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PRACTICAL AND COMPUTER ASSESSMENTS OF IGNITION HAZARDS DURING TANK WASHING AND DURING WAVE ACTION IN PART BALLASTED OBO CARGO TANKS

J N CHUBB

CULHAM LABORATORY
Abingdon Berkshire

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UKAEA Culham Laboratory, Abingdon, Berks

1. Introduction

Electrostatic sparks are a possible source of ignition for the explosions which have damaged a number of very large crude oil tankers and OBOs* over the last few years. A number of people have shown that electrostatically charged mists can be generated in cargo holds by tank cleaning operations with high pressure water jets(1,2,3,4) and by sloshing in part ballasted tanks due to ship motion(5,6). It seems plausible that conducting bodies such as slugs of water approaching projections in the tank space where electric fields are concentrated, or leaving such projections and moving to the tank wall, could become electrically charged and cause electrostatic sparks on reaching the wall. Under the right conditions, and with an inflammable atmosphere present, these sparks might form a source of ignition. In our work at Culham on the problem of tanker explosions, which is described in this paper, we have calculated the quantities of electrostatic energy which may be expected to be released from conducting bodies inside cargo tanks and have examined experimentally constraints on the incendivity of discharges from such bodies. We have also developed radio techniques for monitoring the occurrence of low energy electrostatic sparks and have used these in shipboard studies in conjunction with flash photography to find the practical circumstances associated with the occurrence of sparks during tank washing and during sloshing in part ballasted tanks.

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* OBO - oil or bulk ore carrier

2. Computer Studies

2.1 Background

A charged mist within a cargo tank gives rise to an electric field at the tank wall which will concentrate at any projections into the tank space. Conducting bodies in the tank space may acquire electrostatic charge by

(a) induction as they leave a projection where the electric field is concentrated;

(b) by polarisation as they approach such a projection;

(c) by corona or water spray neutralisation of polarisation charges; or

(d) by direct aerodynamic sweep-up of charged mist particles.

At best, corona or water spray charging only achieves the same charging as would be achieved inductively, but without direct physical contact - so the hazard will be no greater than with induction or polarisation charging. The amount of electrostatic energy released when a body inductively charged at a projection is discharged at the tank wall is the same as that which would be released by the same body uncharged coming from this point on the tank wall up to the projection.

Calculations of the quantities of electrostatic charge which conducting bodies may be expected to acquire by induction in a variety of circumstances within cargo tank spaces have been made using a computer program, POTENT, which was developed at Culham. This program enables potential and electric field distributions to be calculated by relaxation methods in a wide variety of two-dimensional and axi-symmetric structures. Different potentials may be ascribed to individual parts of the structure and regions of space charge may be introduced which do not need to be constrained by conductor boundaries. The results of calculations may be stored and used as input for further investigation of regions of special interest.

As a charged body approaches an earthed surface the capacitance increases and the potential and the electrostatic energy fall. For spherical bodies these variations have been calculated in each case studied and the potential of the body compared with the breakdown strength of the remaining gap to find the gap and energy at which a spark discharge may occur. If the breakdown gap is too small (below about 1 mm - which is equivalent to a breakdown voltage of about 4.5 kV) the spark would not be able to ignite inflammable hydrocarbon vapour mixtures.

2.2 Tank washing

Calculations have been made on the charge and energy acquired by slugs of water leaving a washing machine in a cylindrical simulation of an OBO cargo tank and leaving the ends of stiffeners in a two dimensional model of a VLCC cargo tank(7).

Figure 1 shows the potential distribution in a cylindrical model of an OBO cargo tank with a charge density of 30 nC m^{-3} - typical of that for charged water mists during tank washing. A cylindrical slug of water 1 m long, 20 mm diameter leaving the 4.25 m long, 100 mm diameter cylindrical projection simulating a washing machine would take away an induced charge of 450 nC and have a free space energy of 5.9 mJ. If this water slug reached the base of the tank where the ambient field is about 21 kV m^{-1} without breaking up, it would release about 3.2 mJ of energy at a potential of 19.2 kV. The field along the slug at the washing machine is fairly uniform at 0.8 to 1 mV m^{-1}, so as the charge and capacitance scale roughly in proportion to length, it appears that a discharge above the minimum energy for ignition (0.2 mJ) can be expected for slugs as small as 100 mm long, 20 mm diameter.

Figure 2 shows the potential distribution in a cross-section of a VLCC cargo tank with a uniform charge density of 30 nC m^{-3}. Calculations were made of the charge induced on 100 mm and 200 mm radius bodies leaving the webs at the ends of a stiffener in the middle of one side of the tank. Analytical studies and separate calculations in axi-symmetric geometries indicated that the charge on spherical bodies would be about twice that on one diameter length of cylinder in the two dimensional calculation. On this basis the charges on the 100 mm and 200 mm radius spheres were 65 and 240 nC. These bodies have free space energies of 0.19 and 1.3 mJ. If they retained their spherical shape on arrival at the tank wall the increase in their capacitance would reduce these energies to 0.047 and 0.33 mJ and their breakdown gaps would be 0.2 and 0.5 mm. Although these discharges would be non-incendive this result could have been modified if the body had changed shape before arrival at the wall.

2.3 Sloshing in part ballasted tanks

Calculations have been made on the charge and energy acquired by slugs of water leaving the tips of waves at the centre and at the side of a half ballasted OBO cargo tank(8).

Figure 3 shows the potential distribution within a cylindrical model of a part ballasted OBO cargo tank with a wave at the centre of the tank and a charge density of 30 nC m^{-3}. Table 1 lists the quantities of charge induced on spherical and cylindrical water slugs, and the breakdown gaps and energies released if these bodies, without breaking up, fell back to the general surface of the water, or reached the tank wall, where the ambient electric field was about 15 kV m^{-1}.

Figure 4 shows the potential distribution in a cross-section of an OBO cargo tank with a wave near one side of the tank and a charge density of 30 nC m^{-3}. Table 1 lists the quantities of charge induced and the breakdown gaps and energies which can be expected when the bodies either fall back to the water surface or reach the tank wall where the ambient field is around 15 kV m^{-1}. The charge on spherical bodies in these two-dimensional calculations was taken as before (section 2.2) as being twice that on a diameter length of a cylindrical body.

2.4 Aerodynamic sweep-up of charged mist particles

The mobility of charged mist particles in an electric field is very low (3×10^{-7} m^2 v^{-1} s^{-1}(1)) so the collection of particles by a body moving in the tank space will be determined by aerodynamic processes with little influence by the ambient electric field or the charge already on the body. If the collection efficiency of a body were unity over its projected cross-section the minimum size of sphere to collect the minimum ignition energy of 0.2 mJ over a 50 m path length in a charge density of 30 nC m^{-3} would be 260 mm diameter. Using equations derived by Langmuir in his studies of aircraft icing(9), and taking a mean droplet radius of 10 microns, we have calculated the maximum energies which would be acquired by spherical and cylindrical bodies thrown on a maximum trajectory across an OBO tank 40 m long and 20 m high. A 300 mm diameter sphere would acquire about 3.5×10^{-6}J and a 1 m long 20 mm diameter cylinder about 15×10^{-6}J. Smaller energies would be acquired with smaller mist particles.

It is clear that aerodynamic sweep-up of charged mist particles does not present any ignition hazard.

3. Constraints on incendivity of electrostatic discharges

The discharge of charged conducting bodies in a cargo tank space is likely to involve breakdown to a water surface or layer, and to involve movement of the discharge surfaces.

Some studies we have done on the time delay to breakdown between a sphere and a horizontal water surface show that when a charged body approaches slower than about 0.5 m s^{-1} the breakdown involves mechanical instability(10) of the water surface. Above this velocity breakdown is as between smooth rigid electrodes. Ignition tests suggest that the incendivity of a discharge from an isolated charged body is reduced by a very slow approach to a water surface.

If an incendive spark occurs from a conducting body approaching a surface the flame front may fail to reach the surrounding inflammable gas mixture if the approach speed is too high in comparison to the flame propagation speed. Some calculations of this quenching effect(7) for a sphere approaching a plane surface are shown in figure 5. Some ignition experiments were carried out in which 12.5, 25 and 62.5 mm radius surfaces were dropped into water in a 5% propane air mixture. The results are included in figure 5. Although the agreement between theory and experiment is not very good, it is clear that quenching is a real effect and requires approach velocities of only a few m s^{-1}. The practical importance of this is that bodies thrown upwards are more likely to be relevant to ignition events than those falling to the bottom of a tank.

4. Practical Studies

Laboratory and outdoor studies have shown that radio observations using a tuned loop aerial provide a sensitive way to monitor the occurrence of low energy electrostatic sparks, and to separate sparks from corona discharges. Since corona is in general non-incendive - but sparks may be - radio observations form a useful technique to monitor events which could present an ignition hazard.

In initial studies we used simple superhet receiver units at 150 MHz and 10 MHz. To avoid the shot to shot variation in output signal associated with frequency changing in a superhet and to take better advantage of the bandwidth of the aerial system, we have now changed to simple straight-through receivers in which integrated circuit elements are used to provide wide band amplification of the signal induced in the aerial circuit for transistor detection. The overall gain of these detector systems at 40 MHz varies from around 46 to 72 db over their operating range.

We have used this radio technique in shore tank studies at the Shell Laboratories in Amsterdam (KSLA)(11) and during shipboard studies on m.v. "Furness Bridge"(12) and on m.v. "Jedforest". During recent studies on m.v. "Jedforest" radio equipment was used(13) to monitor the occurrence of sparks during tank washing and during sloshing in part ballasted cargo tanks due to ship motion. Two aerials, spaced well apart, were mounted inside a cargo tank, and each inside aerial had a separate outside aerial mounted nearby. Sparks were considered to occur in the tank only if coincident signals were observed on the two inside aerials without signals being observed on either outside aerial. This arrangement eliminated interference from external sources and the effect of small scale events very close to either aerial. At the instant of occurrence of a definite spark within the tank space the circumstances inside the tank were photographed by flash photography using two cameras with wide angle lenses (28 mm f/2.8 with HP4 film) and Braun F700 flash units for illumination(13). In the tank washing studies a number of low energy sparks were recorded and the photographs taken showed that when sparks occurred the opposed pair of jets of the washing machine were directed straight down to the tank bottom and straight up to the underside of the hatch cover, with water cascading down from the hatch cover into the tank space. An example of such a spark triggered photograph is shown in figure 6. Although individual photographs do not pinpoint the location of individual sparks, and the radio observations cannot yet give a quantitative measure of their energy, it should be possible to learn about the circumstances responsible for the occurrence of sparks by looking for common features in a series of photographs. These flash photographs also provide information on the size of water slugs and the position of cleaning jets for feeding back into computer calculations of electrostatic field distributions and calculations of discharge energies.

5. Conclusions

Computer calculations show that it is not difficult for fairly modest sizes of conducting bodies, such as slugs of water, to acquire incendive quantities of electrostatic energy during tank washing operations and during sloshing in part ballasted tanks when charged mists are present in the cargo tank space. The hazard presented by these charged bodies depends upon the speed of their approach to the discharge surface. Since the combined probability of a body with enough energy approaching a surface sufficiently slowly in an atmosphere which is in the inflammable range is likely to be very low, it is not surprising that explosions have been fairly infrequent occurrences.

Radio detection can be used to monitor the occurrence of low energy electrostatic sparks in practical operations, and flash photography triggered from the radio equipment can show the physical circumstances associated with individual sparks.

Acknowledgement

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Table 1: Electrostatic energies released by bodies leaving wave tips during sloshing

Body	Wave	Charge (nC)	Free Space Energy (mJ)	Breakdown gap (mm)	Discharge energy (mJ)
1 m long cylinder 40 mm diameter	3 m high wave at tank centre	449	1.1	2	1.1
100 mm radius sphere	"	362	5.9	3.5	2.2
150 mm radius sphere	"	464	6.7	2.5	2.1
100 mm radius sphere	1 m high wave at tank centre	166	1.25	1	0.37
200 mm radius sphere	"	418	3.9	1.25	1.1
150 mm radius sphere	(Figure 4)	192	1.1	0.58	0.28
300 mm radius sphere	"	588	5.2	1.0	1.2

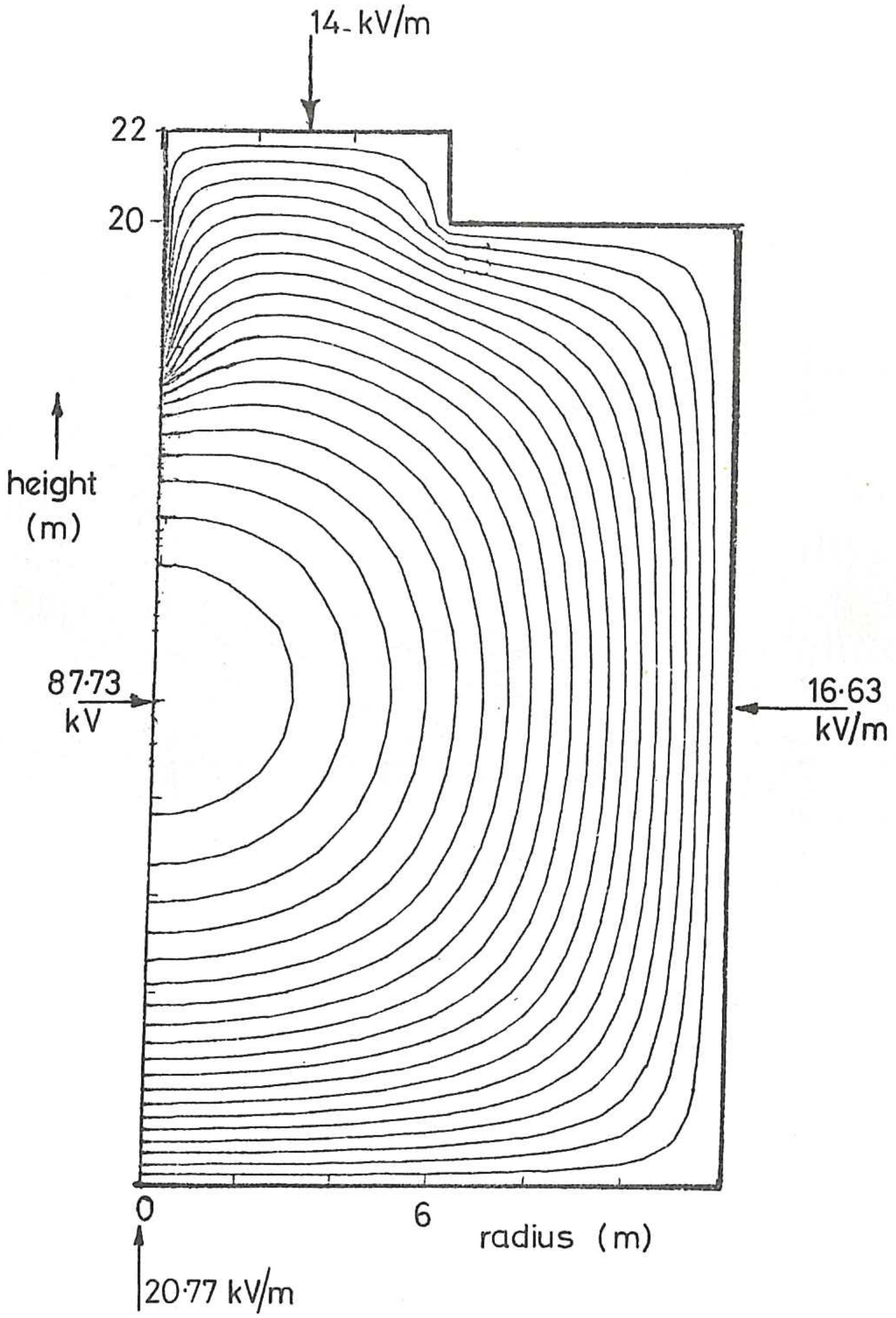

Fig. 1: Potential distribution in OBO cargo tank with slug of water at end of washing machine. Charge density 30 nC m^{-3}. Equipotentials at 4.39 kV intervals.

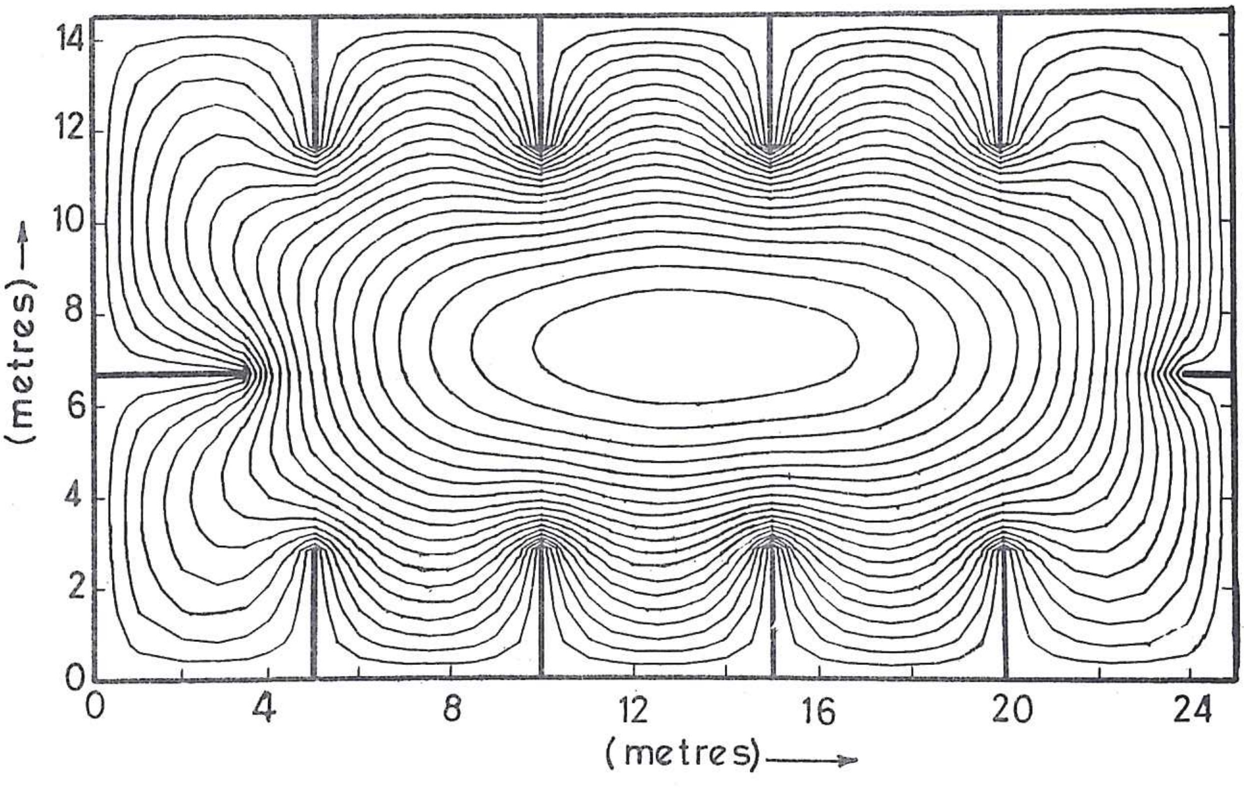

Fig. 2: Potential distribution in a VLCC cargo tank with a charge density of 30 nC m^{-3}. Equipotentials at 2.34 kV intervals. Maximum potential 46.9 kV.

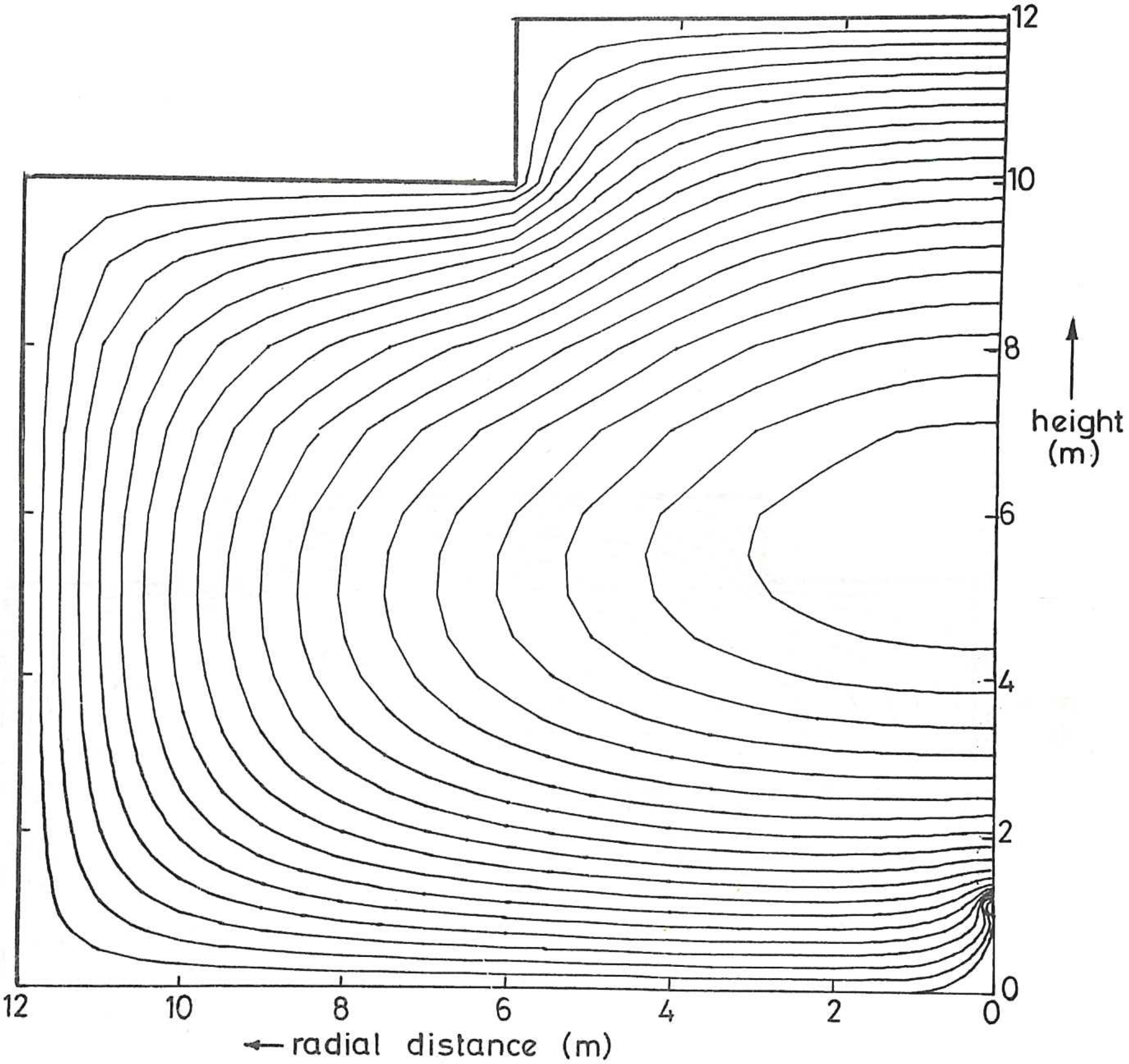

Fig. 3: Potential distribution in an OBO cargo tank with a 1 m high wave at centre. Charge density 30 nC m^{-3}.

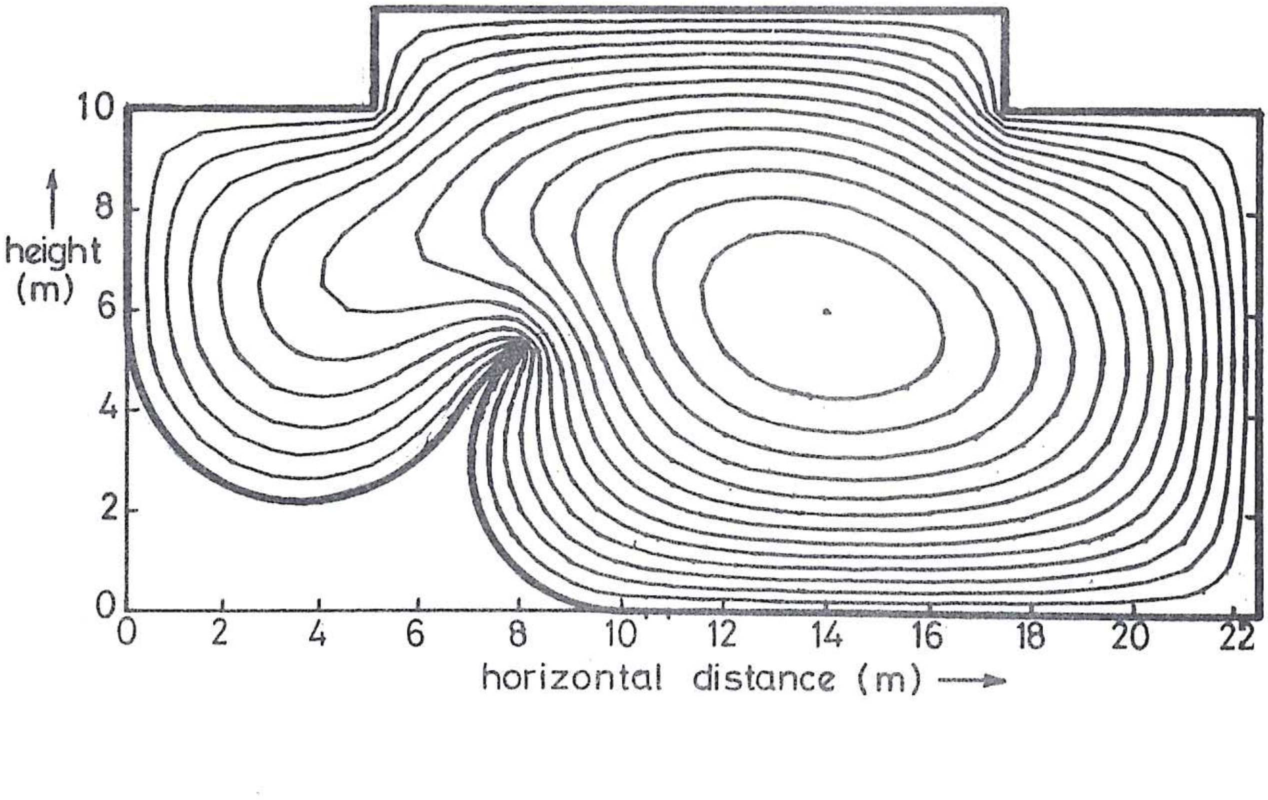

Fig. 4: Potential distribution in rectangular tank with 5 m high wave near tank centre. Charge density 3 x 10^{-8}C m^{-3}. Potential contours at 3.0 kV intervals. Maximum potential 42 kV.

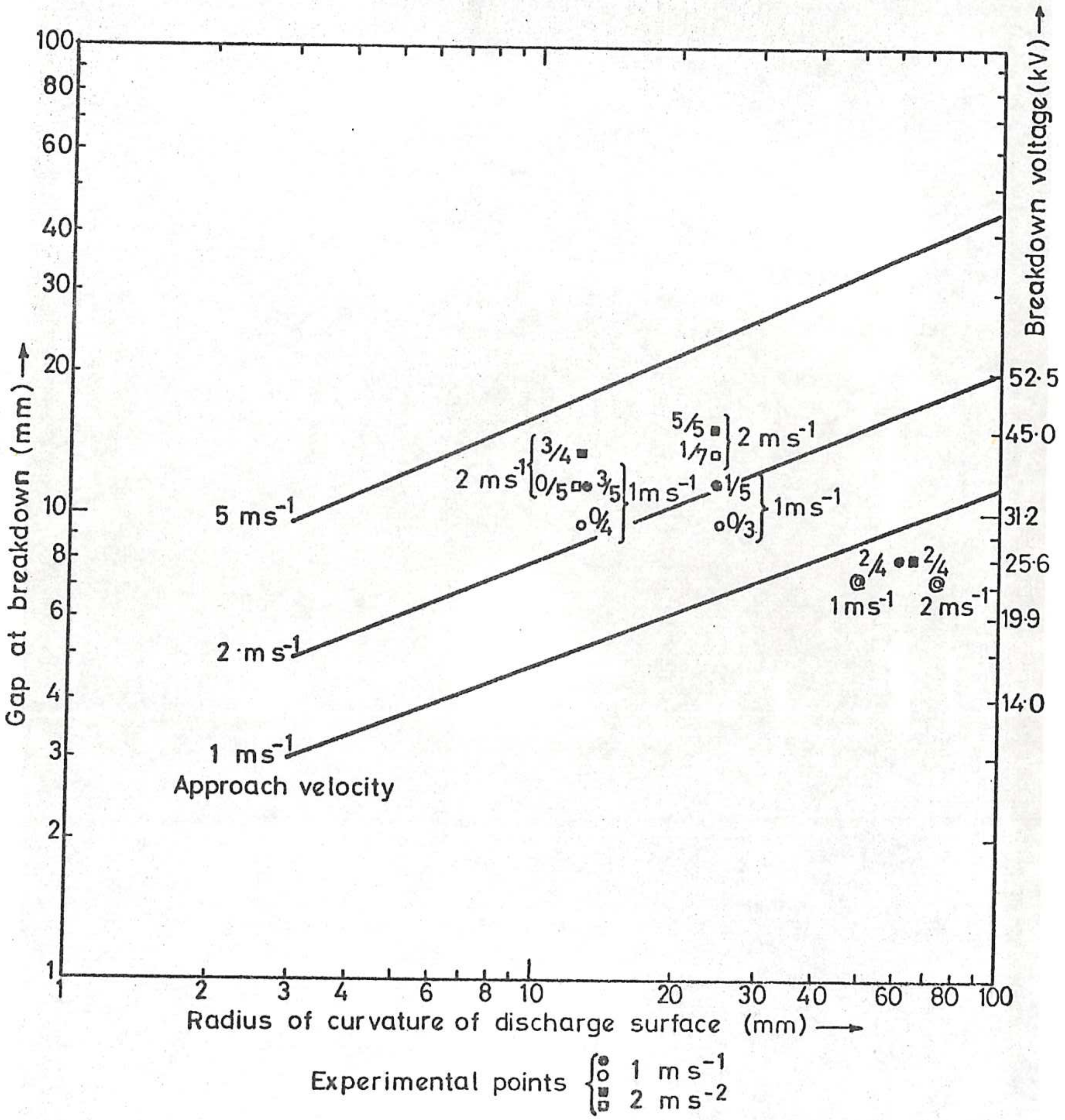

Fig. 5: Gaps and breakdown voltages at which quenching occurs for various approach velocities.

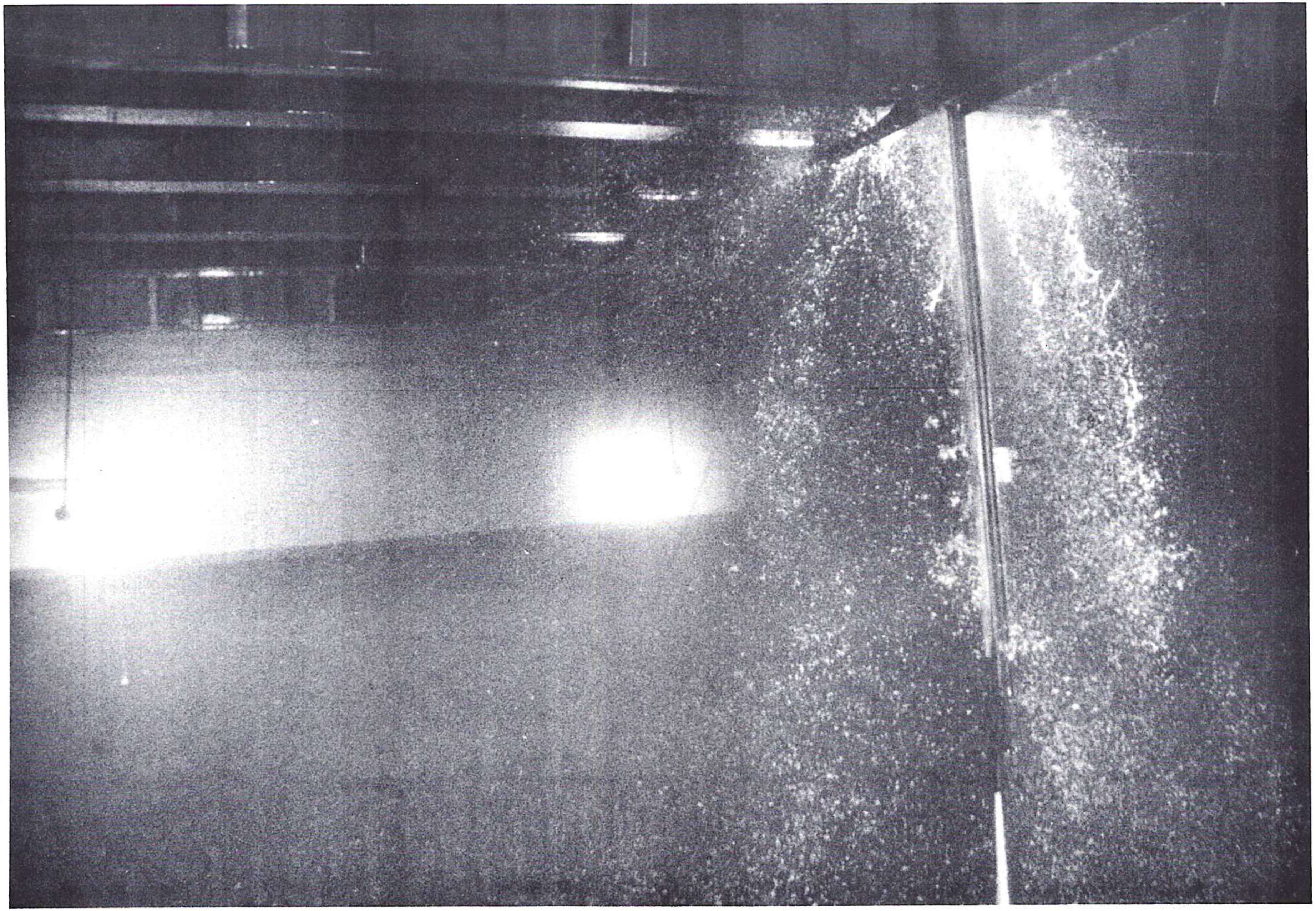

Fig. 6 Photograph of tank washing at the instance of occurrence of a spark in the tank space.