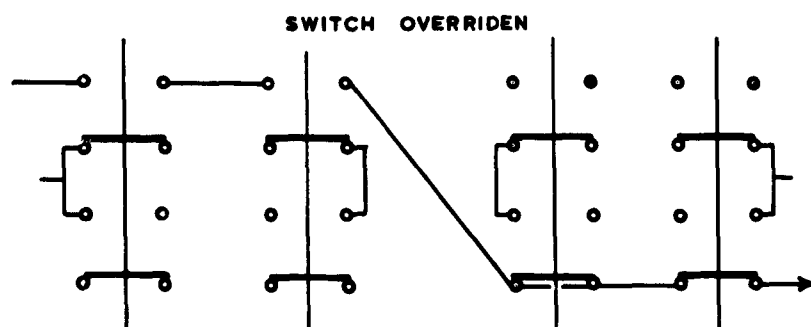
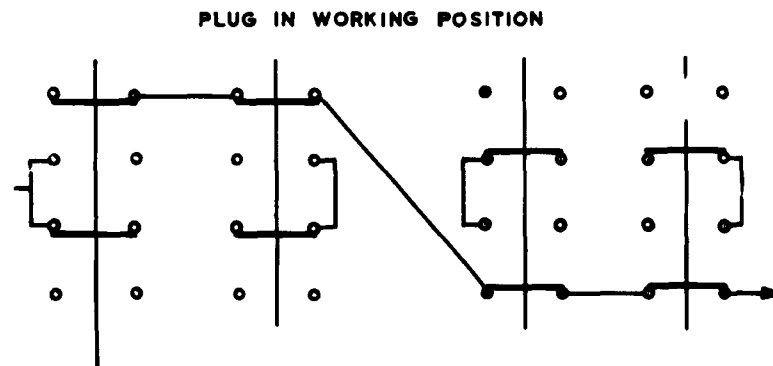
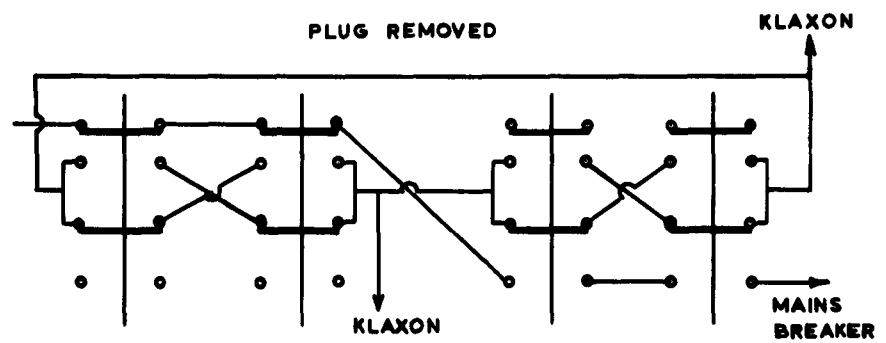


FIG.21 ACTION OF TWIN GANGED BULGIN TYPE M1 MICROSWITCHES



**FIG.22 ACTION OF QUADRUPLE CABLE INTERLOCK
MICROSWITCHES**

gain access to the control room door switch it is necessary to remove the door.

Similar microswitches are used for the plug interlock on the E.E.T. trigger generators. The mechanical design is shown in figure 18 and it can be seen that these may be countered by a less determined attack than the hinge switches. The electrical operation is depicted in figure 22.

The third type is a simple plunger switch shown in figure 9, fitted in the copper box at B. These are easily tampered with and rely on rugged construction for reliability.

10. INSPECTION

Most codes of practice stipulate regular inspection of safety interlocks by an autonomous safety section. A.E.L. has no such section and emphasis was placed on producing safety devices which really did fail safe rather than place reliance on inspection by interested parties.

This situation is far from ideal and it is suggested that regular inspections be made from outside the establishment if it is not possible to appoint a competent internal safety officer.

11. CONCLUSION

The system devised attempts to steer a course between the twin pitfalls of having to provide overriding facilities and stimulating a desire to outwit the interlocks. Experience will show if it is successful.

12. ACKNOWLEDGMENTS

This project was initiated by Mr. H. H. Margary.

The application of the basic ideas was thrashed out in discussions with the Drawing Office sections headed by Mr. Abercrombie and Mr. Harrison, Mr. Newcombe of the first section meriting individual mention for his suggestions. These sections were also responsible for the more tiresome design work.

Mr. Winter and Mr. Freeth of the Ministry of Works rendered yeoman service in translating our unusual wiring diagrams into hardware and much help was given by the latter in keeping our schemes within the spirit of the I.E.E. regulations.

A. G. H. Troughton (S.E.O.)

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A P P E N D I X

The Origin of the Earth Pulse

It is usually possible to assume that a 'good' earth will maintain at an unvarying potential although this is clearly suspect where much energy is handled by an earth return. The circuit for generating underwater sparks is represented by figure 4 and when the switch is closed a purely circulatory current flows. The earth point does, in fact, suffer a sharp change in potential and it is difficult to see how this 'earth pulse' arises.

The earth must be considered as having some impedance and it is usual to specify earths in terms of impedance to infinity. To give a numerical value, three ohms would be considered a very good earth in a normal laboratory installation. Suppose, in the case considered, that the earth resistance may be represented by a resistance r in series with a perfect earth. The perfect earth in turn is most conveniently considered as an infinitely large capacitor. Distributed stray capacitances appear across all components and these may be represented to a good approximation by lumped capacitances to earth from either side of the major components and shunting the component. A simplification which will not otherwise effect the analysis is to make the load a pure resistance without strays and replace the switch by a short circuit.

The result is shown in figure 5, Z representing the inevitable impedance between common earth point, shown as a heavy dot, and the earthy side of the condensers.

This may be simplified immediately for the scheme in figure 6 in which C' comprises $C + C_0$ and R' an impure combination of R and C_A . The circulatory current I will divide between arms A and B of the parallel network and the potential of the common earth point becomes i with respect to earth where i is given by:-

$$i = I \cdot \frac{Z_B}{Z_A + Z_B}$$

since the centre point of A is at earth potential.

The magnitude of I is determined primarily by R and condenser voltage, the rate of current rise by the circuit inductance and the decay again by R . With an infinitely slow current rise i will be zero but with increasing rate of rise the impedance of network A will fall below that of B due to the inductive component in Z . The shorter the current rise therefore, the greater the earth pulse will be.

The only element amenable to manipulation is C_0 but connecting the shields of the condenser bank to the E.H.T. line is not a very attractive proposition.

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