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ELECTROSTATIC CHARGES ON BOARD SHIPS

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Electrostatic Charges On Board Ships

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SYNOPSIS

The fundamental processes of electrostatic charge separation can result in a number of unexpected phenomena, often creating potentially hazardous situations. With the increasing use of new materials for many different applications, it is not surprising to find that electrical charging and discharging processes have adopted new and unpredictable behaviour. In marine applications, this is especially relevant to glass reinforced plastic (GRP) for hull and fuel tank fabrication; and all the ignition precautions needed with the bulk handling and transport of incendive materials. It is the unpredictability of electrostatics, coupled with the fact that so little energy ($\simeq 0{\cdot}2$ mJ) can have such disastrous results, which makes it important.

INTRODUCTION

In general, all materials will, to a certain degree, exchange charges when they come into contact with any different material. At the point of contact a potential will be created as a result of this. This contact, or zeta, potential will depend on a number of factors, especially dependent on the electrical conductivity of the materials.

If the materials in contact are conducting and grounded, then no, or very little, potential will be measurable as the charges rapidly leak away to ground. With insulating materials, on the other hand, charges will be retained with potential remaining across the contact point, resulting in energy storage capability. It is this fundamental characteristic of insulating materials which so often results in a potentially hazardous situation, especially when flammable materials are being handled.

The fundamental processes involved in the creation of the zeta potential are beyond the scope of this paper; a number of published reports cover this topic very adequately(1).

Liquids, solids, and gases to a lesser extent, all exhibit this contact charge exchange phenomenon. If the situation is dynamic, with relative movement at the contact interface, then the charge exchange is usually accentuated(2). An example of how a hazardous situation may arise from the flow of liquids in a pipe, for example, is illustrated in Fig. 1.

If the tank and pipework is metal and earthed, then the positive charge shown in Fig. 1 will harmlessly leak to earth. However, with the fuel flowing and with low conductivity to earth, charge accumulation within the storage tank can create very hazardous situations. A possible spark source arises at any protrusions, such as monitoring devices, placed inside the tank.

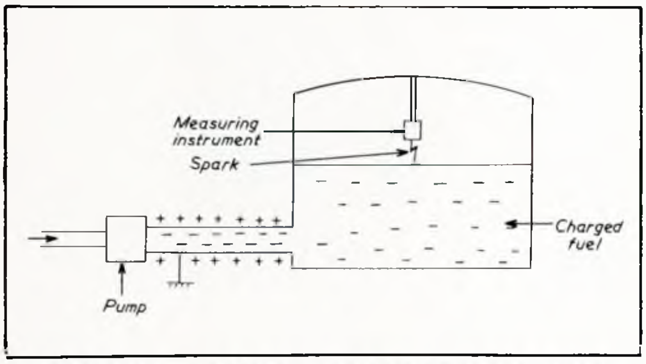

FIG 1 Schematic of charging in tank filling operations

Liquids are perhaps by far the most difficult materials fully to understand in terms of electrostatic behaviour. Not only will they charge when pumped through pipes but they can also exhibit very violent charging when fragmented or atomized in any way. This again is an extremely complicated phenomenon in terms of the fundamental theory. It will suffice here to deal only with the basic process and how to ensure a hazard-free operation.

This charging process will occur in all liquids, but its extent will be determined by a number of factors such as liquid conductivity, degree of atomization, etc. It is interesting to note that even water will cause charge build-up when subjected to fragmentation(3), and the importance of this will become evident later.

PLASTIC PIPES AND TANKS

It is unlikely that the use of GRP material for fuel tanks and pipes in sea-going merchant ships would at present be allowed by the regulatory authorities, due to the risk of spillage in a fire situation, however caused. However, in naval ships such items are already in use for their antimagnetic properties.

The charge separation resulting from flowing liquids has been widely investigated(4,5). From metal pipework at least, the positive charge can be safely discharged to earth as shown in Fig. 1. More recently, however, the situation has been further complicated by the increasing use of glass reinforced plastic (GRP) for fuel containers and fuel pipework. With the use of electrically insulating tanks it is not surprising to find a situation where charge relaxation becomes a major problem.

Even with highly insulating fuels (conductivity less than $10^{12}\Omega$/m), charge relaxation to metallic, well earthed tanks can be accomplished with at least some degree of efficiency. With the use of insulating tanks, however, no charge sink is available and the problem of charge accumulation is greatly accentuated.

An extensive research programme has been carried out on a 2500 gallon fuel testing facility(6), and it has been shown that charge tends to migrate to the tank walls where it is stored, the walls constituting the dielectric of a capacitor. Charge decay rates appeared to be relatively independent of fuel conductivity and depend primarily on the bulk and surface conductivity of the tank.

A schematic of the experimental rig is shown in Fig. 2. Two tanks were used for the tests, one metal and one GRP. In this way the behaviour of the fuel could be compared for both conducting and insulating tanks.

A novel feature of the installation was the use of charge injection to control the charge input level to the tank(7). Also, a novel charge density meter(8), with no moving parts

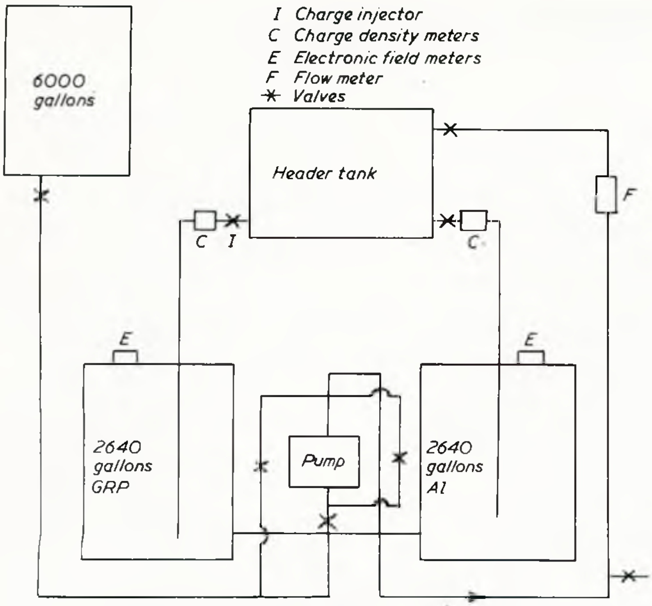

FIG 2 Full scale fuels hazard testing rig

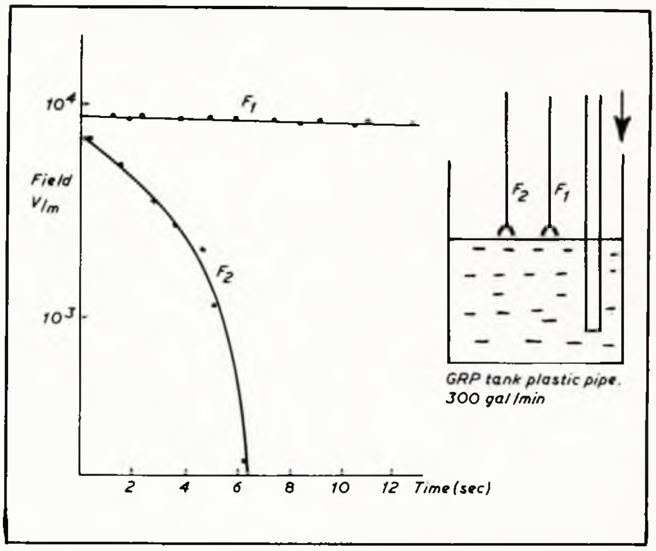

FIG 4 Surface potential measurements during tank filling through plastic pipe

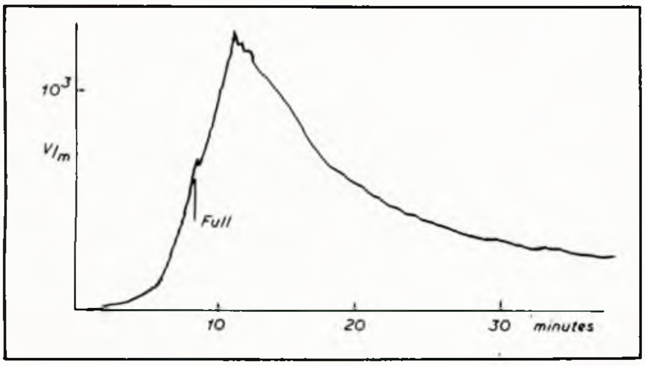

FIG 3 Typical charge relaxation behaviour for diesel fuel in GRP tank

was used to determine the charge density in the fuel. Diesel fuel in a conductivity range 10 ≃ 30 (picosiemens/m) was used as the test fuel. A typical result for charge relaxation in the GRP tank is shown in Fig. 3.

It is interesting to note that the electric field at the surface of the fuel increases even after the filling sequence is completed. This increase was found to be due to the migration of charge to the fuel surface and tank walls. The very slow decay rate is typical of electrically insulating tanks. For the same fuel in a metal tank the electric field decay would have been completed in the order of seconds and not minutes as for the GRP tank.

In addition to the special peculiarities associated with GRP fuel tanks, there is also the question of how fuels will behave if delivered through electrically insulating pipes or pipes which may have isolated sections fabricated of insulating material. One of the effects of using insulating, or plastic, pipes is clearly shown in Fig. 4.

Two field mills(2) were used in this particular investigation, and Fig. 4 illustrates how the electric field will decay for fuel in a GRP tank at two different measuring locations. Field mill F_2 was located near the centre of the tank and measured essentially the fuel surface potential. In less than about seven seconds, the potential had decayed to an immeasurably low value. Why this happens will become clear later.

The field mill, F_1, on the other hand, showed a steady value of electric field for a long time, even after the filling sequence had been completed. This was eventually identified as being due to charge accumulation on the plastic filling pipe itself. Fuel entering the tank would be charged to one sign, leaving an equal and opposite sign of charge on the internal surface of the filling pipe.

With the pipe itself being insulating, charge retention on the pipe can result in potentially hazardous situations due to highly energetic sparks along the length of the pipe to the nearest earthed object.

In the tests referred to in Fig. 4, the pipe was fabricated of polyvinylchloride. A similar situation has proved disastrously hazardous when PVC ducting was used to convey powdered material from paper sack containers into bulk storage silos(9). The product handled was chocolate crumb but the charging process would be the same for most powdered products.

The handling of powdered materials and grain in ships, which usually creates fine particle dust clouds, should be evaluated very carefully in terms of the materials used for pipework, earthing procedures and electrical characteristics of the product.

The experimental system referred to in Fig. 4, where PVC was used in conjunction with diesel fuel and a GRP tank, probably represents the worst combination of materials as regards electrostatic charging and charge retention. On a number of occasions, extremely energetic sparks were recorded and located as tracking along the outer surface of the PVC filling pipe.

Ignition did not occur, since the discharges were occurring below the fuel surface. If they had been above the fuel surface the probability of ignition would have been much enhanced.

One interesting, and as yet not completely explained, phenomenon resulting from these high energy discharges was that, immediately following the discharge, the entire volume of fuel in the tank appeared to be electrically discharged. This would suggest that, as a result of the high energy discharge, a high density of ions of both polarities were injected into the fuel, having the same effect as corona discharger bars used in high-velocity paper and other insulating web production plants.

In addition to the use of plastic pipes for fuels, which are known to be hazardous but not completely understood, another major new development is the use of fuel tanks fabricated of insulating material. For land-based storage of various fuels, GRP is becoming increasingly popular. In special marine applications, it has also found a new and interesting role. A minehunting vessel HMS *Wilton*, and a mine-counter-measure-vessel HMS *Brecon*, have been fabricated entirely of GRP.

This has raised a number of questions regarding the safety of such projects, especially with respect to electrostatic charge behaviour on board and lightning protection of the superstructure. Never before have such large structures been fabricated almost entirely of an electrically insulating material. Not unexpectedly, traditional safety precautions immediately become obsolete.

With a hull and superstructure fabricated of insulating material, the electrostatic problem arises basically from the inability of electrical charge to be conducted safely to earth via the sea. There are many areas which are potentially hazardous in this type of vessel. Some of these are:

i) Charged fuel in tanks.
ii) Charged personnel.
iii) Lightning protection of vessel.
iv) Fuel and oil leakages in engine room.

Charged fuel in tanks

Assuming that during refuelling in a GRP ship the fuel enters the tanks in a charged state, then the charge will not be able to relax to earth and will naturally accumulate over a period of time. If the tank is completely isolated from earth, then the charge will relax to the tank walls and will be evenly distributed. In the more usual situation, however, where the tank is in the bottom of the ship, it is now known that most of the fuel-borne charge will relax to the base of the tank—this being the area closest to earth(10).

A technique now adopted for fuel discharging involves the use of a small earthed plate situated in the base of an insulated tank. Typically, for a 2,500 gallon tank filled with diesel fuel in the conductivity range $10 \simeq 30$ ps/m, a grounded metal plate of area 1,000 cm^2 was demonstrated as being extremely effective in terms of fuel discharging. The performance of such a plate discharger will obviously depend on the fuel conductivity, and it has yet to be determined just how low the fuel conductivity can be before this technique becomes ineffective.

For removing changes from fuel in insulating tanks, there is as yet no known universal solution. The use of anti-static additives (ASA) can aid in reducing charge separation during tank filling but as soon as the fuel arrives in the tank the effect of ASA in terms of conductivity enhancement will be of little benefit if in-tank charging occurs.

Charged personnel

A potential hazard which is often overlooked is the possibility of personnel becoming electrically charged. This phenomenon can often be experienced simply by touching metallic door handles on dry days. Although the resulting, usually unexpected, mild electric shock can be a source of amusement, the energy involved can be quite high, easily well in excess of the minimum ignition energy of stoichiometric hydrocarbon vapours. Taking into account quenching distance considerations and assuming a minimum ignition energy of around 0·2 mJ, it can be shown that a potential of about 4 kV on the human body may lead to a hazardous situation(11).

This can arise in one of two ways. The person must be electrically isolated either as a result of wearing insulating shoes, or of standing on an insulating floor. The latter is especially relevant to personnel working on GRP ships, where they will be electrically isolated from earth. At the present time there is no known solution and perhaps the only guideline is that, as long as the relative humidity is above about 60 per cent, charges will not be retained on the human body. At this humidity all surfaces will be coated with a water film, thus providing a charge leakage path to earth.

The degree of hazard due to charged personnel will, of course, depend on the environment. For example, in a ship's paint store, where a variety of solvents may be used, a maximum ignition energy of around 0·2 mJ should be considered as the maximum safe limit. A potential of 4 kV on the human body is not difficult to achieve, especially in low humidity.

The maximum safe body potential in the ship's magazine is rather difficult to specify, but it would probably be above 4 kV. However, in order to allow a good margin for safety, an overall maximum of 4 kV should not be exceeded.

Even in metal ships the problem of personnel charging can occur if insulating shoes are worn. Unlike GRP ships, the solution to the problem is rather more straightforward. Conducting footwear is now commercially available and should always be worn in potentially incendive situations.

Lightning protection

The question of lightning protection must also be considered separately for both metal and GRP ships. In a metal ship very useful operational experience has been accumulated over the years and lightning protection could be said to be reasonably well understood. As with all such systems, the aim basically is to conduct to earth as quickly as possible the very large currents associated with a lightning stroke. Ideally, the path of the conductor should be straight and positioned as far away as possible from important electronic equipment, the fuel tanks and magazines.

The axial electric field set up by the current in the conductor can induce high-voltages on components in its vicinity; and mechanical stresses are set up if the path of the conductor deviates from a straight line.

Accommodation of these restraints is not too difficult on a metal ship but the problem can be very complex indeed on a GRP structure. Screening of the conductor itself poses a problem, and should its path not be exactly linear, the limits of mechanical stresses and strain on the GRP structure should be carefully considered. There is as yet insufficient information available, and hardly any operational experience that can be drawn upon for GRP ship lightning protection.

Fuel and engine oil leakages

In the event of small punctures in pipelines or components involving fuel or oil under pressure, there is always the possibility of leakage occurring by way of an atomized liquid jet. As mentioned earlier, this invariably creates charge separation within the liquid which may under certain circumstances, result in a hazardous situation.

Exactly where the leakage might be, and whether the puncture was in an earthed metallic component or in an insulating component, will dictate the degree of hazard. It would be impossible to detail all the possibilities here but it should be emphasized that atomization of fuel in any form is something that should be avoided at all times, from the electrostatic point of view.

TANK WASHING

The explosions that have occurred on very large crude carriers as a result of tank washing are now well known and the findings of extensive research have been well documented[12]. It was back in December of 1969 when three VLCC suffered severe damage caused by explosions in their cargo tanks.

All three ships were in the process of tank washing with high-velocity water jets. Also, the explosions occurred during washing of their centre tanks which had a volume in excess of 24,000 m^3. The three ships involved, *Marpessa*, *Mactra* and *Kong Haakon VII*, were all new and larger than 200,000 tonnes and were some of the first to be classed as 'supertankers'.

With such disastrous consequences of tank washing there were serious doubts as to whether there existed a safe limit to tank size above which ignition somehow occurred.

Initially the source of ignition was not known and a number of investigations were initiated in an attempt to identify the problem. All possible sources of ignition were considered, such as spontaneous ignition, spark from metallic impact, accidental operator error, electrostatic charging and a number of other, perhaps less likely, causes.

In this particular example, however, some pattern had developed: all ships were tank washing their centre tanks which were almost identical in volume. Precautionary measures had been taken to control the tank atmosphere. The accidents all occurred within about three weeks of each other, and all three ships were in almost identical global dispositions.

Tank washing on a VLCC involves the use of high-velocity water jets at flow rates of up to 180 m^3h^{-1}, and velocities of up to 40 ms^{-1} at the water-gun nozzle. Measurements taken during, and just after, completion of washing in the centre tanks indicated the presence of electric fields of around 30 $kV . m^{-1}$, space potentials of 40 kV and charge densities of the order of 10^{-8} $C . m^{-3}$. These measurements were carried out under operational conditions but with the tank being inerted.

These three parameters, the electric field, space potential and charge density, gave some indication of the level of electrostatic activity within the tank, although the interpretation of the figures for the purpose of hazard evaluation would prove very difficult. The peripheral electric field of 30 $kV . m^{-1}$ would also no doubt be much higher in the vicinity of protrusions into the tank, such as the washing nozzle head, catwalks and the like.

From very early on in the preliminary investigations on VLCC explosion hazards, it became obvious that the most likely ignition source within the tanks was in fact electrostatic. With hindsight, it would appear almost obvious that electrostatic charge separation might have played an important role in the creation of high electric fields. After all, high velocity water jets impinging on the tank wall would result in severe fragmentation of the water and inevitably create a water/slurry aerosol cloud reminiscent of the situation reported by Pierce and Whitson[3]. Much of the research effort was therefore concentrated on the electrostatic creation of a spark within the cargo tanks.

Early experiments by the Shell research team in Amsterdam showed that, if earthed probes were lowered into a tank containing a charged aerosol, small discharges were observed. These discharges were accompanied by light emission which coincided with the pulses, but were estimated to be of very low energy (about 10^{-6} J, compared to the 0·2 mJ minimum ignition energy for the atmosphere within the cargo tanks).

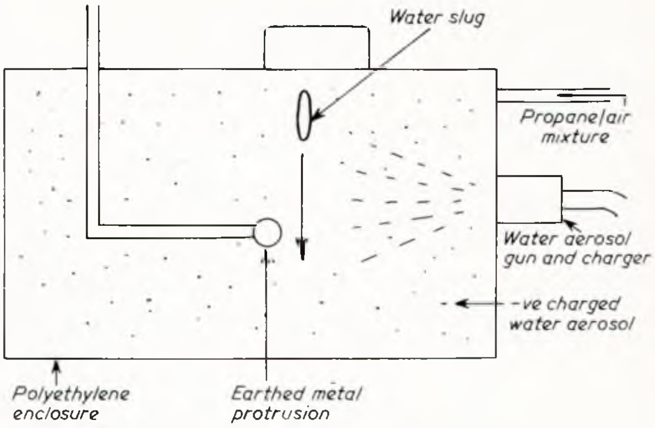

FIG 5 Scaled tank testing facility (volume 12 m^3)

Discharges from water drops

The conditions found within a VLCC during tank washing have been roughly simulated on a small scale. Fig. 5 illustrates schematically an experimental scaled tank testing arrangement. Although the volume of the small enclosure was only about 12 m^3, compared to 24,000 m^3 for a typical centre tank, it was nevertheless possible to scale the electrical conditions within the enclosure at the expense of only one parameter. Conditions created within the enclosure were reproducing exactly both the electric field and space potential as measured on board ship. On the small scale, however, this was only possible at the expense of a much higher space charge density (about 10^{-6} $C . m^{-3}$ compared to 10^{-8} $C . m^{-3}$ on board ship). This was later found to be quite acceptable and did not affect the validity of the scaled experiments.

With this experimental arrangement, it was possible to identify two spark sources that can be created in a charged water-aerosol environment. These were:

i) corona discharges from water drops;
ii) high energy sparks from water slugs.

Corona discharges

Disintegration of the water jets at the tank walls during cleaning gives rise to a cloud of charged water droplets. The coarser drops all assume the same sign of electrical charge, while the particles in the finer mist retain the opposite sign. The way in which the charging between the coarse and fine droplets occurs is not well understood and is at present unpredictable. A small change in the purity of the water may well reverse the sign of the charge on the particles.

Once the bipolar charging has occurred, the larger drops precipitate more rapidly than the finer mist, and this gravitational sorting results in the creation of a unipolar charged aerosol cloud in suspension in the tank.

If earthed protrusions exist within the tank, then wetting will be greatly enhanced due to the aerosol particles being charged—a mechanism which is usefully adopted in electrostatic spray painting. With the excess water therefore accumulating on the protrusion, it will drip into the bulk of the tank under the combined actions of gravity and the electric field[13]. The result will be the elongation of the departing water droplet into a long, sharply pointed, filament at the end of which will be created a small "corona" type discharge. Fig. 6 illustrates schematically the sequence of events leading to this type of discharge.

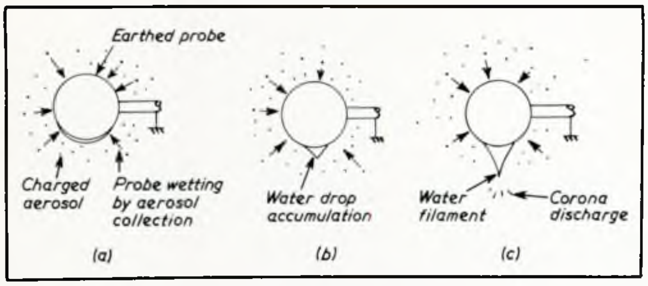

FIG 6 Formation of corona discharge in water aerosol: (a) water collection (b) drop formation (c) onset of corona discharge

Any situation which results in water (or any other liquid) dripping under gravity in an electric field will inevitably result in the creation of corona discharges. Within the tanks of a VLCC during washing these discharges will undoubtedly be widespread, but fortunately the energy involved is well below the typical minimum ignition energy of a tank atmosphere ($\simeq 0{\cdot}2$ mJ). In tanks carrying cargoes around 0·05 mJ for ignition, however, this type of corona discharge would indeed present a serious hazard.

High energy sparks from water slugs

To solve the VLCC explosion problem, it was therefore necessary to identify a more energetic spark. The source found capable of producing such a spark is now generally known as the water-slug mechanism. The sequence of events leading to the creation of such a spark are complicated but scaled experiments demonstrated the validity of the hypothesis. As shown in Fig. 5, the small test enclosure was filled with a charged water aerosol, thus reproducing the electrical conditions within a VLCC during tank washing. A small earthed probe represented a tank protrusion and the entire enclosure could be filled with a representative incendive atmosphere (in this case propane). Shown also in Fig. 5 is an isolated "slug" of water descending through the charged aerosol and arranged to pass in close proximity to the earthed electrode.

As this "slug" descends, it becomes electrically charged by a combination of up to four complex mechanisms (see Appendix). As it approaches the earthed probe, a spark will be created between the "slug" and probe. Measurements of the charge transfer involved in such sparks indicated energies well in excess of 0·2 mJ, and this was later confirmed by repeating the slug release test in an enclosure filled with a stoichiometric propane atmosphere. Ignition was readily accomplished and corresponded with the slug approaching the earthed probe.

The likelihood of this ignition model occurring under normal operations, and therefore its relevance to tank washing might be questioned. No guarantee can be given but at least it is a mechanism which has been proved capable of producing incendive sparks under a simulated tank washing environment. Large isolated slugs of water have been frequently reported in tanks and that, coupled with the charged aerosol, incendive atmosphere and earthed protrusions, creates a situation with all the necessary ingredients.

CONCLUSIONS

Explosions within a VLCC during tank washing have perhaps been the most spectacular demonstrations of the hazards associated with electrostatic charge separation phenomena on board ships. The mechanisms involved are now reasonably well understood and rigid safety procedures have been drawn up (e.g. inerting). This illustrates that it is always the unexpected which is hazardous, and that there is no room for complacency in the field of hazard minimization and control.

With the newer breed of ships now appearing, such as HMS *Brecon*, which are fabricated entirely of GRP, the problem of fuel charging, personnel charging, lightning protection, ammunition handling and so on must be completely re-assessed. Even so, no matter how detailed and well intentioned hazard research programmes might be, there is no reason to suggest that electrostatic phenomena will ever be made to change their historically unpredictable nature.

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APPENDIX: THE SLUG MECHANISM

When a slug is about to be detached from the roof of a tank, it will be charged by induction as a result of the charged water aerosol airborne in the tank. The surface boundary charge will be given approximately by:

$$q_b \simeq 3\varepsilon_0 E_0 \pi a^2$$

where a is the radius of the hemispherical end of the slug, E_0 the electric field due to space charge at the tank wall, and ε_0 the permitivity of free space.

After detachment, the slug will fall under gravity and will collect charge mainly by impact with the charged water aerosol. There will also be a dielectric polarization effect due to the highly non-uniform field. The charge acquired by the slug in falling will be a function of the swept volume during its fall, and the total collected charge q_c will be given by:

$$q_c = A_r d \rho$$

where A_r is the frontal area of the descending slug, d is the distance travelled and ρ the charge density. Another similar process will be the collection of free ions during the descent. This mechanism is usually called the Pauthenier charging and the limit of ionic collection will be given by:

$$q_p \simeq 6\varepsilon_0 \bar{E} a \lambda$$

where $\bar{E}$ is the mean field in the tank, a is the radius of the hemispherical tip of the slug and λ is the length of the slug.

Finally, as a result of the non-uniform field within the tank, created by the protrusion, polarization or dipole charging will cause charge separation to occur along the length of the slug. An expression for this is given by:

$$q_d = 3.8\varepsilon_0 E_p \lambda^{1.5} a^{0.5}$$

where E_p is the intensified field at the surface of the protrusion.

From the scaled tests referred to in the text, approximate values of charge for these four mechanisms can be calculated. It was found that the last mentioned, q_d, was the predominant charging mechanism. Calculation of q_d and further substitution into an energy equation showed that slug discharges were indeed well in excess of 0·2 mJ.

The energy can be calculated from the relationship:

$$\omega = \tfrac{1}{2} q_d \bar{V}_s$$

where $\bar{V}_s$ is the average space potential.

Discussion

COMMANDER M. J. NEEVES (Ministry of Defence) opened the discussion by congratulating Dr Hughes on a very clear exposition of the problems of electrostatic charges onboard ship. As a marine engineer the subject of electrostatics had always been a bit of a mystery to him and he felt Dr Hughes had helped to shed a little light.

His particular interest was in hazards to fuel in warships, and his involvement with Dr Hughes and his team had started with the work he and his colleagues had undertaken for the Ministry of Defence on the hazards to fuel in their GRP mine sweepers. They were concerned that conditions might arise that could lead to an electrostatic spark igniting fuel vapour or mists in fuel tanks of those vessels. He thought it was worth emphasizing that a flammable mixture of fuel vapour and air, or small fuel droplets and air, as well as an energetic spark, were needed to produce a fire or an explosion. It was in order to minimize the risk of a flammable mixture that the RN insisted on high flash point fuels for both ships' propulsion and aviation fuels. Risks of ignition of those were quite low at normal temperatures, although they were concerned at their lack of certainty over margins of safety under high temperature conditions, such as in the tropics or in ready-use tanks sited in machinery spaces.

To gain a better understanding of the mechanism of ignition of fuel mists and vapour in ships' tanks and the conditions needed to relax safely any charge in fuel tanks, the MoD was sponsoring further work at Southampton University. They were of course concerned with GRP tanks, as in the minehunter, but were also worried about metallic tanks protected by epoxy paints. He wished to ask the author whether he thought that potentially hazardous charges were likely to arise in such tanks or whether there should be sufficient relaxation achieved through metallic pipe work and fittings which would in general not be so coated.

MR J. D. BOLDING, CEng, MIMarE (Lloyd's Register of Shipping) made several comments related to cargo pump rooms of tankers:

1) Nylon control air pipes with small metal couplings could create an incendive spark (pressures less than 100 p.s.i.).
2) Air motors driving cargo valves using oil and moisture-laden air could create a static charge on an insulated object in a cargo pump room.
3) Testing of CO_2 horns using compressed air was suspected to be a risk as in 2) above.
4) During a salvage operation, *Alva Cape* blew up when CO_2 was used to inert a naptha tank due to CO_2 "snow" particles.

MR R. F. CLARKE CEng, FIMarE (Marine Advisory and Technical Services) raised the following comments and questions.

A mention had been made of insulated tanks as being potentially dangerous for high static build-up. Was it dangerous to use epoxy material to coat tanks completely, as was quite common in product tankers and other tankers, which might not be fitted with an inert gas system?

What effect did a pipe made of material of high conductivity have on the discharge or build-up of electrostatic potential of a liquid being pumped through the pipe? How much effect did a pump have on the electrostatic build-up of a liquid passing through it?

The author had mentioned the electrostatic build-up in liquids, but Mr Clarke wished to know how much research had taken place concerning electrostatic build-up in gases and vapours: did they behave like liquids?

Author's Reply

To Commander Neeves the author replied that the use of metallic pipework did not necessarily mean that the net charge separation during pumping would be less than in insulating pipework. In the case of an epoxy coated metallic tank, the charge behaviour within the tank would be different to that in a tank fabricated entirely of GRP or similar insulating material. In the case of tanks situated on the ground or in the sea, for example, then charge relaxation in the painted metallic tank would be expected to be evenly distributed to the walls and base of the tank. For a GRP tank, it was known that charge would predominantly relax to the base of the tank.

It was impossible to predict the electrostatic behaviour of particular systems, but a good guide in all potentially incendive situations was that the use of insulating materials should be avoided if at all possible.

The comments of Mr Bolding had been very relevant to the presentation and discussion. The author would only like to add by quoting work carried out by Leonard at the Naval Research Laboratory, Washington DC, which was of special relevance to point No. 3: "Generation of static electricity by carbon dioxide in inerting and fire extinguishing systems", J. T. Leonard and R. C. Clark, *Inst. of Phys. Conf. Ser. No. 27 (1975), pp 301–310.*

Mr Clarke's first question had been similar to that asked by Cdr Neeves, and the author would answer by repeating that the behaviour of particular systems could not, in general, be predicted. The electrostatic behaviour depended so much on the materials used. However, the use of highly insulating materials had in the past indicated an accentuation of the potential hazard from charge retention.

In general, there was no direct relationship between liquid charging and pipe conductivity. Again, there was no general pattern of charging with pumping; but it was likely that charging behaviour would be different on pumps and different from pump to pump.

Electrostatic charge separation during movement of gases and vapours was usually negligible. However, if the gases or vapours contained small solid particulate matter or liquid droplets, then charging could be greatly accentuated. For example, a steam jet was usually a very good charge generator.

Late Contribution — *received after the author had made his reply*

MR. D. J. WALKER BSc, CEng, MIEE, RCNC, (Ministry of Defence) wished to comment on the question of lightning protection requirements for GRP Ships.

In a metal ship, there was only a very minimal concern about the effect of lightning strike unless the ship happened to be carrying oil, gas or some other dangerous cargo. Metal warships were such that lightning strikes had very little effect, since the current flowed through the structure of the ship to dissipate its energy into the sea. Naturally, the input stages to radio and radar equipment had to be hardened to reduce the effect of any induced voltage.

However, on a GRP warship the effects of a lightning strike were far more significant since the lightning current had to pass through the ship and into the sea without causing significant damage to equipment or structure. It was interesting to note that there had been several accidents involving GRP yachts with aluminium masts which, when struck on the mast head, passed the lightning current down the mast and into the sea through the GRP hull, with rather disastrous results.

The possible effects of a lightning strike to a GRP warship were classified into three different categories:

1) *Ship critical*—where the structure of the ship was damaged sufficiently to threaten the safety of the ship;
2) *Mission critical*—where the functioning of vital operation equipment was jeopardized;
3) *Nuisance*—in which only minor structural or equipment damage was incurred.

Nowadays, it was considered essential to ensure that ship critical damage was avoided by providing an adequately designed lightning protection system, consisting of an air terminal and a down conductor routed by the most direct path through the ship to a lightning earth plate where the energy might be safely dissipated into the sea.

The protection of mission critical equipments from induced voltage effects was very much more difficult and costly to achieve. The system cable layout and positioning needed to be carefully arranged so that the cables were either physically separated from the lightning conductor, or the area of the loop formed between the equipment wires and the lightning conductor was minimized.

There was, in general, nothing to be gained by screening the lightning conductor as the external fields created by the passage of the lightning current were not reduced by the presence of the screen. That was due to the fact that the screening process required the flow of a return current to cancel out the field created by the down current and, with lightning effects, the return current was diffused.

The design of a warship manufactured from non-conducting materials was, therefore, very much a compromise between the elimination of the effects of induced voltages due to the lightning current and the cost to the ship both in the design of the system and the layout of equipment.

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