Fire Research Note No 1074

USE OF NITROGEN-FILLED HIGH EXPANSION FOAM TO PROTECT A 500-TONNE FUEL TANK

by

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August 1977

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SUMMARY

An aviation fuel storage tank was filled with nitrogen foam to observe foam behaviour and particularly oxygen contamination in aged foam. For comparison, gas inerting with a stream of nitrogen was included in the test series. In one test a hot cutting procedure was monitored for void formation and oxygen contamination of the foam.

The tests showed oxygen contamination was low in foam up to 3 hours old. Voids and oxygen introduced by hot cutting were, in these tests, rapidly purged. The use of foam enabled the tank to be inerted using less nitrogen than with the gas alone, with the additional advantage of visual indication of the inerting medium.

Department of the Environment Fire Research Station of the
Building Research Establishment

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INTRODUCTION

Tanks which have been used for storage of flammable liquids may present a major hazard when their repair or demolition is required. The hazard may be continuous as with volatile liquids or it may arise during operations, notably by the decomposition of solid residues by a hot cutting torch. The problem may arise in a wide range of occupancies, but is particularly severe with fuel storage facilities, chemical plant, and industries where flammable solvents are used.

A number of methods are available for safe working in repair or demolition of tanks but all have limitations. The safe methods are: avoidance of hot working, removal of flammable materials, or removal of air within the tank; in practice more than one method may be required to be used. If air is not to be removed from the tank, then either all traces of flammable material must be removed, to permit hot working, or the freely available flammable material must be removed prior to cold working. Cold working has practical disadvantages in that it may be slower than hot working, skilled manpower for it may be less readily available, and certain types of repair activity cannot be undertaken. Removal of flammable material can also be time consuming, particularly where tenacious residues are present and where special constructions may have to be put inside the tank to clean the less accessible surfaces, eg the underside of the roof. Obtaining protection by removal of air, that is by introduction of an inert gas, avoids some of the labour-intensive requirements, but operational difficulties may be encountered particularly on large tanks. Ensuring that the whole of the atmosphere within the tank is safely inerted, both at the beginning of the operation and during its progress, when openings in the tank may be formed, can become difficult and would require expertise in gas analysis. There remains a need for an inerting method which requires simple criteria to describe safe conditions and which will cope effectively with hot cutting procedure.

A relatively new and promising approach uses high expansion fire fighting foam with an inert gas as an inerting medium. The advantages of the method are:

1. Positive displacement of flammable vapours from within the tank
2. Visual indication of the inerting medium
3. Possible suitability for hot cutting, subject to rapid replacement of foam destroyed by the heat.

A full investigation of all aspects of the technique was not possible, with the resources currently available, so with the large fuel tank which was available for experiments, the investigation concentrated on the following aspects:

a. to investigate whether a large tank could be satisfactorily filled with high expansion foam, without forming large voids within the volume or on the underside of the roof;

b. to establish that foam stability was sufficient to enable the tank to be filled at an acceptable rate;

c. to examine the extent to which air (oxygen) could penetrate the top surface of the foam in the tank and thereby dilute the nitrogen which originally formed the bubbles. Conversely, the extent to which nitrogen from the bubbles would dilute air above the foam layer could also be examined;

d. to study the effect of hot cutting of the metal of the tank on adjacent foam and whether large voids would be opened up in the process;

e. to compare the inerting provided by the foam with that due to the introduction of nitrogen gas alone.

In addition to the aspects studied in the present work, other factors are of practical importance and should be considered in relation to the widespread adoption of the technique. In particular, the rate at which flammable vapour can diffuse through the foam must be taken into account, and the behaviour of solid deposits of relatively low ignition temperature may also be important. The present work was aimed at answering those questions which were particularly applicable to the large volume tank which became available for the experiments.

For technical and economic reasons the usual choice of inert gas is nitrogen, although carbon dioxide, inert gas from burners, and even argon may be used as conditions require.

The synthetic foaming agents used for high expansion fire fighting foam, normally filled with air, are applicable to the inerting process. The requirements for foam for inerting are:

1. Good fluidity for reaching corners, purging pipework, etc, although in special circumstances a 'stiff' foam may be required.

2. Low drainage rate, since drained foam is likely to be

   a. less fluid

   b. more susceptible to contamination by diffusion of flammable vapours.

3. Reasonably dry, to minimise losses while hot cutting.

4. Commercially realistic.

Conventionally, foams are characterised by expansion ratio and drainage rate. For the present exercise expansion ratio has some effect on ease of hot cutting while drainage rate may reflect problems of increasing stiffness and vulnerability to contamination. However a quantitative description of fluidity was desirable. A foam generator suspended above a clean flat surface will normally form a conical heap of foam. In this exercise the base angle of this cone (the repose angle) was estimated but two problems were presented:

a. a foam with low repose angle in bulk may present a relatively steep angle as its leading face moves across a surface;

b. the surface of foam is usually uneven and, on small quantities, it may be difficult to decide on a mean value.

Since nitrogen foam inerting has been used on a commercial scale the present programme of tests aimed to examine, in more extreme conditions, some of the factors discussed above. In particular there was concern over the problem of limited access for foam relative to tank volume, as this is one situation which leads to aged foam with associated problems of drainage, stiffness and contamination.

TEST PROGRAMME

The final choice was influenced by tank availability and size, costs, staff available etc as well as the technological aspects. The series thus became

1. Gas inerting to provide a basis for comparison (nitrogen).

2. Filling with foam from the top of the tank with a target fill time of 2 hours.

3. Filling with foam from near the base of the tank with a target fill time of 2 hours.

4. Filling with foam from the top with a target fill time nominally 5 hours.

The generation of foam is largely based on empirical procedures and, on the scale of these tests, requires considerable support facilities. The services of contractors for foam generation were therefore employed.

DESCRIPTION OF TANK

Given that the scale of these tests was intended to be realistically large, the choice depended on tank availability. By courtesy of the Property Services Agency a cleaned disused aviation fuel tank was made available on a former airfield. This was an above-ground steel tank 14.6 m (48 ft) diameter with cylindrical walls 3.7 m (12 ft) high and a conical roof 4.6 m (15 ft) above base at its peak. Capacity was thus around 670 m^3 (23,500 cu ft) (Fig.1). For foam access a number of 0.61 m (2 ft) diameter manheads were available. For a base fill one near ground level was chosen; for a top fill one in the roof but close to the wall. A 15 cm (6 in) manhead near the peak of the roof served as principal vent.

The tank was surrounded by rough soil but, about 23 m (25 yd) away, hard standing was available for vehicles, storage tanks etc. Recording and control were centred in the caravan on hard standing (Fig.2).

As a basis for design for monitoring the tank during a foam filling exercise it was assumed that a void not exceeding 1% of tank volume could be tolerated. This figure is the highest desirable since under the worst conditions an explosible void of this size might lead to tank disruption. However, the exercise is essentially aimed at producing information relevant to industrial conditions rather than guaranteeing comprehensive safety of an actual hazard. The 1% criterion corresponds in the present tank to the equivalent of a 1.8 m (6 ft) cube and would require at least 150 sampling points for full coverage.

The basic criterion for safety is the absence of an explosible atmosphere. However gas analysis on the scale implied above would be very demanding on equipment and time. In the light of equipment available, gas analysis covered 27 sampling lines; these could be moved upwards as the fill progressed. These gas analysis lines were supplemented by foam detectors which, in conjunction with gas analysis, may be used to infer safe conditions. On the assumption that a source of ignition would arise only external to the tank, eg sparks from a cutting torch, foam detection points were confined to positions close to the walls and roof with an inner ring to allow for spark penetration.

EXPERIMENTAL

Foam characteristics: it was impracticable to determine foam characteristics reliably on the exposed test site. Preliminary tests at Fire Research Station, Borehamwood, had shown that the larger of the generators used (designated 12 in) produced foam with expansion ratios from 115 to 300 and half drainage times from 4.2 to 25.5 min. These figures do not correspond to each other and there was no simple relationship between generating conditions and foam characteristics. Operational conditions at the site were not identical but if differences are discounted then, based on the laboratory tests, the expansion ratio was probably in the range 120-180 and the half drainage time was of the order of 20 min. For a fill from the base the back-pressure of foam may have affected the characteristics somewhat. Again although conditions were different the small (designated 4 inch) generator used for most of the last test probably produced foam of similar expansion ratio and drainage rate.

Gas analysis

For oxygen determination, paramagnetic oxygen meters with a recorder outlet were used. With the aim of filling the tank in two hours or more a determination at each sample location at 10 minute intervals seemed adequate. A sample rate of one per minute per meter was allowed. These factors led to the construction of 3 banks each containing 9 sample lines of 6mm bore mild steel with a tenth line to fresh air for frequent calibration checks. A diaphragm pump was used to transfer the samples. The appropriate line was chosen by opening a solenoid valve operated by a 'master' cam timer on a 10 minute cycle. As the air/foam interface was the principal interest, provision was made to move the sample points vertically as the fill progressed. Each bank was arranged as a 3 x 3 matrix horizontally and vertically. One bank of 9 was allocated to three points of the 'quadrant' while the other two banks were used to sample one 'quadrant' more intensively (Fig.3). Part of the intensive sampling framework can be seen in Fig.4.

To remove foam from the gas sample two stage foam breakers were used (Fig.5). Each compartment contained 15 cm^3 of de-foaming agent and the design allowed any large accumulation of foam liquid in the first compartment to siphon itself out when the de-foamer was not on line.

Since the sampling required physical removal of foam, channelling through a thin layer of stiff foam to atmosphere could lead to spuriously high oxygen readings. With possible exceptions in the last, there is no evidence of channelling during these tests.

One of the gas sampling banks is shown in its weatherproof housing in Fig.6.

Foam detectors

Two varieties were used: one depending on the electrical conductivity of foam and the other on its optical absorption.

Conductivity plates: These comprised a pair of 10 cm square copper plates, parallel and separated by 10 cm to form a conductivity cell (Fig.7); the outward facing surfaces were painted to provide insulation. The electrical cables were also the means of suspension. In operation 12 V DC was applied across the selected pair of plates and the current measured. (DC was found preferable to AC as problems due to polarisation were less than those to capacitance). The plates could give rise to spurious readings if mounted close to metal walls or fittings. They do provide a comparative indication of foam condition but quantitative interpretation would only have been possible if

a. the foam liquid was of constant known composition
b. the relationship between conductance and drainage (which may not be linear) was known.

As a check on continuity of foam between successive pairs of plates the input potential was also applied across one plate each of successive pairs. Because of their simplicity the conductivity plates were used to give coverage to approximately 1% void detection.

Optical detectors: To supplement the conductivity plates, photoconductive cells were used in conjunction with a light source (Fig.8). The 12 V 0.1 amp light bulb was mounted in a lampholder with clear domed cover. An enclosed light path was directed to one bulb by acrylic tubing and a second path, open for half of its length, directed to the second cell. The cells formed two arms of a Wheatstone bridge completed by two sections of a small trimmer resistor external to the tank. With no foam present the bridge was balanced. When foam penetrated to the open light path the bridge was unbalanced to give a potential of 1-2 V. No quantitative interpretation of results has been attempted but foam movements caused output variations. The optical detectors may be mounted close to walls, trusses etc and were used to supplement conductivity plates in the shoulder and roof of the tank. One set of five was suspended across the tank to give a general picture of foam movements.

Recording system and tank layout

Groups of 5 or 10 were adopted for all systems. Continuous recording of all sample points was not practicable and, fortunately, not necessary. The core of the system was a single pen chart recorder set to a 0–10 mV range since this range corresponded to full scale deflection on the oxygen meters. The input was controlled by banks of relays. Each recording cycle was triggered by a cam on the master timer.

1. Oxygen analysis: the output from each meter was fed successively to the pen recorder for a second or so towards the end of the minute sampling period. The position of the corresponding valve opening was noted manually but since only one note of this per test was needed, the system was virtually fully automatic.

2. Conductivity plates: these were arranged in groups of 5; with 3.7m tank height this allowed a 0.9 m vertical separation between each pair. With 10 sets of 5 distributed round the outer (wall) ring the horizontal spacing averaged 4.6 m. A second ring of 10 was arranged 1.8 m from the wall. In the roof two sets were paired to give a ring of 5 close to the roof and a second ring 0.9 m vertically below. The full layout is shown in Fig.9 and a general view of the tank in Fig.10. Distribution of points was uneven because the tank was found to be reinforced by 11 roof frames. These provided convenient supports for equipment but re-design to modules of 11 was not practicable. In each case two sets of 5 pairs were wired to a 20 way plug which was mounted on a board near the recorder. (Cables were thus up to 43 m (140 ft) long to reach from tank to recorder). To record a specific set a flying socket, connected via relays to the recorder, was pushed onto the required plug. Associated with the 20 way plug was a miniature coaxial socket across which a fixed potential (in the range 0–10 mV) was applied. This supplied a means of identifying which set was plugged in.

3. Optical detectors: Four connections were required for each detector; two for the 12 V power supply to the bridge and bulb and two for metering bridge balance. Thus one set of five detectors occupied a 20-way plug. A similar selection system to that of the conductivity plates was designed but in the time available only two sets were mounted. Of these one set was that suspended

1.2 m above the tank floor along a diameter to monitor foam movements. This was permanently attached to 5 channels of a 6-point rapid response recorder. The other set was, in practice, checked on the computer-data-logger system though facilities existed to record on the pen recorder.

4. Relay system: A bank of relays to regulate access to the pen recorder was provided for each detection system. The circuit (Fig.11) arranged that as one relay switched off, its successor was switched on until the cycle was completed. The cycle was initiated by closure of the switch of 1 of 10 cams on the master timer. This switching led to successive monitoring of the outputs from the 3 oxygen meters, 10 pairs of conductivity plates (which, inclusive of cross-linking of plates, led to 18 outputs) and 5 optical detectors. It is perhaps worth emphasizing the difference of relay function. For the oxygen meters and optical detectors each relay allowed a potential, which existed continuously, to be applied to the pen recorder. For the conductivity plates they switched a 12 V DC supply to the selected pair of plates. The current was then determined by the potential drop across a standard resistor which was continuously in circuit. To avoid a partial short circuit of the oxygen/optical inputs an additional relay was necessary to switch out this resistor while the oxygen/optical inputs were being measured.

RESULTS AND DISCUSSION

Gas inerting: Test 1

Nitrogen was introduced via a diffuser near the base of the tank. Owing to the difficulties with a heat exchanger, flow rate was not constant throughout the period. However, the obvious feature of the results was the virtual absence of a concentration gradient within the tank. The extremes found for two sampling positions are shown in Fig.12. Because of nitrogen supply problems the purge was not completed to normal operating levels. The volume of nitrogen used was quoted as 1270 m^3 (45,000 cu ft) ie almost 2 tank volumes.

Using the relationship for perfect mixing $c = c_{max}\, e^{\frac{-tv}{V}}$ where

c = final oxygen concentration

c_{max} = initial oxygen concentration (21%)

t = time (hr)

V = tank volume m^3

v = purge rate m^3/hr

then the final oxygen concetration to be expected is 3.0% (cf 4.9% average for 8 sample points).

Foam inerting: Test 2

Top filling with the 12 inch generator was used with a target fill time of 2 hours. The stream of foam was continuous and spread rapidly and evenly across the tank. The repose angle of fresh foam was 10–15° from horizontal with a leading edge 0.6 m (2 ft) high of rather steeper angle (30–60°). As the gas analysis shows (Fig 13) very little air diffused into the foam and there is only slight dilution of air above the foam by nitrogen.

Foam inerting: Test 3

Base filling with the 12 inch generator was used with broadly comparable results to the first fill. Simulated columns with hardboard surfaces 230 mm (9 inch) square cross-section were installed and as can be seen from the photograph (Fig 14) foam flowed round to leave an almost indiscernible 'valley' in one case and a visible but shallow valley on the second.

There was a failure of water supply for 20 min during the fill and a subsequent instability of foam supply for a time. Typical gas analyses are shown (Fig 15).

When the tank was full of foam after a total period of 145 min an oxyacetylene torch was used to cut the tank. This was synchronized as far as possible with the gas analysis system. At the analysis point close to the cut, oxygen concentration rose to a level of 6% and may have been still rising when the analysis cycle moved on. However, the other sampling points to either side and those 1.8 m from the wall showed no perceptible rise and, at the next cycle, concentration was again close to zero at all points. As can be seen (Fig 16) foam moves quite closely behind the flame to purge any void. To ensure safe conditions the foam generator was used to maintain the level of foam in the tank. A more detailed study with a purpose-built analysis system is desirable.

Foam inerting: Test 4

The foam provided from the 4 inch generator for this top fill test did not descend as a continuous stream. This would be undesirable in practice because

a. descending, separated clouds of foam may generate electrostatic charges
b. tank atmosphere may be occluded in the mass of foam.

As the fill progressed, foam breakdown increased correspondingly. After 3 hours a layer 1.2 m (4 ft) had formed across most of the tank but progress had become very slow. Repose angle of the bulk foam was again only a few degrees but the leading edge was high and steep (say 60°).

The 4 inch generator was removed and the 12 inch generator in base fill position was used briefly with the intention of pushing the old foam to the main gas analysis system. The oxygen concentrations for 3 analysis points showed $\leqslant$ 1.5% oxygen while the fourth, which was arguably most susceptible to sample channelling, showed 3-4% oxygen. Typical results are shown in Fig.17.

Foam behaviour: general

1. The output from the suspended optical detectors showed a continuous ripple indicating foam movement while foam generation proceeded but with relative quiescence when foam supply ceased.

2. The conductivity plates showed

   a. that while the wettest foam was most frequently found near the bottom, it could also be found half-way up the mass of foam

   b. that foam near the top or, for the slow fill, near the outside edge, might lose at least 95% of its electrical conductance. Despite this it appeared still to offer a useful barrier to oxygen diffusion.

FUTURE REQUIREMENTS

Weighing estimated costs against benefits a future programme might include the following progression:

1. More detailed examination of oxygen introduction and foam breakdown by a cutting torch.
2. Measurement of diffusion of volatile and gaseous hydrocarbons through foam.
3. Development of a simple method to describe foam mobility.
4. Examination of potential void situations.
5. Correlation of variables in foam properties. (This section is a considerable programme in itself).

CONCLUSIONS

1. Tests with the 500 tonne tank, under practical conditions, showed that it could be satisfactorily filled with high expansion foam containing nitrogen without forming large voids which could present a hazard if flammable vapour and air were present. Filling either at the top or the base of the tank gave satisfactory results.

2. Foam breakdown did not present a significant problem during a filling period of 2 hours. In general faster filling is preferable for both technical and economic reasons.

3. Sampling of the gas within the tank showed that there was a relatively sharp change in composition when the foam arrived at the sampling point. There was some evidence of nitrogen entering the air immediately above the foam, particularly with the filling at the base of the tank, but not sufficient to give protection. Once the foam reached the sampling point the oxygen concentration dropped to a very low value.

4. The rapid decrease in oxygen concentration at the foam surface indicates that, on a practical scale, the visible presence of the foam at a point implies a low oxygen concentration in the foam.

5. When hot cutting of the wall of the tank was in progress, concentration of oxygen adjacent to the cut rose. The gas pocket was however purged rapidly, and visibly, by the foam which emerged through the cut. As the cutting proceeded, the foam emerged progressively through the cut, indicating that the volume of space inside the tank which was not filled with foam was confined to that immediately in the vicinity of the hot cutting.

6. When the tank was inerted by introducing nitrogen, but without the foam, good mixing occurred with the air initially in the tank. The oxygen concentration dropped steadily but even after about 2 tank volumes of nitrogen had been introduced the oxygen level was still above that readily obtained by the use of foam. In practice, continuous monitoring of the atmosphere would be necessary, without the benefit of the visual presence obtained using foam.

7. Although the tests covered only some of the aspects in a full assessment of the technique, the clear outcome of the tests encourage further serious consideration of its use where flammable materials may be present in a tank which is to be demolished or repaired.

ACKNOWLEDGMENT

This exercise was greatly facilitated by the willing co-operation of many organisations and individuals notably Mr E C F Davies of BOC Ltd and Mr S Wilson, Consultant to John Kerr (Manchester) Ltd whose experience was invaluable, to staff of Property Services Agency at Croydon, Letchworth, Cambridge and Alconbury who made site arrangements and to Station Officer Fensom of Northamptonshire Fire Brigade for site communications. Thanks are also due to Messrs S C Roberts, J Webb, K Farrell and I Fulton for design and operational aspects in difficult conditions and to the transport, workshops and service sections for their help.

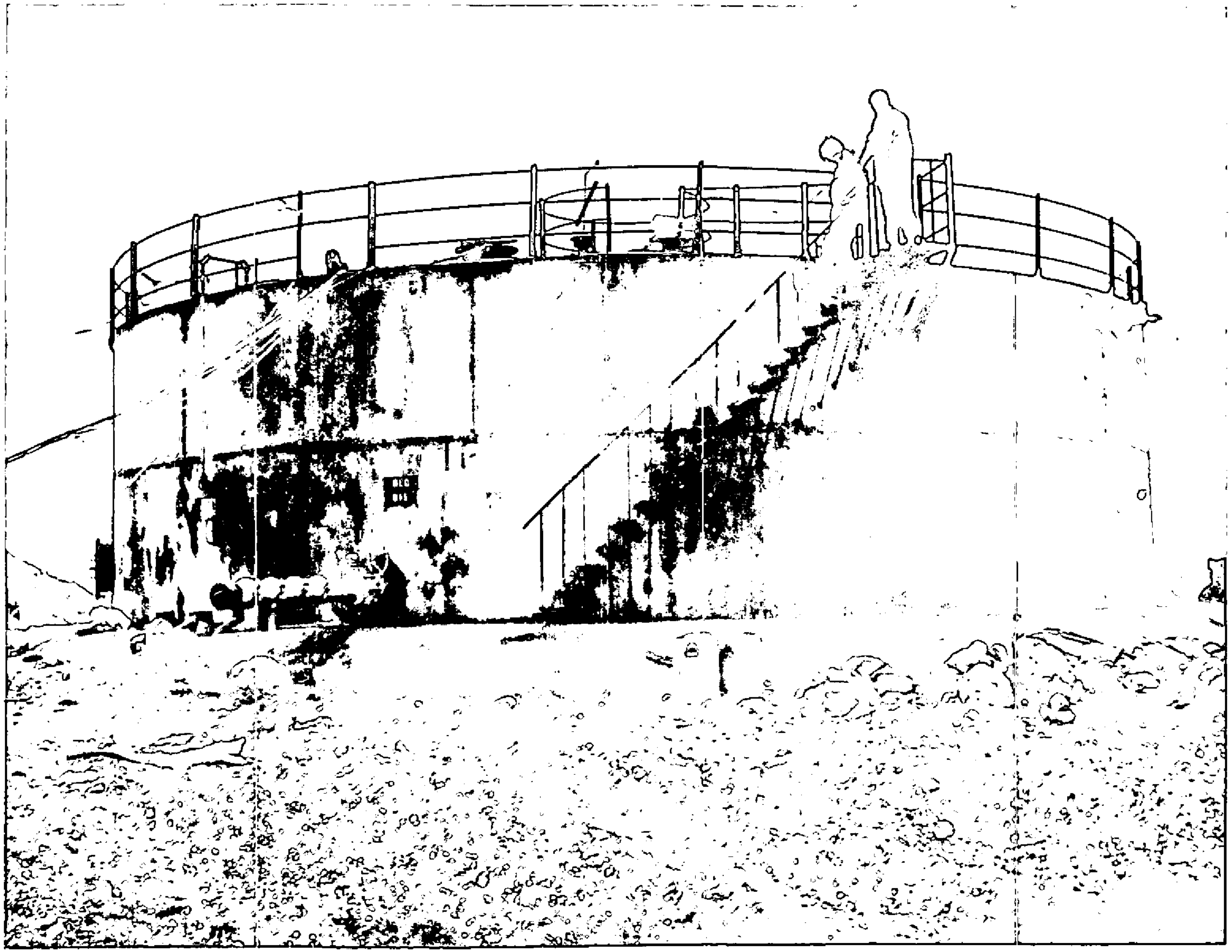


FIG. 1. GENERAL VIEW OF TANK

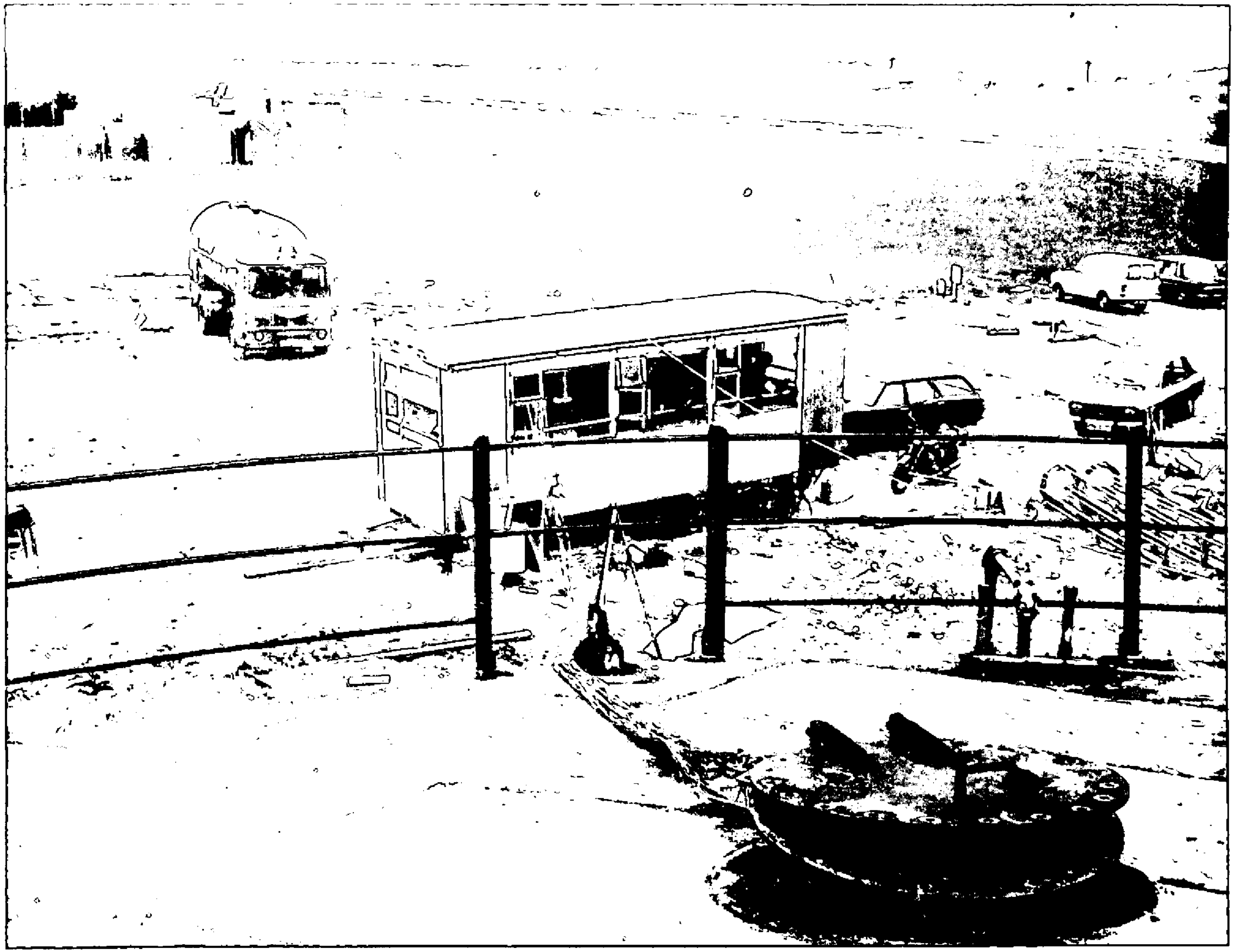
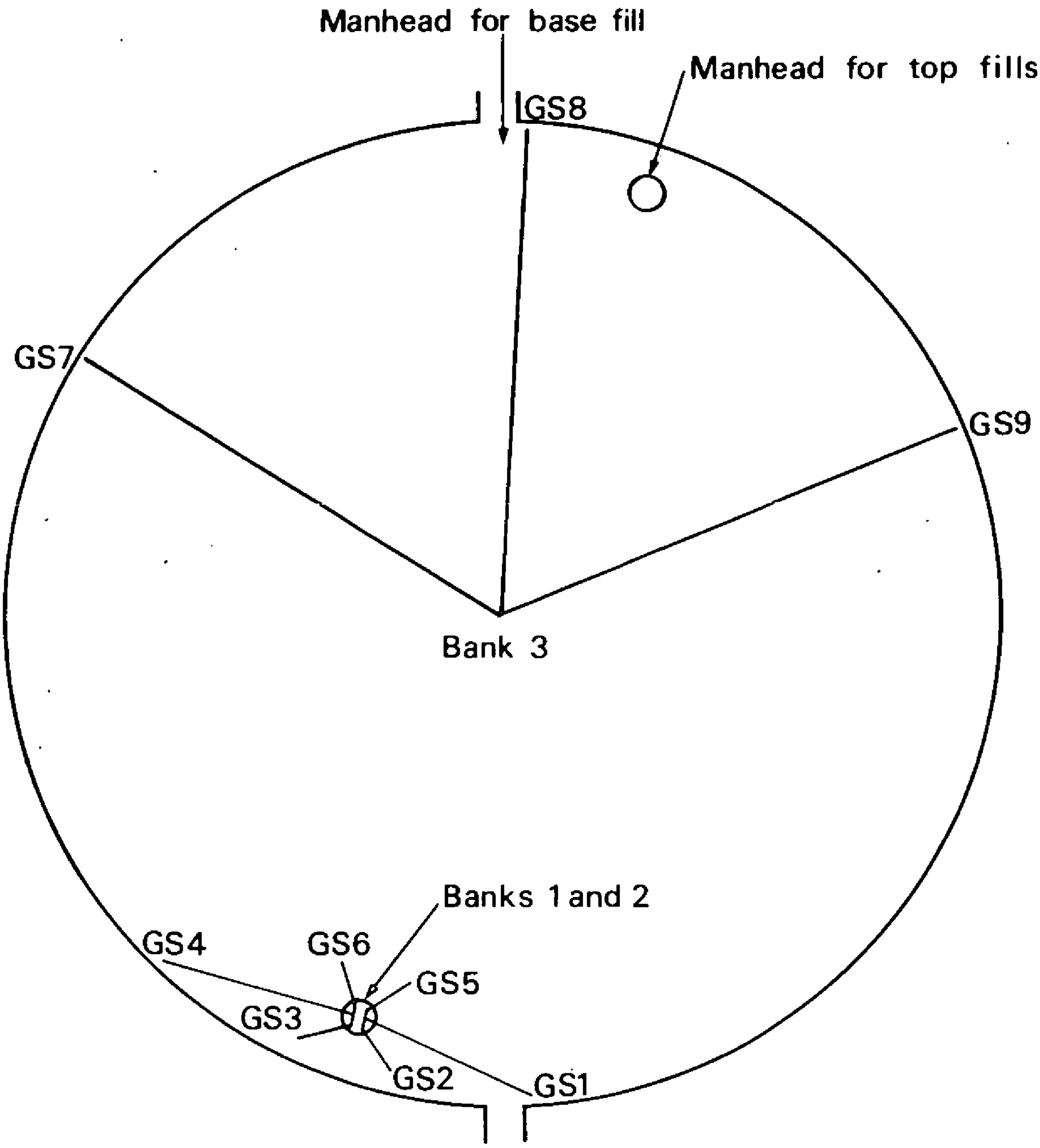
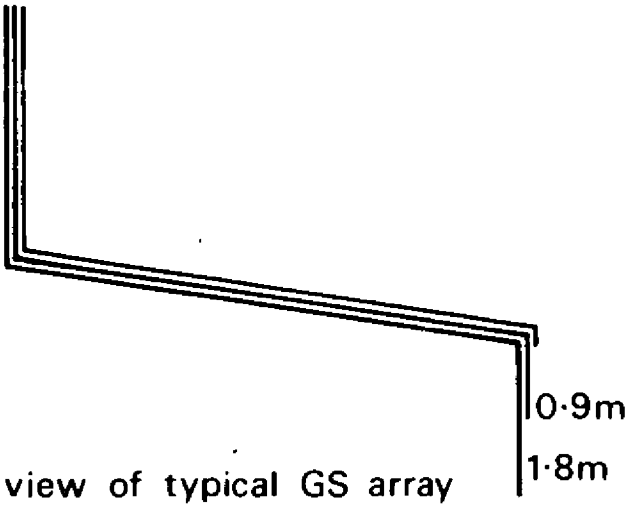


FIG. 2. INSTRUMENT CARAVAN WITH WIRING FROM TANK



a) Plan view of sampling points



b) Side view of typical GS array

Figure 3 Arrangement of gas sampling lines

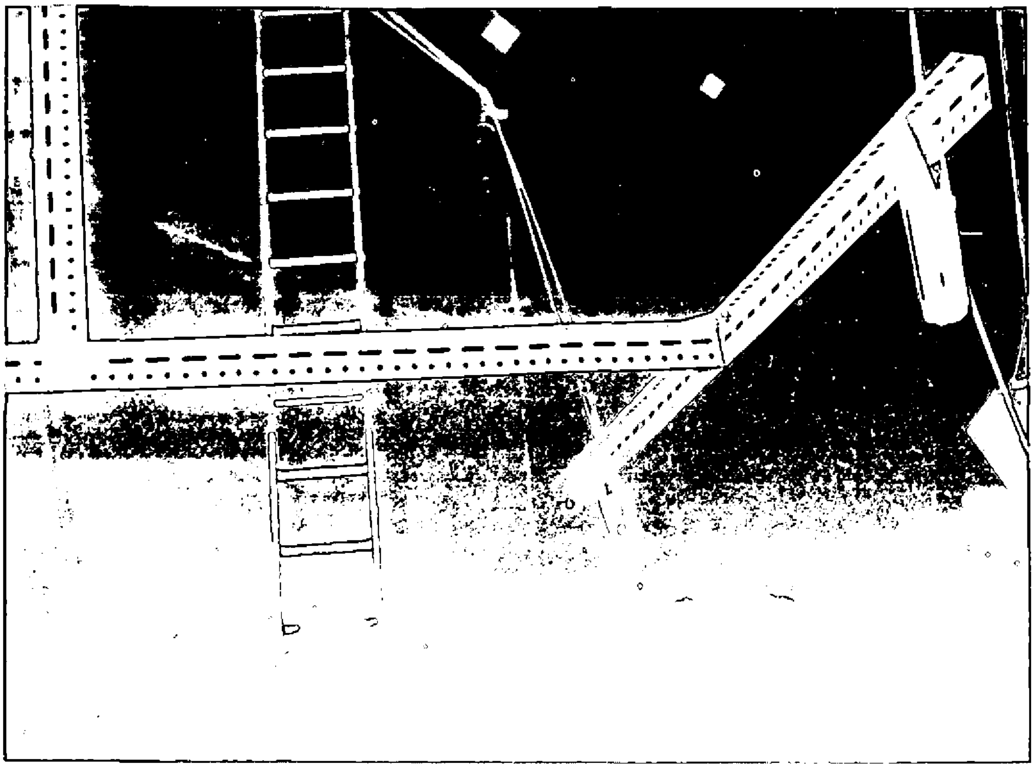


FIG.4. PART OF SAMPLING FRAMEWORK
WITH FOAM BREAKERS AND PIPEWORK

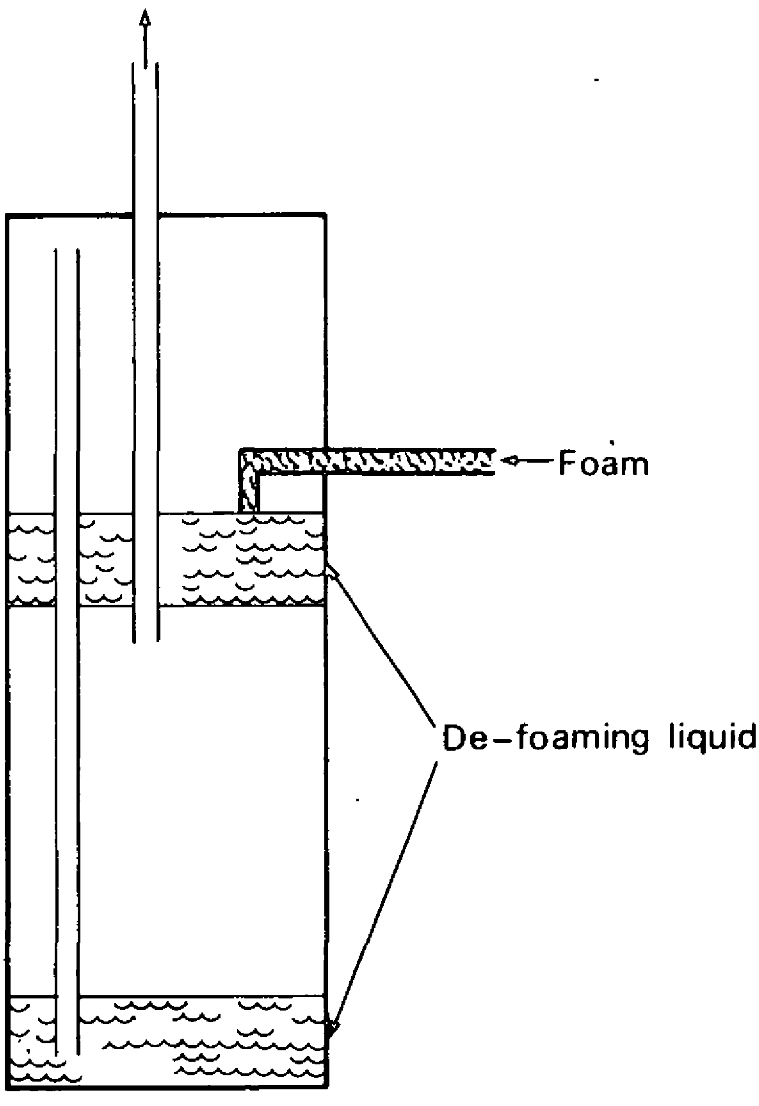


Figure 5 Foam breaker

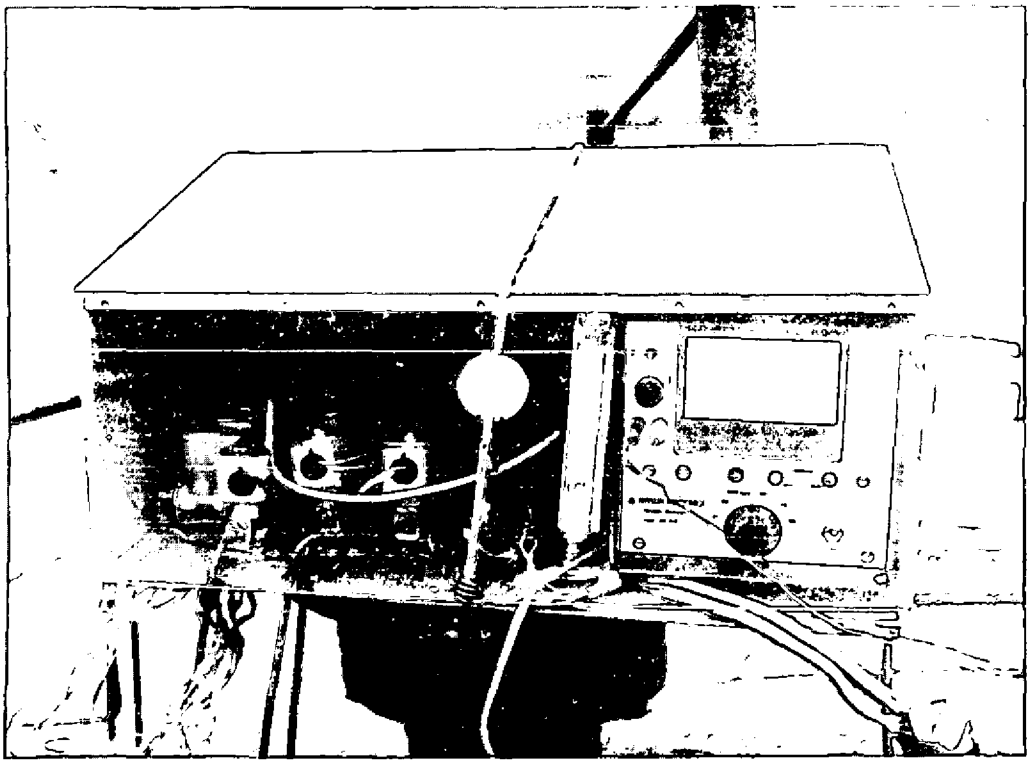
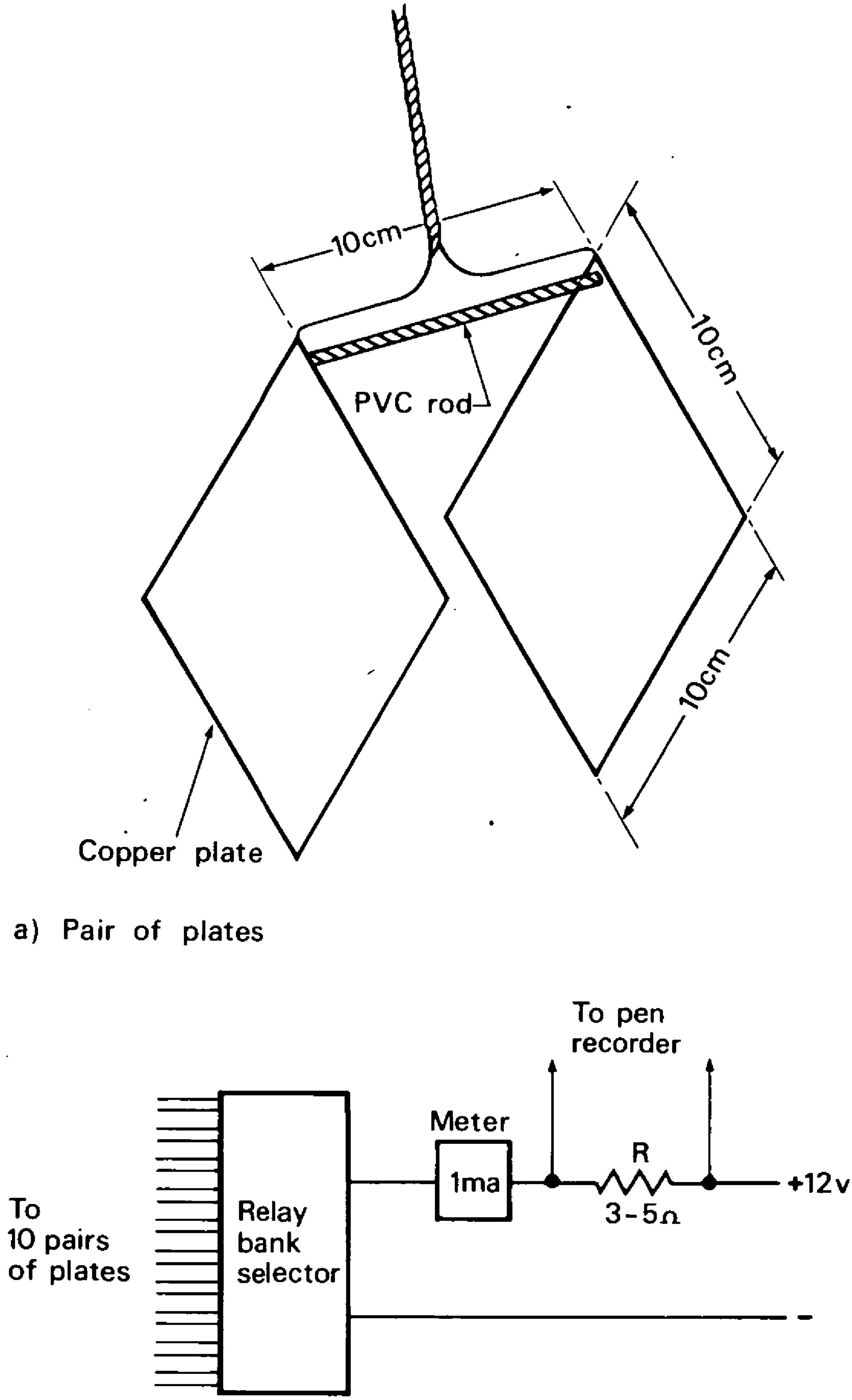


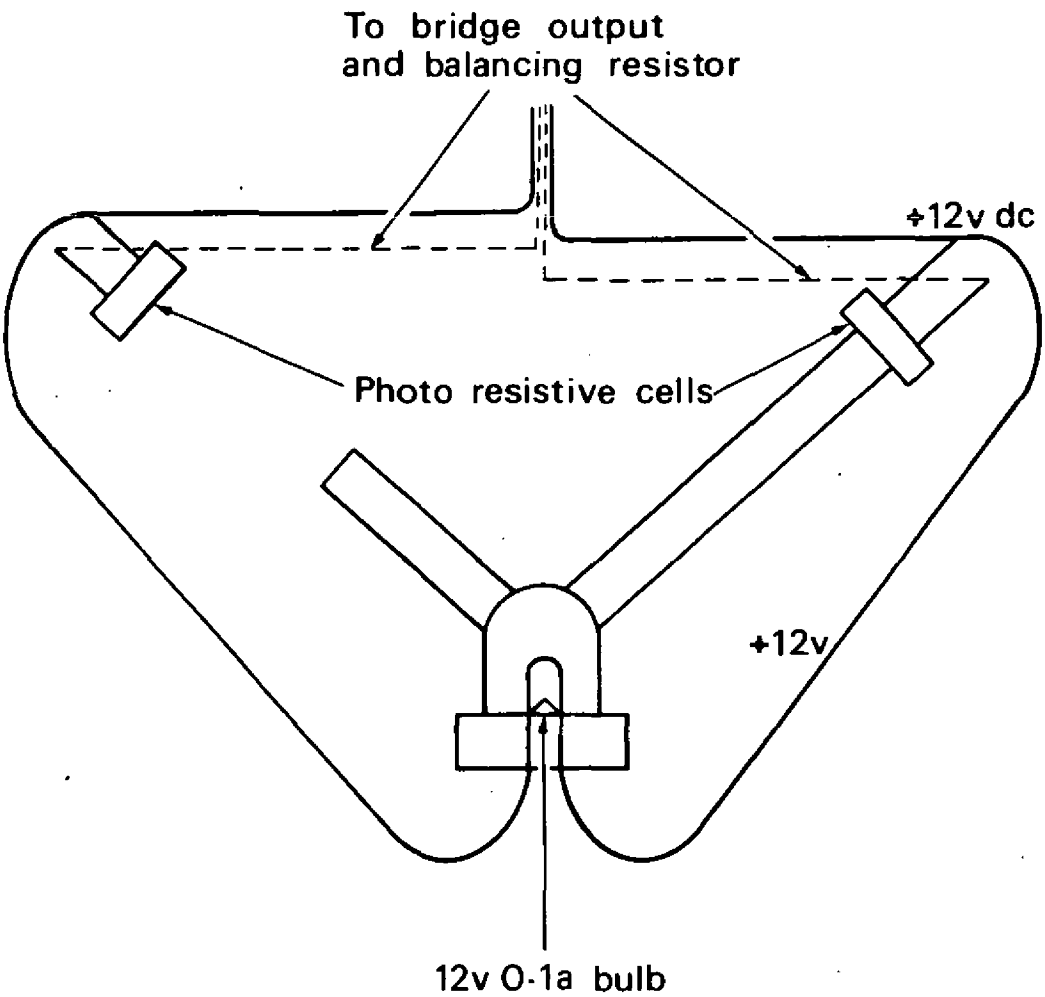
FIG.6. SAMPLING BANK WITH OXYGEN METER



a) Pair of plates

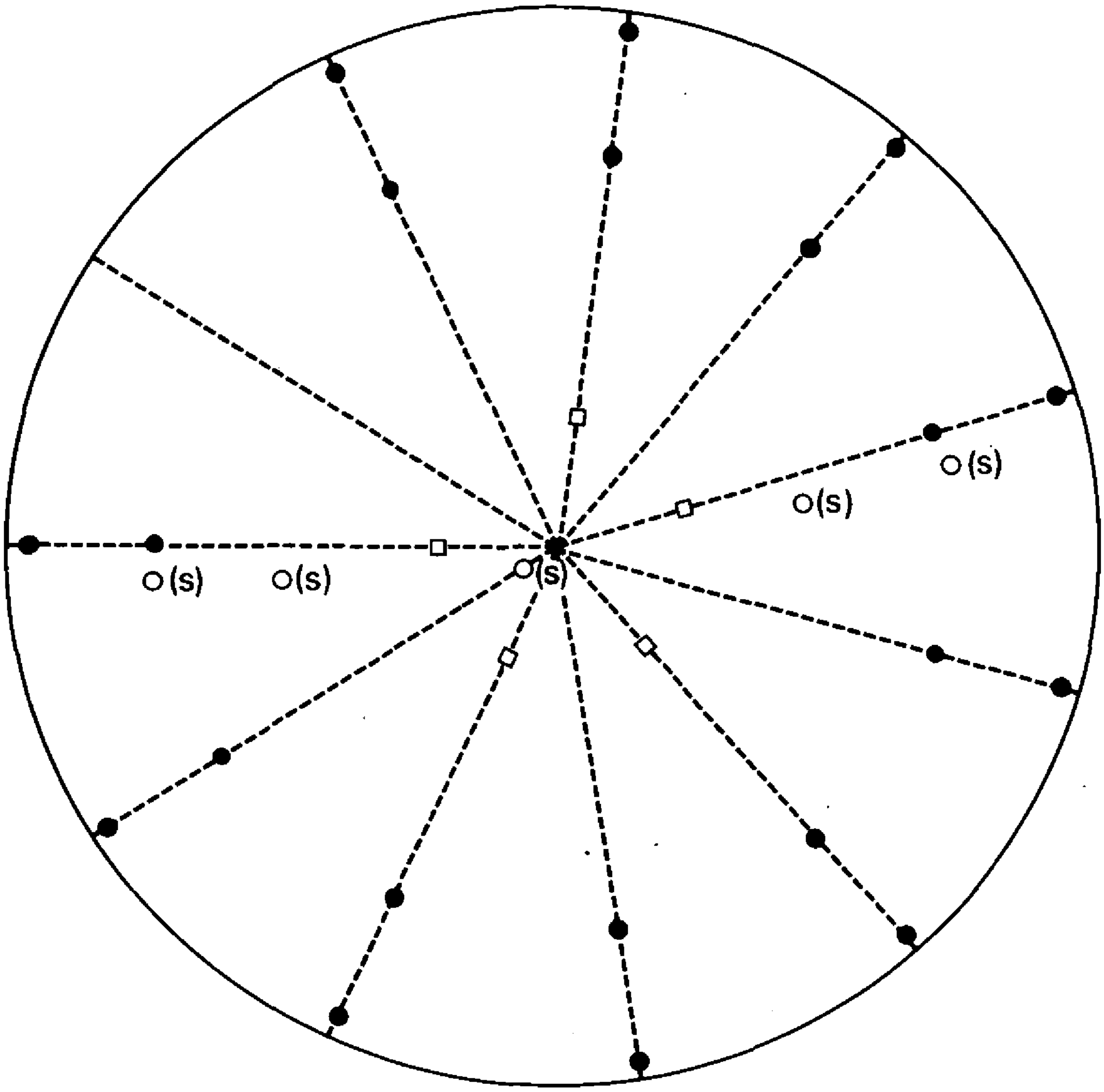
b) Schematic circuit diagram

Figure 7 Pair of conductivity plates and associated circuit



Components supported by 10 gauge copper wire framework with all junctions bedded in polyester resin (not shown)

Figure 8 Optical detector



● Hanging position for set of 5 or 2 pairs of conductivity plates

□ Optical detector in roof (associated with conductivity plate pair)

O(s) Hanging site for optical detector 1·2m from tank base

Figure 9 Plan view of conductivity plates and optical detectors

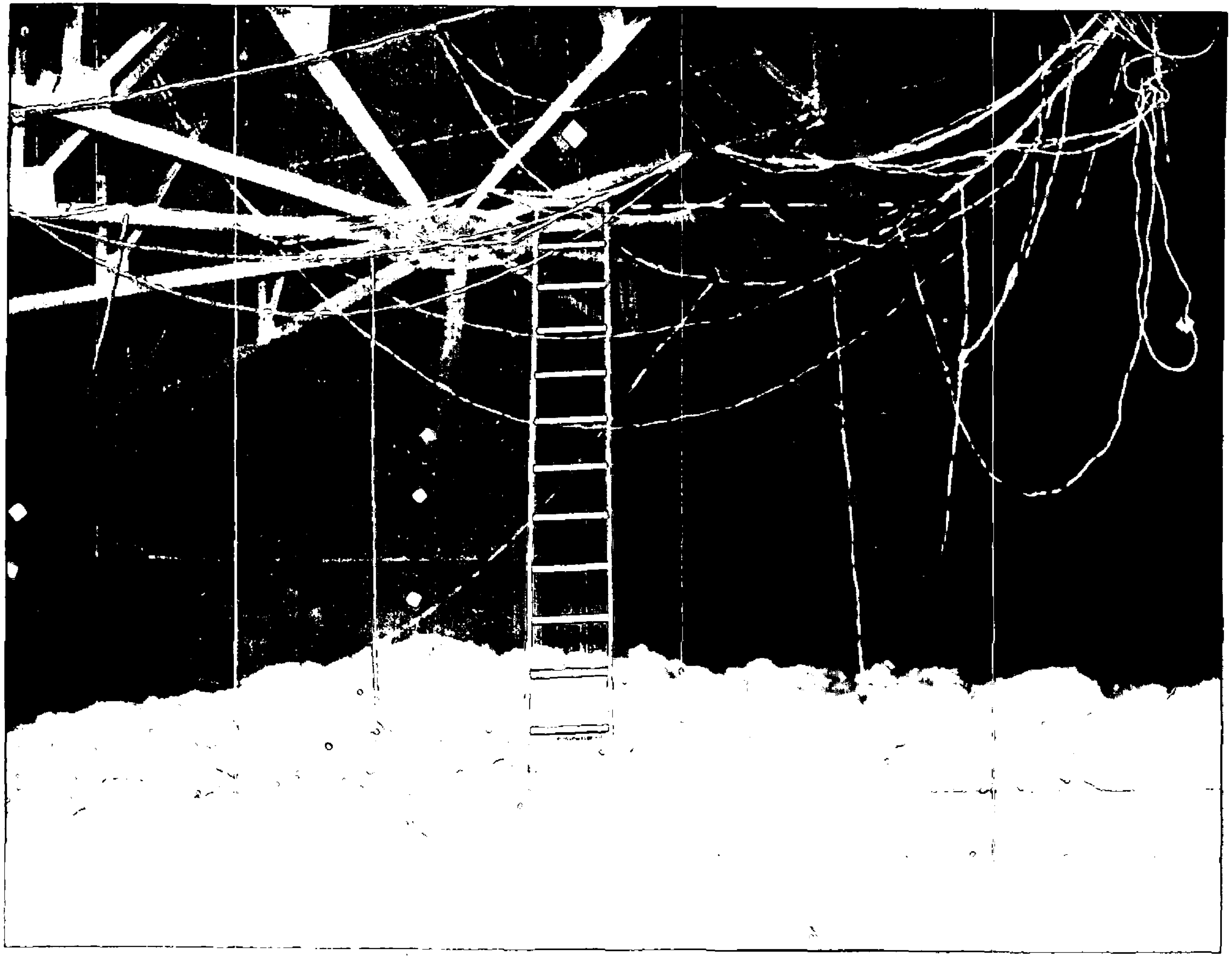
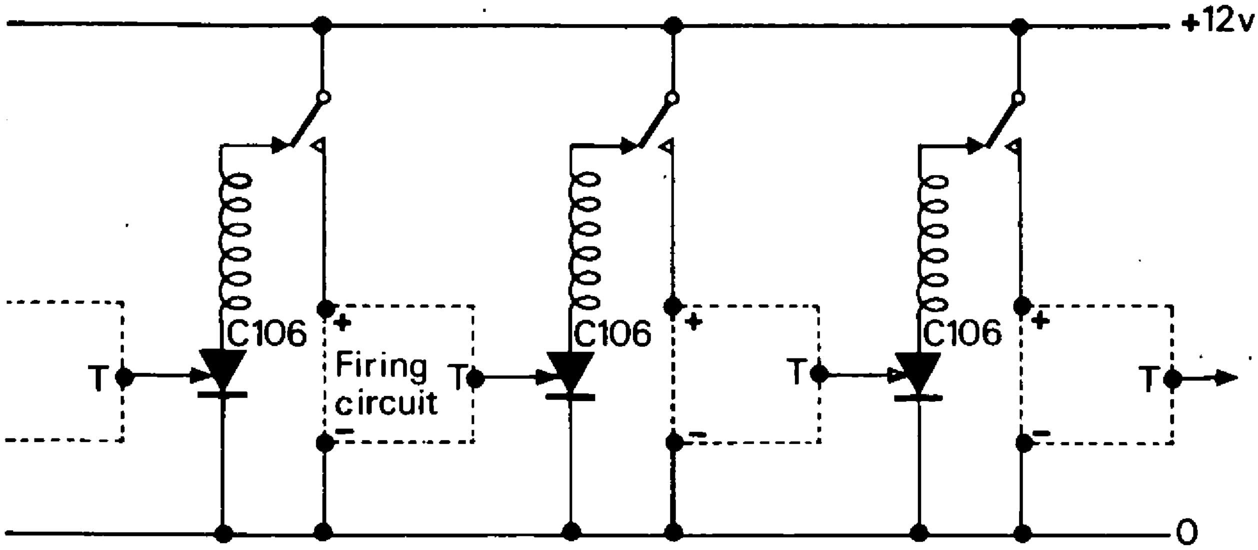
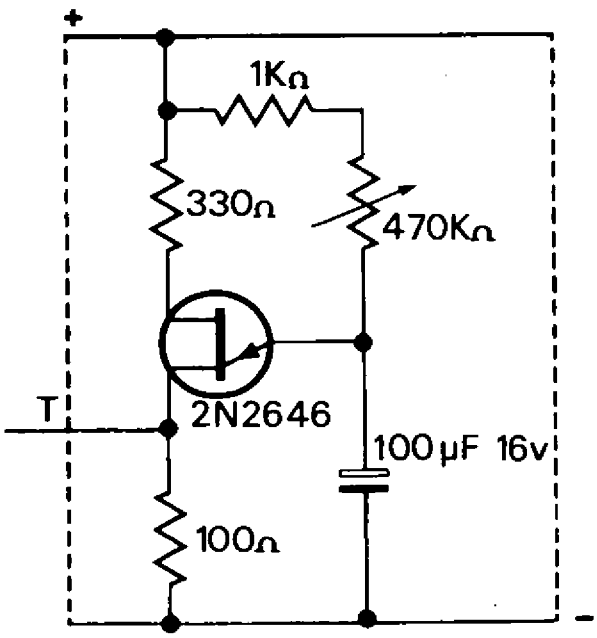


FIG. 10. GENERAL VIEW OF TANK INTERIOR
AT EARLY STAGE OF FOAM INJECTION



a) General



b) Firing circuit

Figure 11 Successive triggering circuit for data relays

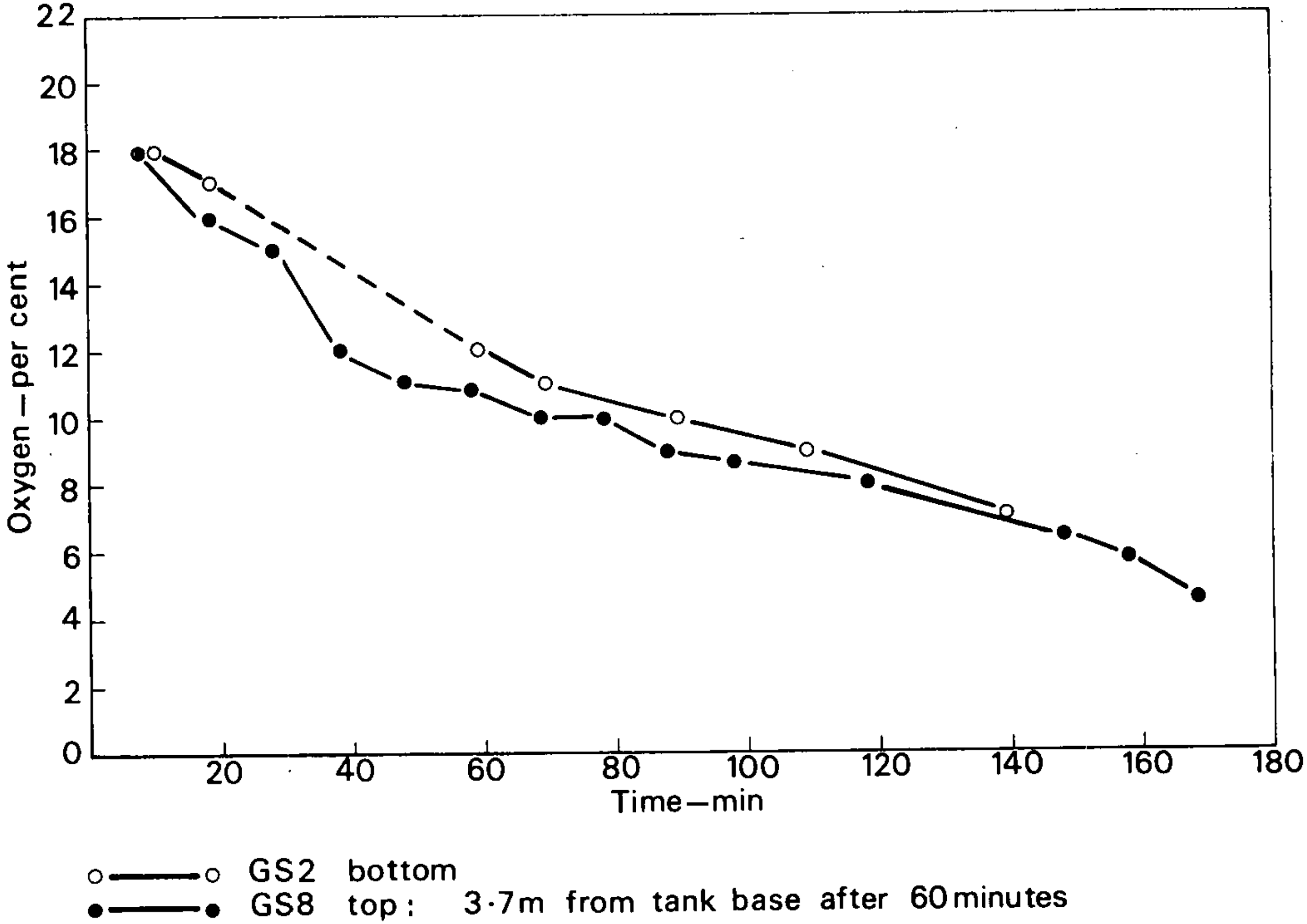
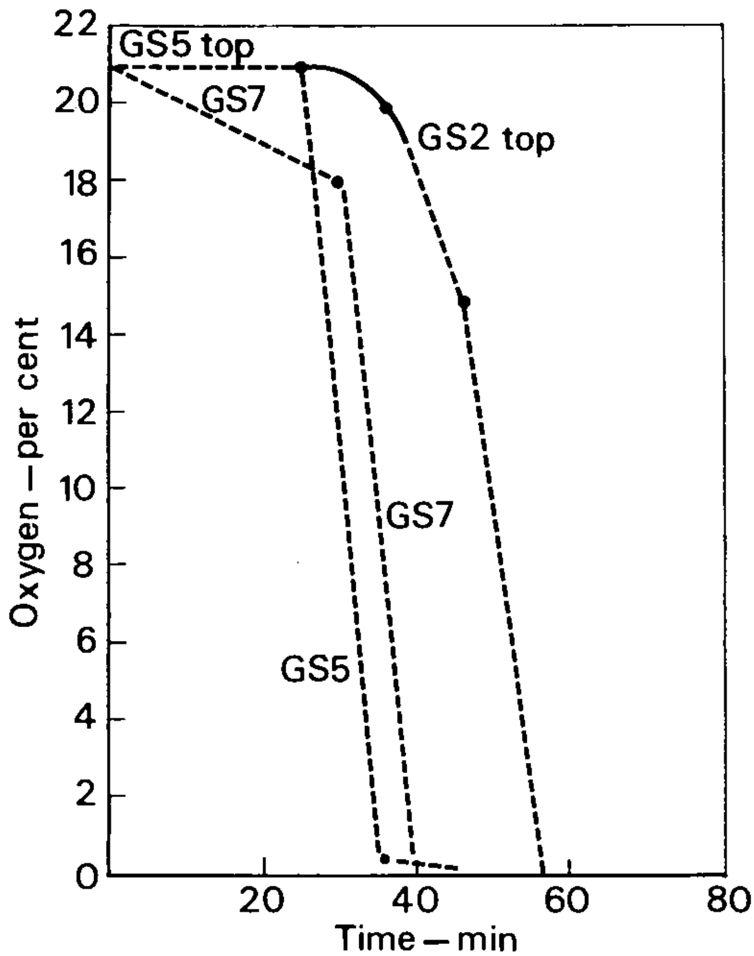


Figure 12 Test 1: Nitrogen gas inerting



GS2 top : 2·7m from base of tank
GS5, GS7 top 1·8m from base of tank

Figure 13 Test 2: Top fill

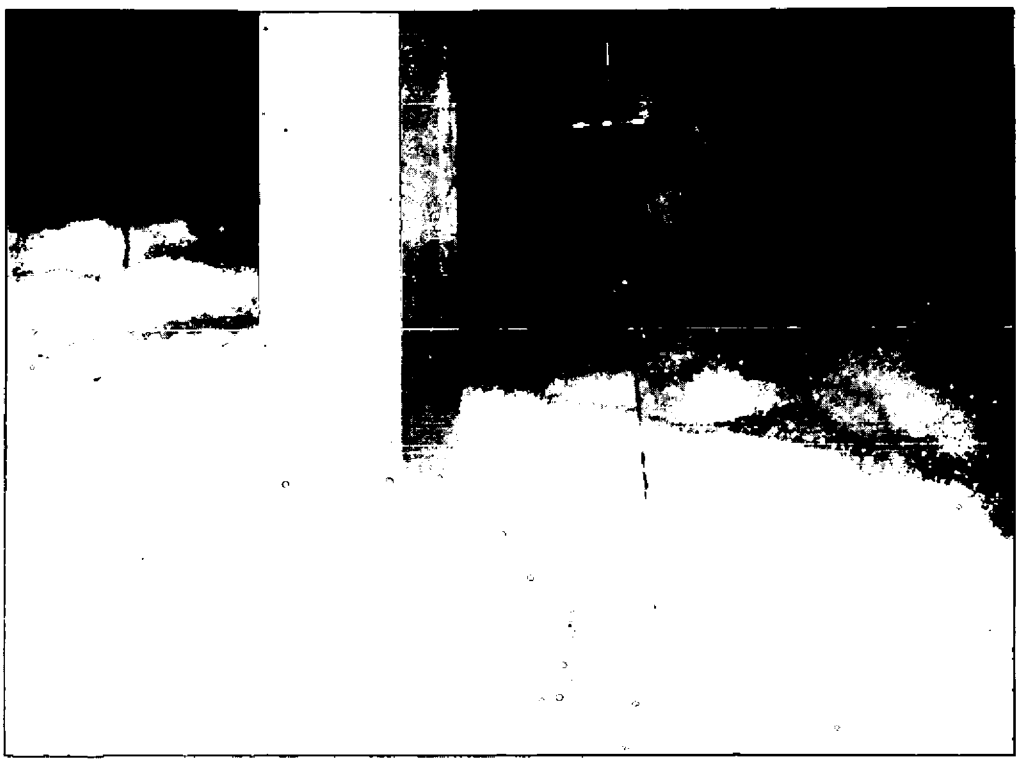
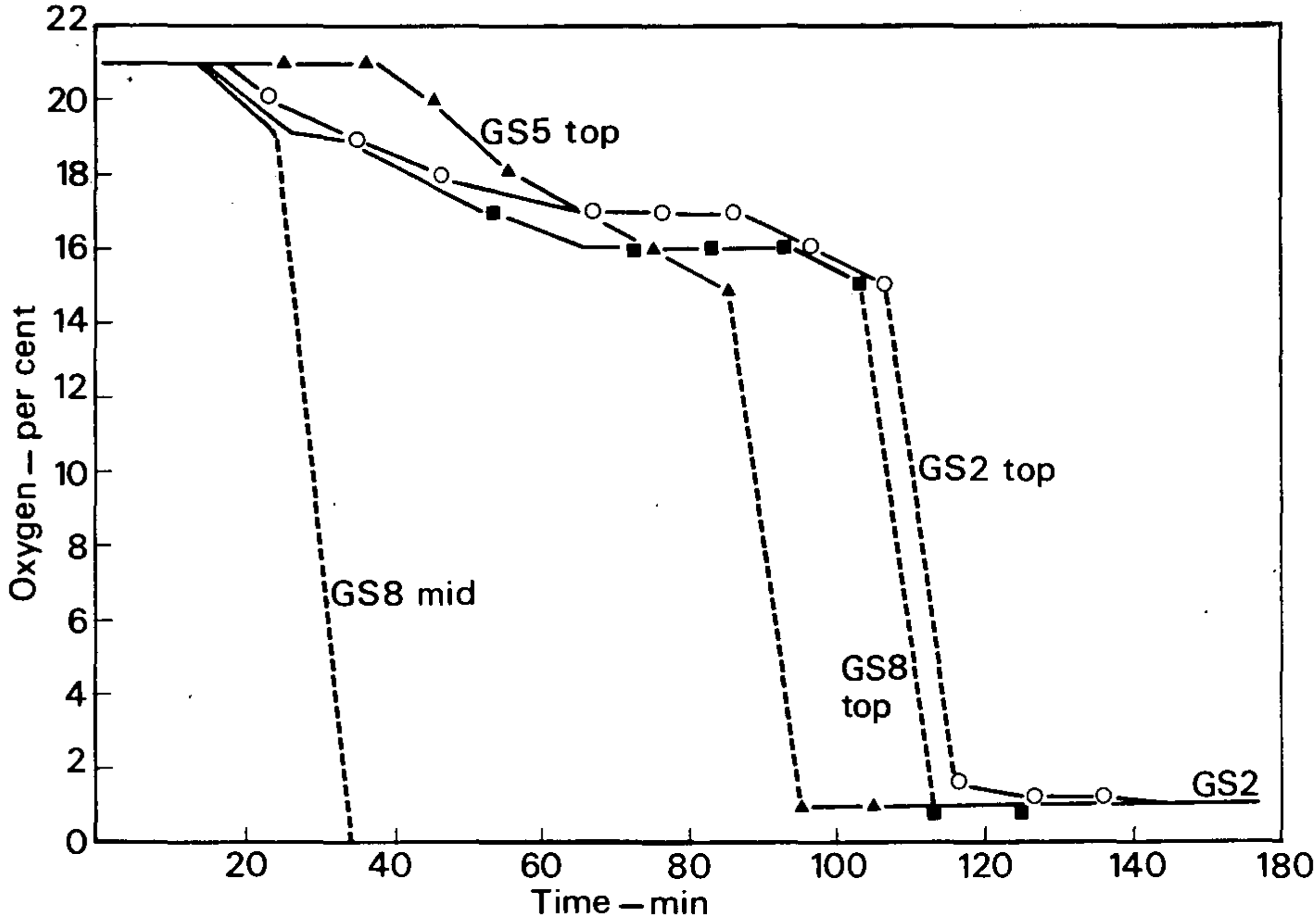


FIG. 14. FOAM AROUND PILLAR



GS2 top: 2·4m from tank base
GS5 top: 2·4m from tank base
GS8 top: 2·7m from tank base
GS8 mid: 0·9m from tank base

Figure 15 Test 3: Base fill

FIG. 16. HOT CUTTING SHOWING FOAM PURGING

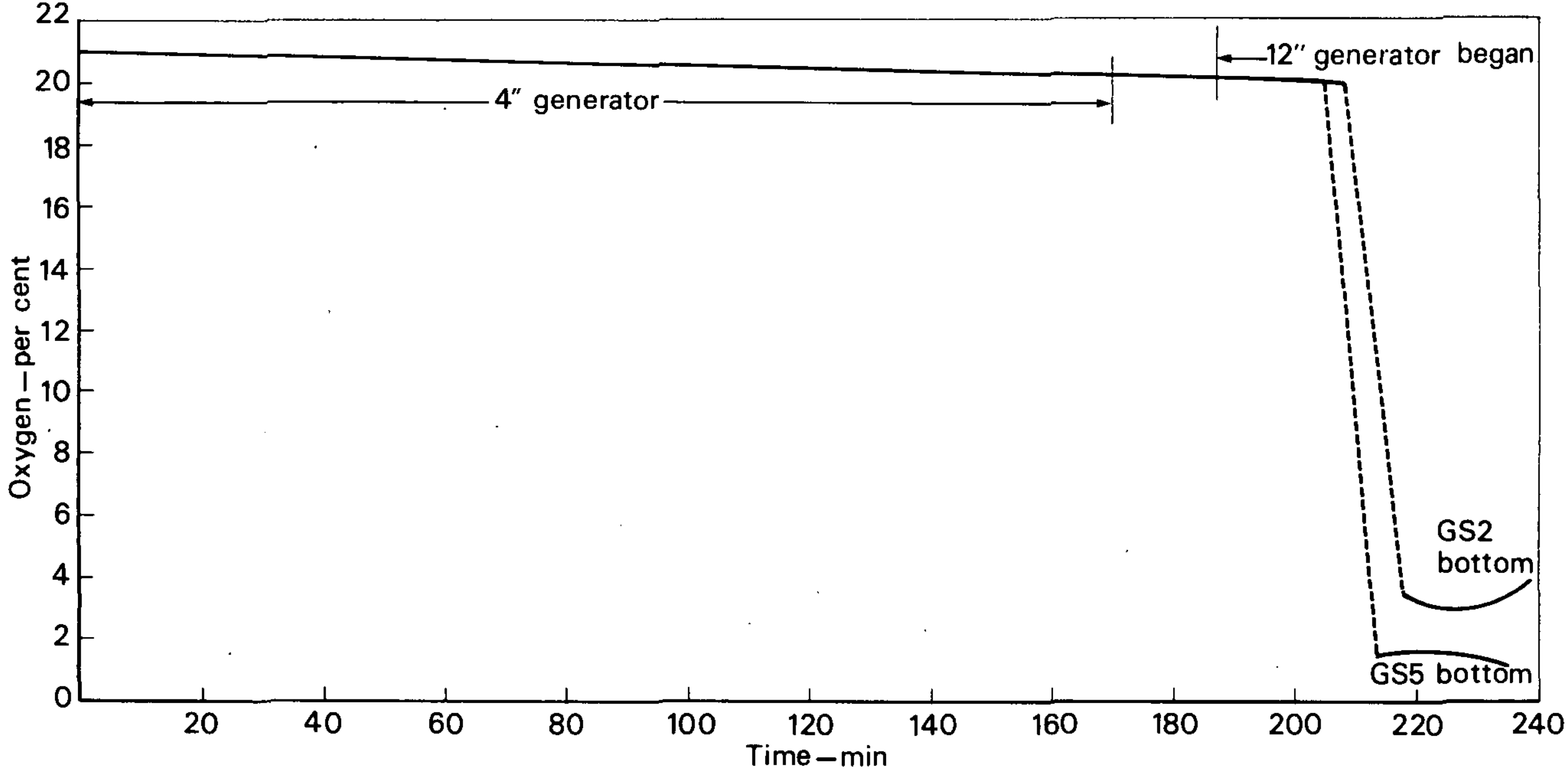


Figure 17 Test 4: Slow top fill