ELECTROSTATIC HAZARDS IN SHIPS' FUEL SYSTEMS

BY

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Introduction

Petroleum-based fuels have been used on board ship for many years and it has long been recognized that these fuels carry with them potential hazards. Over the years rules have been formulated to allow the safe handling of petroleum fuels and, provided the rules are observed, hazards are regarded as minimal. Fundamentally, a safety rule is designed either to avoid contact between a source of ignition and a flammable atmosphere or to avoid the formation of a flammable atmosphere. Under normal storage and handling conditions shipboard fuel does not become mixed with oxygen in the correct proportions for an ignition source to produce a fire. Gasoline is normally so volatile that too much hydrocarbon is present to allow the mixture in air to burn; it is 'over rich' and gasoline stowages are designed to avoid production of a flammable mixture. The more flammable of the aviation fuels (AVTUR) presents a special hazard but it is not normally carried on board ship and for the present discussion can be excluded.

Fires do occur from time to time and this must mean that circumstances that the safety rules do not cover either exist or have arisen, or that the rules have been broken. It is one of the functions of N.G.T.E. (Cobham) to examine the conditions under which fuels are handled and to advise on the possibility of hazard, particularly when novel procedures or materials are involved. Studies have included prediction of the flash point that would result if different fuels become mixed and how the incidence of explosion and fire hazards depend on the ratio of free space to fuel in ships' fuel tankage.

Recent work has been concerned with the generation of static electricity in fuel systems and the major part of this article is intended to describe this work up to the stage that has now been reached.

Electrostatic Charging

The principles underlying the production of static electricity are well known but it is worth repeating some of the basic points since the impact on ships' systems can be so important.

The electrical condition of an interface between two media is fundamental to the production of static electricity. It was suggested by Helmholtz in 1879 that an electrical double layer, of positive and negative charges, is generally formed at the surface of separation between two media. This double layer is regarded as being made up of a fixed layer of charged species, firmly held to the solid, and a more diffuse mobile layer extending into the liquid. The relevant (net) charge of the diffuse layer is equal in magnitude but opposite in sign to that of the fixed layer. FIG. 1 is a schematic representation of the structure of the double layer; in one case it is supposed that the fixed layer is positively charged, while in the other case it is negatively charged. The difference in potential, representing the separation of fixed and diffuse double layers is known as the zeta potential (ζ).
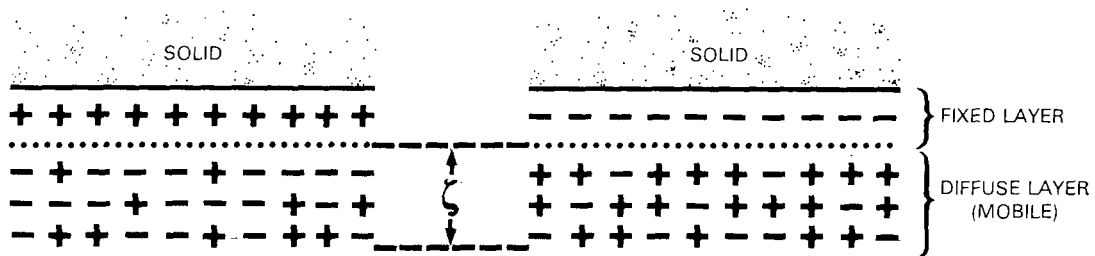

FIG. 1—REPRESENTATION OF ELECTRICAL DOUBLE LAYER

A zeta potential can, in principle, exist between any two media. While this is undoubtedly an over simplified view of the origin of charge at an interface, it is also a useful concept in studying electrostatic phenomena. When motion takes place between two media the electrical double layer is sheared and charged species associated with the mobile layer are carried away. The magnitude of any observed charge depends on the zeta potential, the velocity of separation, and the rate of relaxation of the charge. The rate of relaxation is determined by the electrical conductivity of the medium. Charge relaxes exponentially and the

expression, $\tau = \dfrac{\varepsilon \, \varepsilon_0}{K}$ is used,

where ε = permittivity of the medium
ε_0 = permittivity of free space
K = conductivity of the medium
τ = time for charge to relax to 36·8 per cent. of its original value; this is usually referred to as the relaxation time.

Typical conductivities and relaxation times for a number of liquids charged by pumping through pipes are shown in TABLE I. The relaxation times in TABLE I apply assuming there is a pathway to earth.

Measurement

The first point with regard to measurement concerns the magnitudes of the quantities involved; these quantities are current, voltage, resistance, charge, and electric field. But it is worth remembering that a current of 10^{-6} amps is large on the electrostatic scale, a potential of 10^3 volts is modest, and that a resistance of 10^6 ohms is very low. All this applies constraints to the type of equipment used for electrostatic measurement.

TABLE I—*Conductivity values and relaxation times*

Material	Conductivity (K) siemens/metre	Relaxation time (τ) seconds
Distilled water	10^{-4}	7×10^{-6}
Crude oil	10^{-7} to 10^{-9}	$1\cdot8 \times 10^{-4}$ to $1\cdot8 \times 10^{-2}$
Diesel fuel	10^{-10} to 10^{-12}	$1\cdot8 \times 10^{-1}$ to $1\cdot8 \times 10$
Aviation fuel	10^{-11} to 10^{-14}	$1\cdot8$ to $1\cdot8 \times 10^{2}$
Highly purified hydrocarbons	$<10^{-15}$	$>1\cdot8 \times 10^{4}$

Field

The most commonly measured parameter is electric field. There are a number of instruments available but they must be used with care since their very presence can distort the field and render the measurement meaningless. Ideally a field meter should be placed so that it lies in a surface at earth potential, e.g. in the roof of a tank. From this position, the field due to a charged fuel in the tank can be measured with certainty. Field is not, however, a fundamental measure of the electrical condition of a substance because the voltage or surface potential of a body is affected by the surroundings; in particular, it is altered by the capacitance of the body with respect to earth.
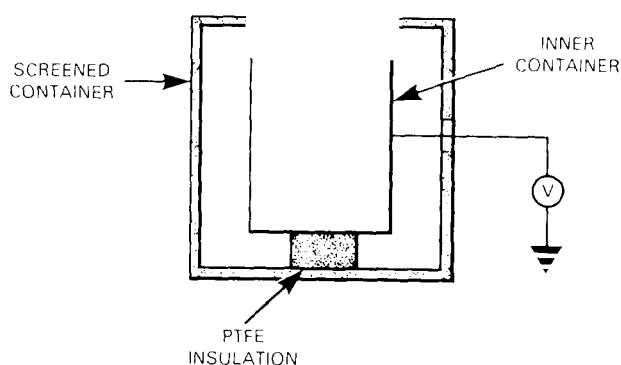

FIG. 2—FARADAY PAIL

Charge

The quantity of electricity associated with the body is called its electric charge, Q. The relationship between charge, voltage, and capacitance is given by,

$$Q = CV$$

The most satisfactory way of measuring Q is by use of a 'Faraday pail', see FIG. 2. The body charge induces an equal and opposite charge on the inner walls of the pail giving them a voltage defined by the capacitance to ground (C) of the pail and its associated output cable. This voltage can be measured with a suitable electrometer with calibrated leads.

Charge Density

A useful parameter when considering materials in large quantities is charge density; this relates the charge to a given quantity of the material. It is usual to refer to charge density of fuels in terms of micro-coulombs per cubic metre ($\mu C\ m^{-3}$). The instrument most commonly used for this purpose is in principle a field meter made to be immersed in the fuel and to measure the field in an earthed cage. These instruments are satisfactory but can be unreliable in use due to the number of moving parts. A more recent development shown in FIG. 3 has no moving parts. This charge density meter operates by measuring the streaming current I_s. The sampling section is about three times the diameter of the fuel pipe and is insulated from the pipe. The residence time of fuel in the
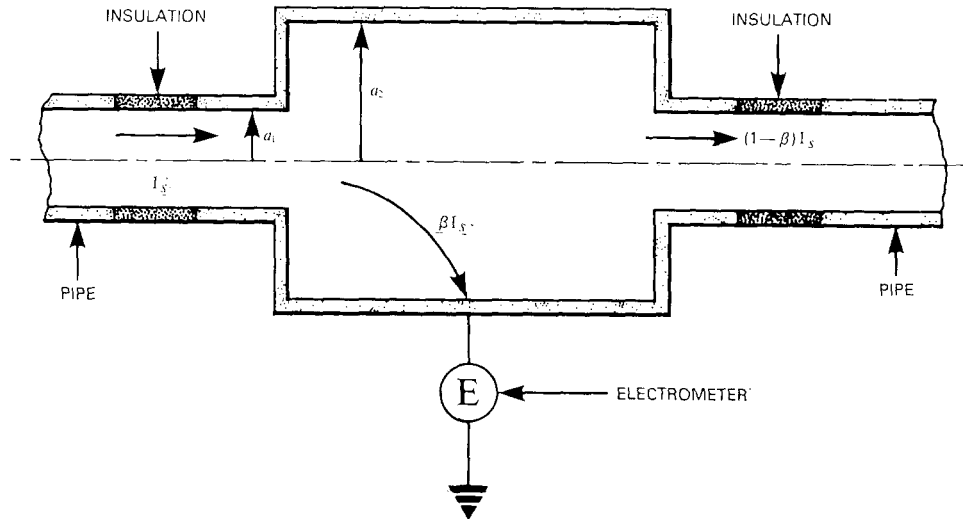
FIG. 3—CHARGE DENSITY METER

sampling section is large compared with the charge relaxation time, and an appreciable fraction β of the streaming current I_s relaxes to the wall and is measured by an electrometer. The charge density ρ is related to the measured current, βI_s, by the relation: $\rho = \beta I_s / \pi d^2_p v$ where d_p is the pipe diameter and v the flow velocity.

Charging in Fuel Systems

Pipes

Following from the classical principles of charging, it is evident that a liquid flowing along a pipe will acquire an electrostatic charge. As already suggested the amount of charge produced depends very much on the materials and the circumstances. Firstly, charge is generated when the electrical double layer is sheared, and the amount of charge produced depends on the zeta potential and the rate of shearing, which in practice means pumping velocity. Secondly, the amount of charge remaining depends on the relaxation time. It can be seen that the net charge will be the resultant of charging and relaxation. Several attempts have been made to predict the charge in a liquid flowing through a pipe, the best known equation being that proposed by Schon[1]. However, the predictions are not completely satisfactory and are at best a substitute for experimentally determined values. They do not, in any case, include non-metallic pipes or the effect of filters.

Insulating pipes do not allow charge to be injected to the fuel continuously although initially the rate of charging may be very high. An opposite charge is induced on the outside of the pipe and this effectively prevents, or inhibits, further charge injection.

Filters

The effect of adding a filter to a pipework system is generally to increase the rate of charging simply due to the increase in fuel velocity in the filter. There are, however, a number of additional factors to consider. First, although fuel velocity increases inside the filter medium, the increase in charge due to this may be offset by any reduction in velocity in the filter chamber which would allow charge to relax to earth. Second, the material of the filter medium is important; this has not been fully investigated but cellulosic materials seem to be prone to produce high rates of charge. Another factor to be considered is the charging effect due to the removal of particulates at the filter medium since this represents another double layer shearing process. The magnitude of this effect will depend

on the type of particulate and the filter medium as well as the particulate loading and the fuel velocity.

Tanks

Generally speaking the fuel, after passing through the pipework, flows into a tank. After reaching the tank any charge in the fuel will migrate to the walls of the tank and then to earth, provided an earth path is present. This process would take a second or so for diesel fuel (see TABLE I). If the tank is made of an insulator, like glass reinforced plastic (GRP), then a pathway to earth may not be present and the charge can be contained within the tank for a very long time. In fact, the rate of relaxation would depend on the surface area of earthed metal present, e.g. entry pipe, sounding tube. In a large tank, the surface area of metal present may be proportionally small and the relaxation time can still be several minutes. Contaminated fuel can produce charge inside a tank if it contains particulates such as water or solid dirt. The separation of these particulates on standing produces double layer shearing and charging. The amount of charge produced by this means is almost impossible to predict but would be expected to be small.

Fuel movement

Another effect which may be considered as a charge producing process within a tank is the effect of fuel movement inside an insulating tank. An effect of this kind was suspected in H.M.S. *Wilton* during a sea trial. The measuring techniques available at the time were not sufficiently reliable to be sure that charge was being produced in this way.

As fuel moves over the tank wall the shearing process can take place although, if the fuel moves back to its original position, one would expect the original electrical situation to re-establish. Any net charge produced must therefore appear at the extremities of the fuel's movement and therefore depend for its magnitude on the amplitude of the movement as well as the velocity. The effect could be further influenced by turbulence and the presence of metallic objects or structures within the tank.

Some very small-scale laboratory experiments suggested that charge could be produced by fuel movement over a plastic surface. However, a great deal more work needs to be done to evaluate this as a charge generating mechanism in moving insulating tanks. Equipment to do this has been installed at N.G.T.E., (Cobham) and it is hoped that the conditions under which charging may take place can be reproduced and the mechanism studied. Preliminary experiments suggest that the effect is very small.

Prediction of Charge Distribution

The fact that an insulating tank has been filled with fuel carrying a known charge does not mean that the distribution of charge in the tank is known.
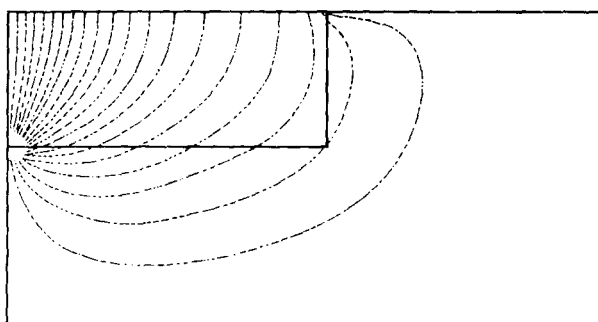

FIG. 4—EQUIPOTENTIALS IN AND AROUND
INSULATING TANK

Charge in a container will tend to migrate to the walls of the container but in an insulating tank most charge will migrate to the container wall nearest to earth. Similarly the introduction of any earthed object will distort the electric field. These general statements are not sufficient to give guidance when designing a tank so that regions of high electrostatic stress can be avoided. By making careful measurements of the field in and

around simple tanks and tanks containing various discontinuities such as baffles and earthed objects, the data can be developed by use of finite analysis to predict the effect of changes in the tank and the objects it contains.

A diagram showing a computer analysis of a simple tank standing on the ground and containing an earthed field meter is shown in FIG. 4. Further development of this technique with improved precision and extended to more complex geometries will enable predictions to be made regarding fuel tanks and systems while they are in the planning stage. This will avoid the necessity of having to alleviate hazards due to design after the system has been built.
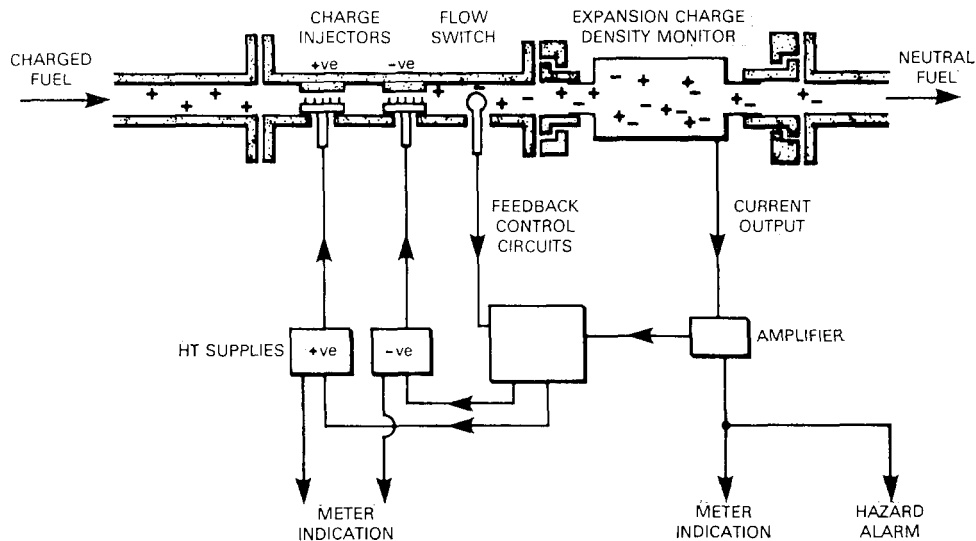

FIG. 5—ELECTROSTATIC DECHARGER

Charge Reduction

Fuel passing along a pipe and carrying charge can constitute a hazard. If, however, something can be done to reduce or remove that charge then the hazard will also be reduced. Two routes may be used to accomplish this. As stated earlier, charge always tends to relax to earth and if something can be done to enhance relaxation then the hazard will be reduced. A reduction in velocity of the fuel allows some relaxation and the introduction of an expansion chamber will have this effect. An example of this is a fuel system which contains a header tank or some similar temporary holding chamber between the fuel supply system and the internal pipe work, e.g. in a ship. The greatest relaxation effect would be obtained with an earthed header tank of large capacity. An increase in fuel conductivity will also allow relaxation to take place more readily, as shown in TABLE I. Fuel conductivity can be increased artificially by the use of additives, known as charge dissipator additives. Some fuels, particularly aviation fuels, are regularly supplied containing charge dissipators.

A further method of removing charge from fuel in a pipe relies on sensing the charge density and injecting charge of opposite sign until the net charge becomes zero. The principle of a commercial development of this method is shown in FIG. 5. The charge density meter employed in this instance is of the relaxation chamber type described earlier.

GRP Ships

The Royal Navy now possesses ships constructed of glass reinforced plastic. Two of these, H.M.S. *Wilton* and H.M.S. *Brecon*, have been examined in some detail to measure electrostatic charges in the fuel systems.

The fuel arriving at the entry point to the ship's system will be charged due to

its passage through the supply system. Ship trials have been done to investigate the charging effect of the ship's own system and to decide on the possibility of hazard within the ship.

Current GRP ships are fitted with header tanks as the first element of the fuelling system. In itself a header tank acts as a relaxation chamber and is an asset, electrostatically speaking. However, the header tank is fitted with flow control equipment and the early design of this equipment gave rise to turbulence and foaming which are electrostatic charge promoting. The design was altered to reduce these effects and the ship trials showed that relaxation takes place on passage through the header tank. As the fuel flows through the pipework into the main storage tanks further charge is produced. The measurements made in the fuel system, including those made in the main tanks during embarkation of fuel, have shown that the charge generated is of a low order and would not constitute a hazard.

The effect of fuel movement inside a ship's tank has not been fully examined. It has not yet been possible to make the measurements on board ship. Preliminary experiments in the laboratory suggest, however, that the effect would be small.

Summary and Conclusions

The work on electrostatics at N.G.T.E., Cobham was started in anticipation of electrostatic problems arising with ships built of insulating material. When the work was started, H.M.S. *Wilton* had not been completed and the amount of charge produced could not be predicted. The study of electrostatics applied to systems on an engineering scale and complexity has not progressed beyond the empirical although great efforts are being made to develop the theoretical foundations. Even measurement techniques are still unsatisfactory so that the interpretation of experimental work is often difficult.

Having said this, the experimental work that has been done in the laboratory, on large scale rigs and on board ship, is consistent in indicating that the charge levels are low. In normal operations of the present ships, no undue charge is produced and hazards are therefore not present.

Until more is understood about charging in complex systems and the prediction of the effect of system design on charge, it will be necessary to test each new design aspect as it arises. Research work now in hand is aimed at improving this situation.

Reference:

1. Klinkenberg, A. and Van der Minne, J. L., 'Electrostatics in the Petroleum Industry' *Elsevier*, 1958, pp. 58–64.