Circuit and Electromagnetic
System Design Notes
Note 3

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A Cheap Megajoule Bank

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1. Introduction

The bank described in this note was designed to be cheap and fast but with a limited rate of firing. The reason for this was that the experiments for which it was designed are of a one-shot nature. For instance, with multi-megagauss fields, not only is the small coil completely destroyed but also the foot or so of feed closest to it gets blown up. Thus the load has to be rebuilt between shots, so the bank could have a very low firing rate without any experimental inconvenience. This meant that solid dielectric multichannel switches could be employed even though these had to be replaced after each shot. In addition, the intended life of the bank was only a few thousand shots. A further feature of the likely loads plus their feeds was that the voltage reversal could be held to 30% or less. Even in the case of a lead short due to dielectric breakdown, such high currents and magnetic fields exist in the feeds near it that the voltage reversal is very modest. The only dangerous load from this respect is a highly inductive, relatively low current load and if these were ever to be employed it would be necessary to use clamping, or voltage derating.

Apart from the bank's rather modest price and compactness, the other features which might be of some interest to others are the new B.I.C.C. condensers used, the multichannel solid dielectric switches and the cheap, vacuum reassembled, transmission lines.

2. Electrical and Mechanical Characteristics

The bank has a capacity of 1736 microfarads, and is designed to operate up to 33 kV. It was built to have a very low inductance in order to deliver energy at a rate approximately 0.5 megamegawatt into matched loads. The measured parameters are

Units	10^{-9} H Inductance	10^{-3} ohms Resistance	10^{6} A Max.Current	10^{-6} secs. Time taken
Short at Switches	0.46	0.12	57	1.4
Short at Load Position	1.0	0.3	33	2

The cost of the bank was £30,000 and it has an anticipated life of 10^4 shots from 30 kV with 30% voltage reversal and 5 x 10^3 at 33 kV with the same reversal. It was built by four in eight months and has a possible firing rate of two per day. The cost of the condensers was then 4.8d/joule.

There are 64 condensers (BICC ES108) each 27.2 μfs rated 30 kV, with an inductance of 5 nanohenries and resistance of 1.6 milliohms. The dimensions are given in Fig. 1. The addition of a strip-line tag connector increased the inductance to 7 nH and the resistance to 3 milliohms. Fig. 2 shows the construction of the tag with the H.T. line in a Melinex loop and edge grading by blotting paper strips.

Each unit was tested by discharge into a short circuit, once from 20 kV (1.0 x 10^6 amps), three times from 25 kV (1.25 x 10^6 amps) with a subsequent over-volt to 37.5 kV. A 10 kilojoule prototype has given 1.8 x 10^6 amps (40 kV charge) three times without internal damage. In normal operation the currents per capacitor are .3 to .5 megamps and as damage is proportional to current squared at least, the testing in this respect was severe. No burning has been seen at any of the condenser couplings. (Fig. 3).

Strip-line connections have been used exclusively in the design of all the feeds used in the bank and indeed the low inductance of the condenser is only obtained when properly tabbed.

Pairs of eight unit assemblies feed a four foot long solid dielectric switch, as shown in Figs. 4 and 5.

Within the one-eighth assembly, two rows of condensers feed the edges of a square collector which is arranged as a folded loop. Current is then taken from the upper fold of the loop to the switch. The effective inductance of the condenser collector is of the order of one-third of the square - i.e. 1/3 nH.

The edges of the .025 cm copper lines have a 2.5 cm wide layer of blotting paper with an outward margin of 2.5 cms Melinex, sealed in a Melinex envelope. This edge grading on a simple plane parallel condenser has been pushed to 120 kV D.C.

Various forms of solid dielectric switch have been described in the literature, mostly working by mechanical or shock rupturing of a plastic dielectric. These essentially have a significant time delay while a shock passes through the dielectric leading to the deformation of this and eventual electrical breakdown. The multichannel switch used in this bank works by exceeding the intrinsic breakdown field of a plastic film along the edge of a thin conductor. For volumes of plastic insulation of the order of 10^{-2} cc, the breakdown field necessary to cause intrinsic failure can be as high as 7 MV/cm. However, such fields can be achieved by using a thin trigger strap; thus a trigger electrode edge of radius .0003 cm. need only be taken to 5 to 10 kV positive with respect to its surrounding electrodes to achieve such a field, providing the edges of the electrode are sealed by greases or liquids against corona discharge which can otherwise grade the field. The reason the positive voltage is desired is that the breakdown of plastics is polarity dependent and the positive edge breaks down more readily than one with a negative polarity on it. Prior to the application of the triggering pulse, care must be taken that the thin metal edge does not depart sensibly from the voltage which the geometry of the switch requires. Owing to the very low energy requirements of the switch (for a single switch a few millijoules suffice to operate it) even a modest corona discharge spikes can cause it to operate prematurely.

In the case of a multichannel switch, a fast pulse is injected up the transmission line formed by the trigger strap and its adjacent electrodes, which causes breakdown but owing to the resistive phase of the solid dielectric breakdown channel, the erosion of the pulse front is relatively slow and as a rather hefty trigger pulse is generated by the trigger circuits, many breakdowns can be obtained along the edges of the trigger electrode. However, the current in these channels is unstable and a series of essentially small stabilising resistances are included in the switch design. The most important of these are the rather thin aluminium electrodes, which are replaced with the plastic, and the intentionally introduced air gap between these and the permanent brass electrodes. Without these many breakdown channels may be formed but the current may still flow through only a few, with resulting electrode metal blow up at the arc root in the brass electrode, which for these high currents can result in considerable electrode damage. The air spaces on either side of the replaceable parts of the gap also allow the current to spread before it reaches the permanent electrodes.

The four solid dielectric switches (each 120 cms long) are triggered by a four-legged Blumlein circuit also energised by the bank power unit. This produces 30 kV pulses with 2 nsec rise time across the trigger line of the switch. Mismatch of the Blumlein to the tapered switch trigger line enhances the voltage spike to 50 kV maintained by the trigger taper.

The switch assembly consists of a trigger strip .00062 cm aluminium between a .005 cm and .012 cm Melinex layer, with .012 cm aluminium strips of foil on the outer surfaces. The switch is assembled with MS704 Silicone Oil to exclude air. Either breakdown occurs directly in the plastic or streamers develop at the field-enhanced edges of the trigger strap, and propagate in the oil to subsequently break the overstressed Melinex. The finite time of the resistance phase of Melinex breakdown allows the pulse energy to remain during propagation, resulting in a large number of breakdown channels. (Fig. 6).

When the switch is used with a 1 mm air gap either side of the triggered switch, the arc channels stabilise to give uniform arc densities and even electrode attack and typically this switch has 1 arc/cm - i.e., in our case, some 500 arcs.

The resulting low current density allows the use of light, easily replaceable switch electrodes. The overall configuration of the bank is illustrated in Fig. 7.

All the feed lines in the bank are in the form of transmission lines and the current density can rise as high as 100 kA per cm. The magnetic pressure from such a current can rise to pressures of the level of a thousand atmospheres or more and even though the impulse is fairly small, owing to the short duration of the pulse, it is difficult and expensive to restrain the motion of the electrodes mechanically. In this bank the current carrying electrodes were made out of annealed copper of .025 cms thickness and this was backed by 0.3 cms of lead to reduce the energy imparted to the metal sheet. Considerable care was taken to avoid mass discontinuities in both the copper and the lead backing, otherwise different velocities could be applied to adjacent areas, leading to tearing along the mass discontinuity. The reason that a relatively floppy electrode was constructed was that a weak D.C. pressure applied uniformly via a sponge rubber backing could squeeze the air space between the metal and the Melinex down to a few thousandths of a centimetre. Thus when the current pulse has passed and the electrode flies up, the gas pressure here rapidly falls to a small fraction of an atmosphere and the instant vacuum so created stops the electrode and reassembles it after a flight of a fraction of a centimetre at most. Since the motion is lossless, the metal returns with essentially the original momentum imparted to it and a strong flat shock moves into the insulator as it hits. This eventually leads to rarefaction or tension waves in the Melinex which can cause spalling and subsequent electrical weakness if precautions are not taken. In this bank the solution adopted takes the form of using multiple layers of insulator, i.e. by the intentional introduction of planes of zero tension strength.

An investigation of Melinex electrical breakdown suggested a relation between the single shot breakdown stress and the chosen peak to peak stress level as a power law:

$$\text{Life} = \alpha \left(\frac{\text{Single shot breakdown stress (Pk-Pk)}}{\text{Working stress (Pk-Pk)}}\right)^{7\,1/2-8}$$

where α is volume dependent.

The main insulation was hence chosen to be .052 cm Melinex. In practice this was 7 x .0075 cms, which should take ~10^5 full voltage firings.

Prototype clump construction of the structure was checked on a one-eighth assembly. Each quarter was fired into a short circuit to obtain parameters. The whole structure was also overvolted to 36 kV.

Measurements of current are obtained from a .05 milliohm series resistor some 300 cms long built into the earthy lower conductor of the main bed. From a knowledge of the initial charging voltage, the value of maximum current is derived by waveform analysis. Four independent oscilloscopes (Mk. 2C) monitor the IR voltage (of the order of 100 volts) directly at the tube.

Calibrated (electrically) pick-up loops of defined cross section are also used to plot current density variations in experiments; signal levels are maintained at 100-1,000 volts.

The bank is fail-safe with nine independent dump resistors ($CuSO_4$ solution), each capable of absorbing the entire 1 megajoule. The bank earth is isolated from the laboratory by 12.5 ohms, and all associated circuits (including the 15 kVa charging system) are fed via chokes.

By alterations of the main bed triggering, the bank may be operated ± 33 kV, but this has not yet been necessary.

3. Operating Experience to Date

After the initial work on one-eighth of the bank, the quarter clusters tested out satisfactorily without any trouble. In addition the same techniques have been employed to build compact 100 kilojoule banks which have given reliable operation. The experiments performed to date have not yet required the bank as a whole to operate to full volts, but a number of firings have been performed at 25 kV and various fractions of the bank have been operated at the full voltage. The difficulties experienced to date have been mainly in the feed area, where dirt from the load can be propelled or sucked up the transmission line between the electrodes. When these electrodes are reassembled by atmospheric pressure any dirt is hammered into the Melinex and leads to electrical breakdown on the next or subsequent firings. Dirt and metal particles can also be injected from the solid switches and extra sheets of folded-back thin Melinex are incorporated in these to catch this debris. A mishap of a different nature occurred once when the bank was being dumped without being fired. Unbalanced voltages developed in the Blumlein circuits, leading to the trigger voltage being moved badly off-balance, and one of the switches fired in a single place. This led to an unintentional part firing of the bank and considerable damage to the electrode at the point where the single breakdown channel occurred. This was cured by paying attention to the different time constants in the various parts of the system, so that satisfactory voltage division at the switches was maintained. Apart from these effects, the bank has been satisfactory and for its cost and size has represented an economical solution to the experimental requirements.

Acknowledgments

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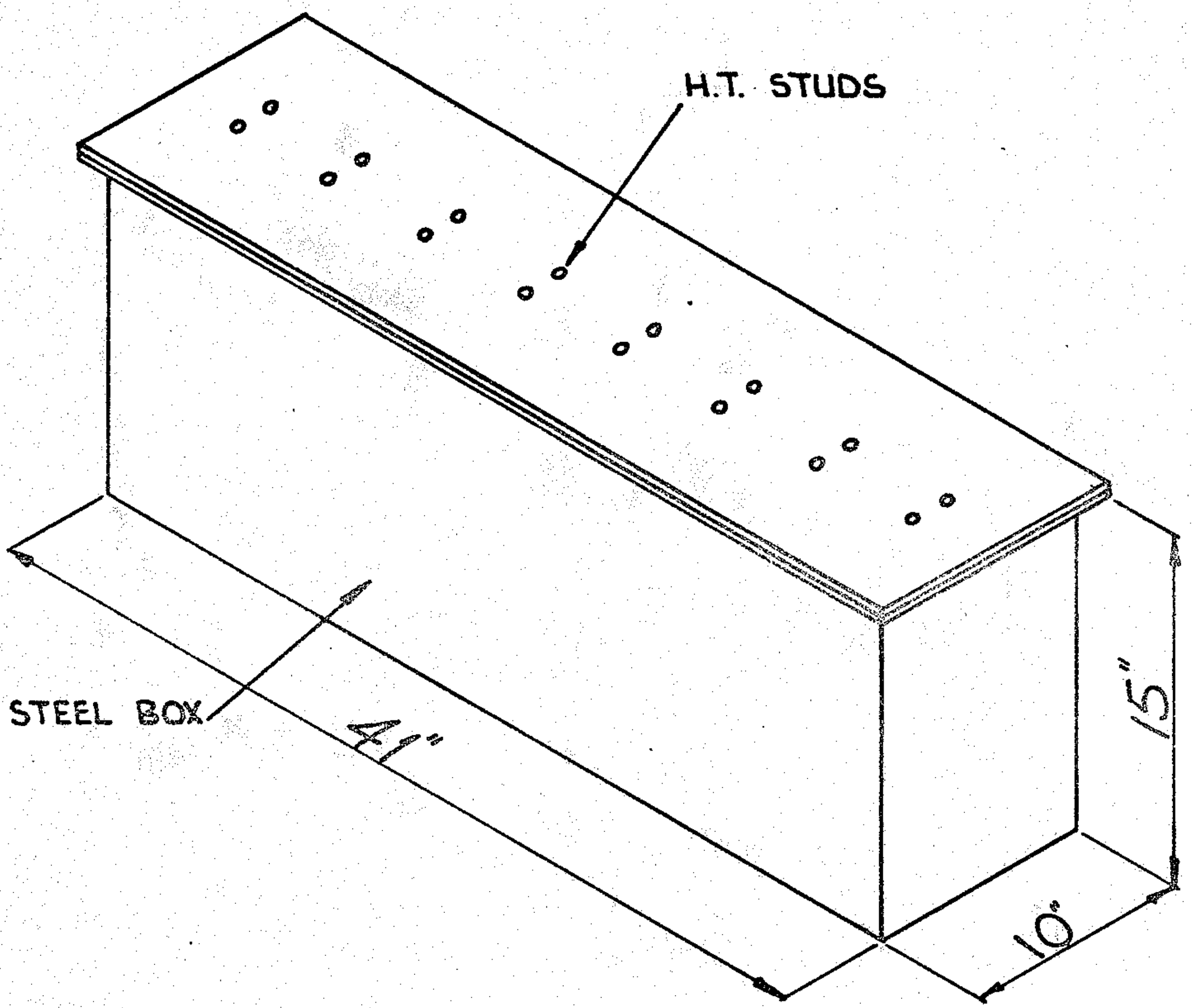
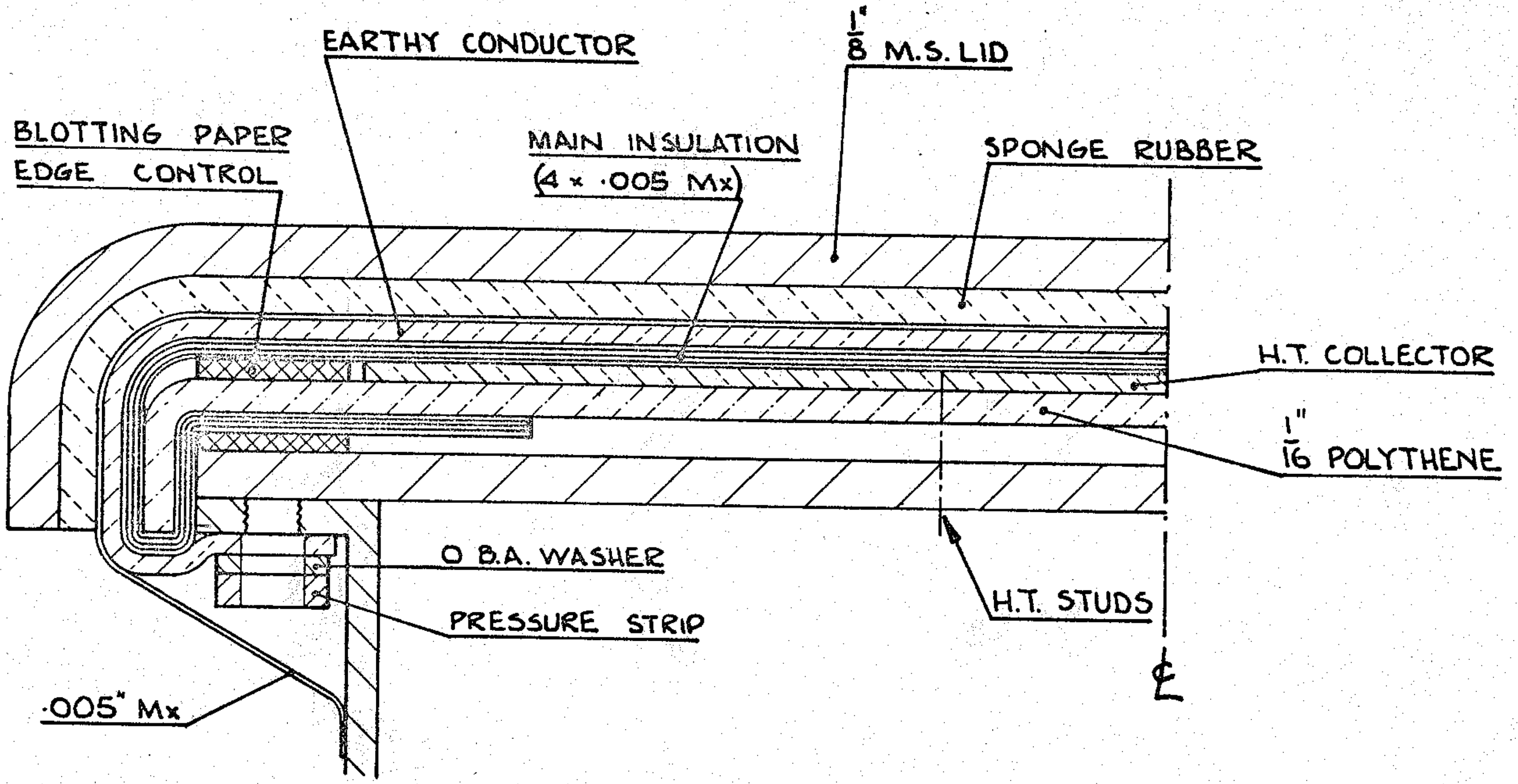
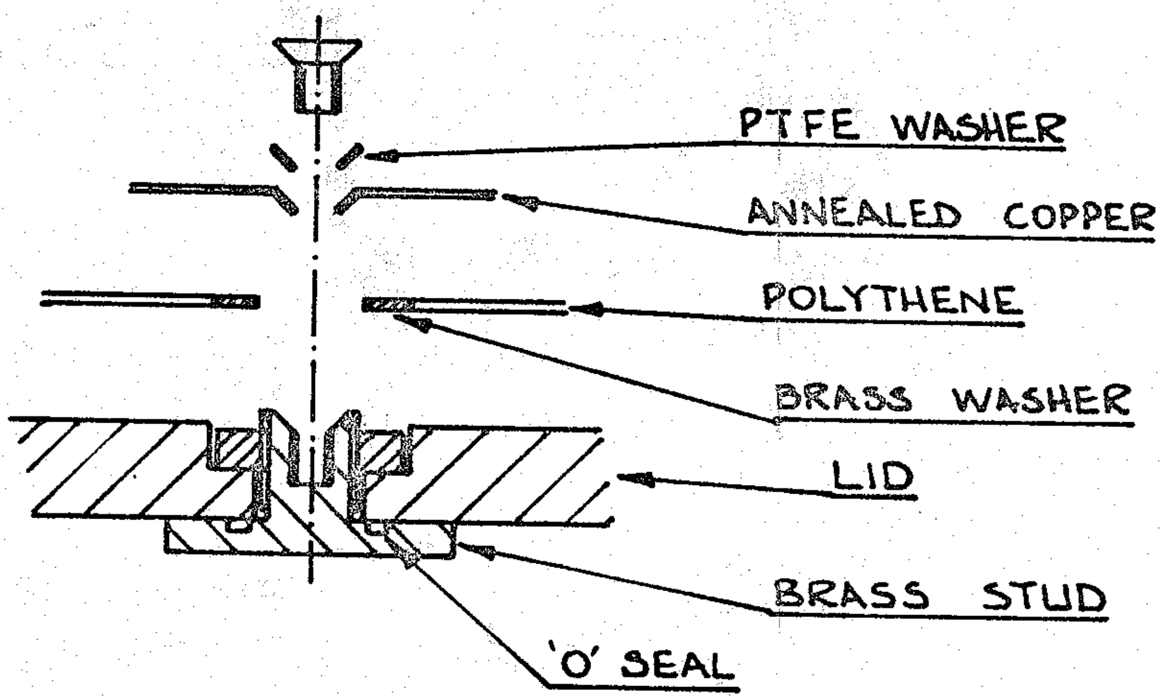


12·5 KJ (30KV) UNIT
BICC ES108 PAPER/CASTOR OIL
FIG. 1



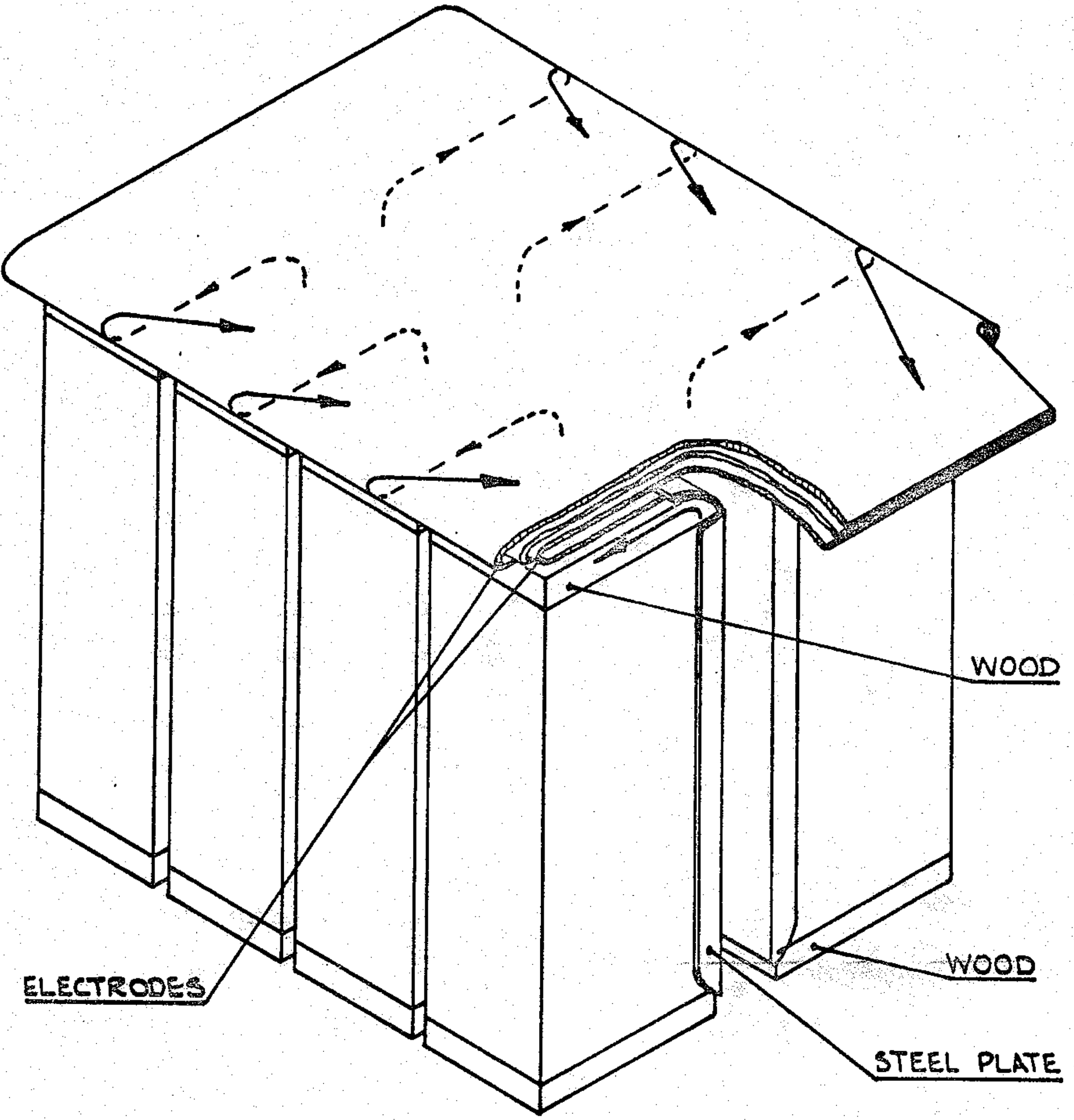
SECTIONAL VIEW OF CONDENSER AND TAG

FIG. 2


PTFE WASHER
ANNEALED COPPER
POLYTHENE
BRASS WASHER
LID
BRASS STUD
'O' SEAL

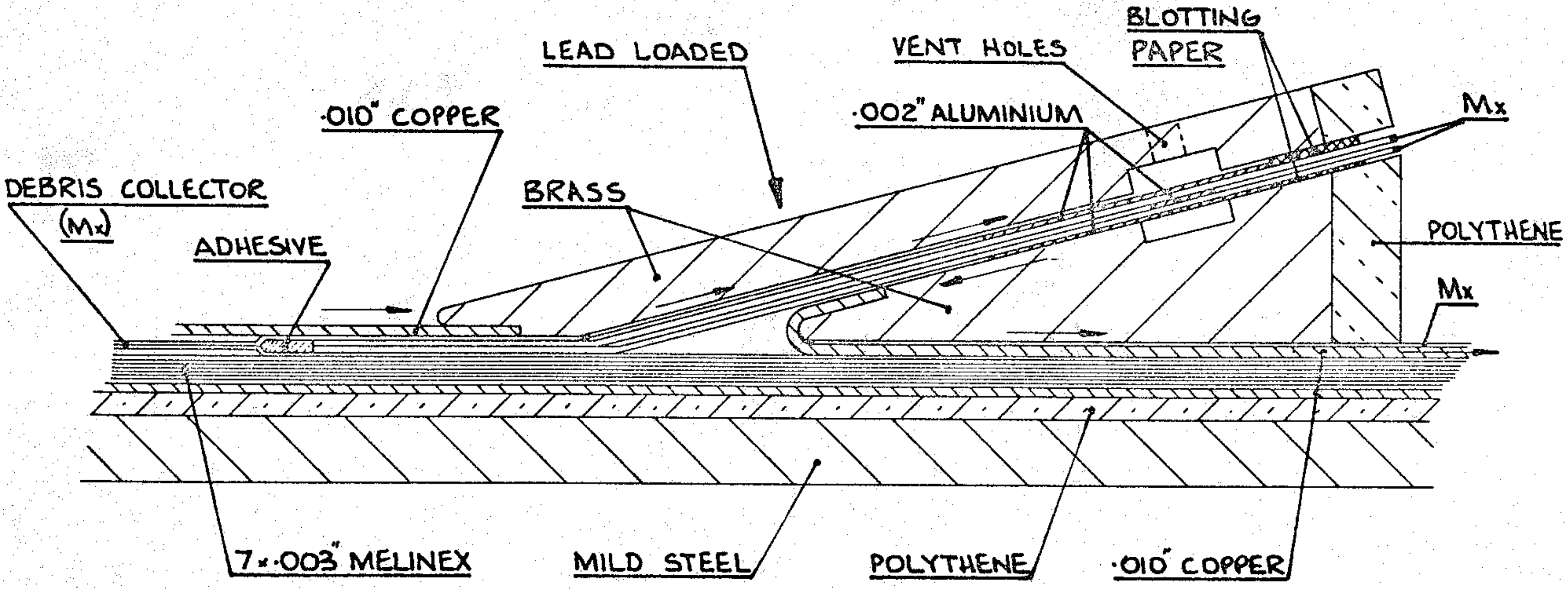
H.T. STUD

FIG.3



$\frac{1}{8}$TH ASSEMBLY

FIG. 4.


DEBRIS COLLECTOR (Mx)
ADHESIVE
·010" COPPER
BRASS
LEAD LOADED
·002" ALUMINIUM
VENT HOLES
BLOTTING PAPER
Mx
POLYTHENE
Mx
7×·003" MELINEX
MILD STEEL
POLYTHENE
·010" COPPER

SWITCH
FIG. 5

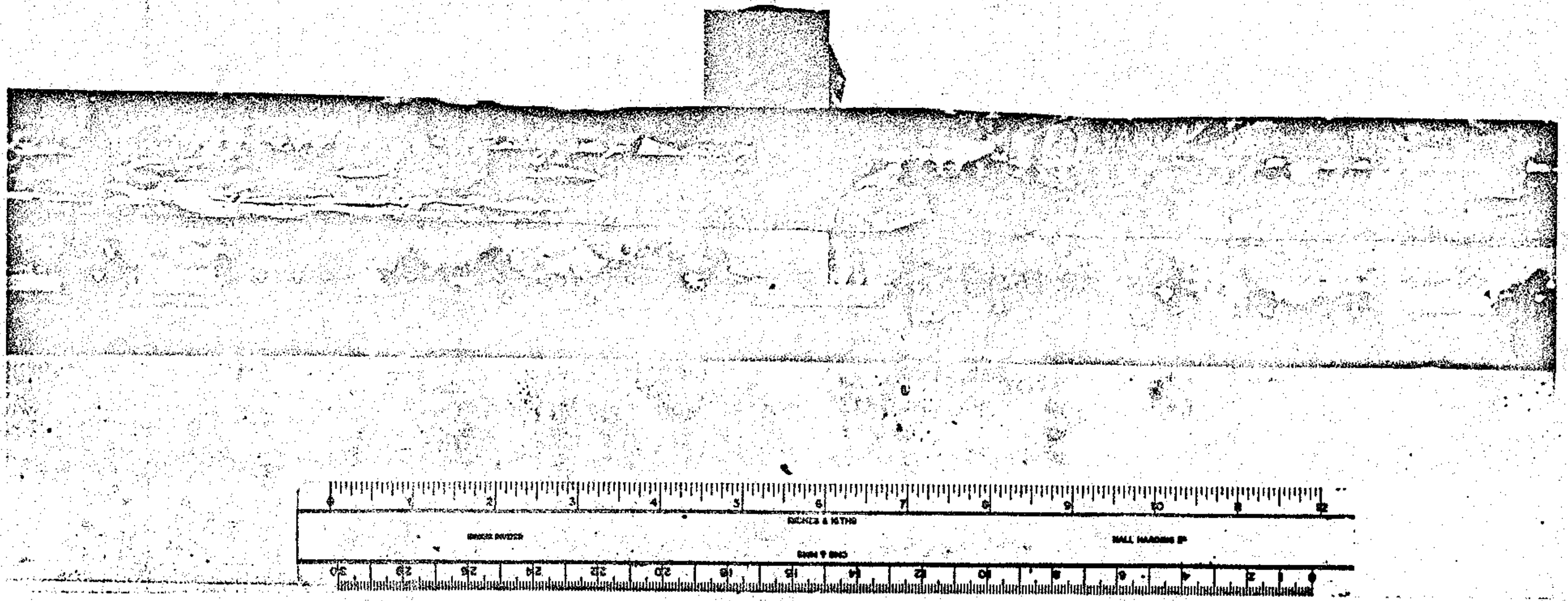


Figure 6

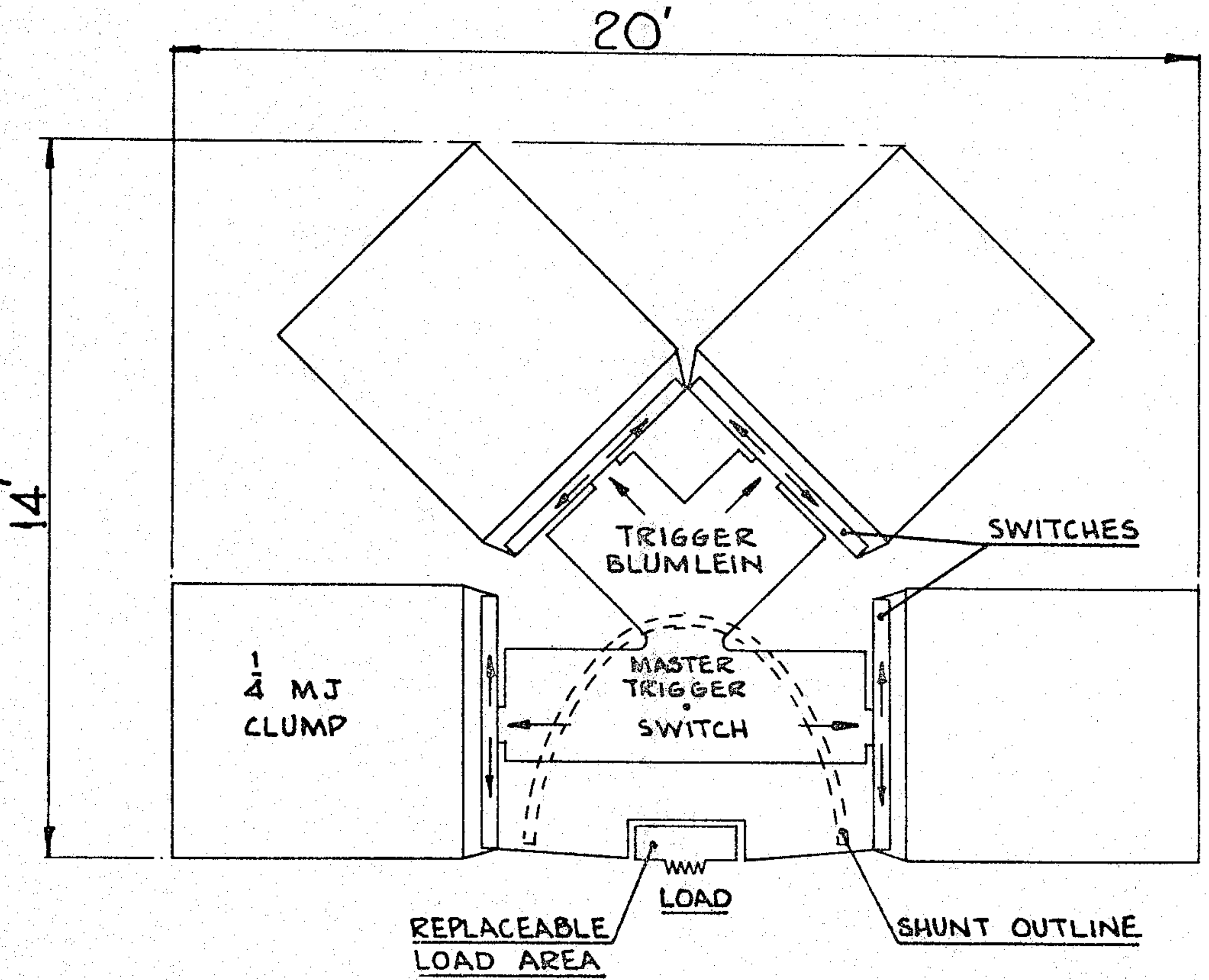

20'
14'
TRIGGER BLUMLEIN
SWITCHES
1/4 MJ CLUMP
MASTER TRIGGER SWITCH
LOAD
REPLACEABLE LOAD AREA
SHUNT OUTLINE

FIG.7