# EXPERIMENTAL INVESTIGATION OF ELECTROSTATIC FIRE AND EXPLOSION ACCIDENTS AFTER AIRCRAFT LANDING AND PREVENTIVE DESIGN

LOU HAN-SENG
The Scientific Research
Institute of Air Force
Beijing, China

## ABSTRACT

This paper is a summary of research on several electrostatic fire and explosion accidents involving fuel tanks after aircraft landing. The research work has, under the fire and explosion environment conditions, endeavored to conduct a series of ground simulation tests and actual flight tests, measure and record the generation and accumulation of electrostatic charges inside of fuel tanks during the whole process from aircraft taking-off to landing and after engine shutdown. The records have indicated that the process of aircraft landing run is the fundamental process of electrostatic charges generating in fuel tanks; and after aircraft coming to a standstill, there is also a process of electrostatic charges accumulating while fuel charged with higher energy and remaining for a considerable long period, unable to be dissipated. Under such conditions, the fires and explosions would take place, only when the fuel tanks contain fuel vapor at the near chemical equivalent concentration and electrostatic discharge sparks of sufficient energy.

The experiment has also showed that the generation and accumulation of electrostatic charge are related with those factors, such as flight mode, tank material, surface insulating ability of fuel tank compartment, anti-sloshing separator material, environment ( locality, weather ), and so on. Accordingly, some principles which should be followed in the aircraft fuel system design were raised. Practice proved that the appropriate measures adopted from these principles can prevent electrostatic fire and explosion accidents occurring inside of fuel tanks after aircraft landing.

Since 1960's, the electrostatic fire incidents during aircraft ground fueling have constantly taken place. Many countries have been engaged in a number of researches and analyses on the subject, and adopted several effective preventive measures. Recently, the number of electrostatic fire and explosion accidents after aircraft landing and engine shutdown in several minutes has steadily increased. This fact directly threatens the safety of aircraft and people . Such kind of fire accident researches and analyses would play an important role in the prevention of accidents and the improvement of aircraft safety.

## FEATURES OF ELECTROSTATIC FIRE ACCIDENTS AFTER AIRCRAFT LANDING

According to the study of aircraft wreckages resulting from post-landing electrostatic fires and the statistical analysis of them, these accidents have the following features:

(1) They took place only in the aircraft with anti-sloshing nylon fabric separators installed inside of fuel tanks(Fig.1).

(2) They took place after aircraft landing and engine shutdown in 2-5 minutes.

(3) There has been a certain space above the fuel surface in the fired and exploded fuel tanks using RP-2 fuel.

(4) They are markedly seasonal. In China, all of these accidents take place from May to August.

## EXPERIMENTAL INVESTIGATION OF THE CAUSES FOR ELECTROSTATIC FIRES AFTER AIRCRAFT LANDING

### 1. Approaches

Fires and explosions of electrostatic origin should satisfy the conditions as follows:

(1) There is a state easy to generate electrostatic charges.

(2) After static electricity generated, its leakage is very few, and there remains an insulating state able to accumulate electrostatic charges.

(3) Something exists and serves as the electrode for discharges.

(4) Electrostatic discharge energies are high enough to ignite flammable gases.

(5) Electrostatic sparks can cause ignition, but only for the flammable gases at the near chemical equivalent concentration.

In the experimental investigation, if we want to ascertain whether fire accidents involving aircraft post-landing result from static electricity, then we must define whether above conditions have been met while these accidents occurring , and conduct a number of studies on the subjects, such as charging state on the fuel inside of aircraft fuel tanks, flammable vapor concentration in the tank, dangerous electrostatic igniting sources, etc..

### 2. The study of charging inside of aircraft fuel tanks

Electrostatic phenomenon is a phenomenon under the combined influence of a multiplicity of factors, and changing with the change of external conditions. Therefore, the study of the causes for electrostatic fires has to be conducted under the condition while these accidents taking place. Static electricity is the simultaneous coexistent phenomenon of electrostatic field and discharge. The configuration of the fuel tank, materials, and installed parts inside of the tank all may have an effect on the electrostatic charging state . In order to achieve electrostatic reproduction, the charging state in aircraft fuel tanks was measured in the field under the condition of actual accidents. The contents of the study include: the states easy to generate static electricity, electrostatic leakage in the tank, and electrostatic energy accumulated.

#### 2.1. Charging state in the fuel tank

There are three electrostatic sources in the fuel tank:
(1) fuel being pumped through a pipe into a receiving tank;
(2) during aircraft maneuvering flight and running, fuel rubbing against the walls of the tank and the nylon fabric seperator , or fuel filtering through the separator;
(3) various floats floating on the fuel surface.

The results of flight test and ground simulation test have shown that when the fuel is sloshing in the tank and when the fuel is rubbing against the tank walls and nylon fabric separator or filtering through the separator, the potential on the fuel surface reaches a maximum which is 5.7 times larger than that when the fuel is pumped through a pipe into the tank, and 47 times larger than that when various floats are floating on the fuel surface. When the fuel is rubbing against and filtering through nylon fabric separators, the potential on the fuel surface is 39 times larger than that when the fuel is rubbing against the tank walls. Therefore. an electrostatic charge is generated mainly in the process of fuel rubbing against and filtering through nylon fabric separators.

Which flight mode will make electrostatic charge easy to be generated inside of a fuel tank? Through the use of an electrostatic measuring device installed on aircraft , from engine start -- flight in the air -- landing to engine shutdown and right after it in the duration of 5 minutes, the change of the level of charge on the fuel has been recorded. All the curves from the record are shown in Fig.2, Fig.3, Fig.4, Fig.5, Fig.6, and Fig.7.

The following are what these curves show: (1) In the process of aircraft running and maneuvering flight, the charging on the fuel surface would change rapidly, especially in the process of landing run, even charge polarity reversal phenomenon would also appear. (2) In the process of level-flight, the level of charge on the fuel is low and the amplitude of change narrow too. (3) While flying in the air, there are generally positive charges on the fuel surface. (4) The charging on the fuel after aircraft landing and engine shutdown has not much relations with the charging in the flight. but mainly due to the mode of landing run. The charge polarity and the level of charge are related to the separator materials and the extent of fuel sloshing. Separators, made of nylon fabric or nylon fabric covered with electro-conductive rubber, usually place negative charges on a fuel, and the maxima of the level of charge measured are $6.28\times10^{-6}$ Coulomb/$m^2$ and $4.45\times10^{-6}$ Coulomb/$m^2$ respectively, both greatly exceed the standard of the safe level of charge for a fuel which is $1\times10^{-6}$ Coulomb/$m^2$ . And separators, made of natual silk and polyster fibre blend fabric with electro-conductive fibre in it, allow the level of charge on a fuel to reach $3.41\times10^{-7}$ Coulomb/$m^2$. (5) After engine shutdown, the level of charge on the fuel is quickly tending towards a stable value which will basically have no change in the duration of 5 minutes recorded.

from above test results, it can be concluded as follows:

(1) Fuel charging in the tank is mainly due to fuel rubbing against nylon fabric separators and filtering through nylon fabric. The electrostatic charge polarity on the fuel surface and the level of charge are related to the separator materials and sloshing extent.

(2) The flight mode which has the greatest effect on fuel charging in the tank after aircraft landing is landing run.

(3) After aircraft landing and engine shutdown, charging on the fuel surface is in an insulating state of electrostatic accumulation.

## 2.2 Electrostatic leakage in the fuel tank

We know that if the fuel is charged with static electricity, then, like any other material, its charges will sooner or later relax or dissipate. There are two ways for charge relaxation: (1) the charge will be neutralized with electron or ion in the air, (2) the charge will leak to ground through some insulators, such as charged insulator, container and its supporters, and then dissipate.

As stated above, there happens basically no charge leakage on the fuel surface in the tank after aircraft landing. It is because that the aircraft fuel tank is a closed container pressurized with the air from engine without any electron / ion bearing fresh air to neutralize electrostatic charges after engine shutdown, and that the aircraft fuel tank is made of rubber material with high volume resistivity (above $10^{12}$ ohm·cm) and the tank bay is made of surface-anodized aluminium alloy plate with high insulativity. Consequently, the leakage resistance from fuel to the ground is very high, according to ground measurements, its value between tank walls, tank bay and ground being more than $10^{12}$ Ohm. Thus, there exists an insulating state for the electrostatic charge to be sufficiently accumulating.

2.3 The effect of environment (locality, weather, etc.) on the charging in the fuel tank

Tests discovered that external environmental conditions have an important effect on the charging in the fuel tank. In a flight test for nylon fabric separators, with other test conditions all the same, the level of charge on the fuel surface measured before typhon and cold current coming is 12 times higher than that after their coming, which may be a phenomenon related to atmospheric electric field. Meteorological observation has shown that every type of precipitation sometimes would receive a positive charge, sometimes a negative charge. However, the rainfall with positive charge is more than that with negative charge, resulting in a quantity of purely positive charges transfered down upon the earth. Rainstorm and precipitation brought in with typhon and cold current would make a great number of positive-charged small water drops float in the air, and the positive charge content increase in the lower atmosphere. Therefore, an increase of positive charge content in the compressed air from aircraft engine would decrease the level of charge on the fuel inside of the tank.

So far as the humidity in the air is concerned, the ground test has shown that the higher the humidity is, the lower will be the level of charge. Nevertheless, this effect is not isolated, but related to the environmental condition such as locality. For example, test has shown that the air humidities both in the South and in the North of China are over 70%, and when their humidities are the same, or even when the humidity in the North is higher than that in the South, the level of charge on a fuel measured in the North would be more higher than that in the South.

In short, the effect of environmental factors is a very complicated problem which we scarcely examined, so that it requires a long-period electrostatic observation, and then we can make this problem clear.

## 3. The study of flammable vapor inside of aircraft fuel tanks

The energy required for a spark discharge to ignite flammable fuel/air mixture varies with concentrations. When the concentration of a flammable vapor comes near the chemical equivalent, the energy required for ignition will be a minimum. The minimum ignition energy for the flammable mixtures of each hydrocarbon is generally in the range of 0.2 to o.3mJ. When the concentration of a flammable vapor reaches nearly to its upper limit or lower limit, the ignition energy will increase according to exponential function, and when the fuel vapor concentration is in the vicinity of lower limit, the energy requirements will be in the range from 5 to 6 mJ. Thus, the electrostatic spark-ignited fire and explosion concept applies only to situations in which the flammable vapor concentration comes up to its chemical equivalent. In defining the cause of an electrostatic fire, it is necessary to measure the concentration of flammable vapor in the fuel tank.

The concentration of flammable vapor produced inside of aircraft fuel tanks varies with those factors, such as atmospheric temperature, fuel temperature, flight altitude, flight speed, flight time, engine operation, braking in landing run, etc.. In the test study, the method adopted is to take fuel vapor samples from the tank after aircraft landing in the field and make analysis and measurement with chromatograph of gases. The results showed that: After the aircraft, with anti-sloshing nylon fabric separators installed inside of fuel tanks, flying in the hot weather, the fuel vapor concentration in the tank is about o.5 to 5% which is just in the flammable concentration range from o.5 to 7.2% for RP-2 fuel. The chemical equivalentconcentration of RP-2 fuel is about 3.5%. Therefore, during such kind of aircraft flying in the hot weather, it is possible to produce a flammable vapor near its chemical equivalent concentration in the aircraft fuel tank. This is one of the important causes for accidents with marked seasonal feature.

4. The study of dangerous electrostatic ignition sources

There are usually three types of discharges in the fuel tank: the first one involving a corona discharge from the fuel surface to the sharp point of some grounded projection, the second, a streamer discharge from the fuel surface to the area of some grounded projection ( with curvature radius larger than 6mm ), and the third, a spark discharge from some unbonded conductors in the tank. Which type of discharge actually occurs in aircraft fuel tanks relates to those factors, such as electric field strength in the tank, configuration of discharge electrodes, gap distance between electrodes, and so on.

Due to the limited current, corona discharges from a fuel surface in the tank usually occur as short bursts. Each burst is made up of discharge energy from 4 to 11$\mu$J. Also, due to their low energy, corona discharges are generally considered non-dangerous.

The streamer discharge from fuel surface to grounded projection can occur at large gaps (over 2.5cm). It is due to the insulativity of fuel, charges would relax to null only at the place where discharge occurs, and still remain at other place. Consequently, the energy of streamer discharges is much lower than that of spark discharges.

Spark discharges can occur between unbonded conductors in aircraft fuel tanks at a small gap width (about 2mm). Spark discharges are a type of high energy discharge which can relax their accumulated charges altogether instantaneously and hence, are considered a greatest danger. It is worthy of note that as there are in the tank some mechanisms for controlling the fuel-usage sequence and measuring the quantity of fuel with their pickup members floating on the fuel surface, and these mechanisms generally consist of rotating shafts, then, while these mechanisms being made of aluminium alloy material, in view of the insulativity of the anodized aluminium alloy surface and the fuel, under certain conditions, there may be a non-conducting state formed between two conductors along the shafts. Therefore, pickup members floating on the fuel surface (such as floats) will become "charge collectors", and two conductor parts along the shafts "condensers". When the electrostatic field strength accumulated in the "charge collector" reaches a breakdown value in the fuel vapor space, a spark discharge will occur at the place where the "condenser" is formed along the shafts. From the electron microscopic analysis of wreckages in electrostatic fire accidents, some "volcanic vent"- likehigh temperature-melted micro-pits, or micro-pits from spark discharges, have been found on these wreckages which are structurally similar to the above mechanism ( Fig.8). The appearance of micro-pits has a resemblance to that formed in the ground test of a "spark discharge" from high voltage and small current (Fig.9). The results of analysis have shown that there really exist dangerous spark discharges inside of the fuel tank, and the electrodes for discharges are two unbonded conductor parts.

## PREVENTIVE MEASURES OF AIRCRAFT FUEL ELECTROSTATIC HAZARDS

The prevention of electrostatic hazards requires to search for preventive measures all-sidedly on the basis of the contents and targets of hazard prevention. The most serious consequences involving aircraft fuel electrostatic hazards are fires and explosions. We know that fires and explosions only occur at the time when both conditions of flammable fuel/air mixture being produced from a fuel and electrostatic discharge becoming an ignition source are met. For this reason, to prevent aircraft fuel from being in electrostatic hazards, measures, aimed at eliminating or limiting related main factors which can create above two conditions, should be adopted. Prevention of electrostatic hazards is a problem which has to be considered by all the sections involving aircraft design, manufacture, operation and maintenance. In order to prevent aircraft from electrostatic fire accidents after landing, measures should be adopted early in the aircraft design stage from the following fields:

1. Prevention of producing flammable fuel/air mixtures

   To prevent from producing flammable fuel/air mixtures, the methods, such as inerting the vapor space of the tank, use of a high flash-point fuel, etc., are proposed in the design of aircraft fuel systems. Inerting the vapor space of the tank would be ideal measure either in preventing from electrostatic fires and explosions or in preventing from lightning strikes. However, this measure would result in an increase of aircraft weight and complicatedness of operation and maintenance. On the understanding that the prerequisite is to meet the requirements of engine performance and aircraft tactical performance, it appears that to use high flash-point fuel and make flammable mixture unable to be produced in the tank would also be a measure to be adopted. But it must be pointed out that the lower limit of the flammability of a fuel under dynamic conditions has to be extended downwards. consequently, the measures to prevent from producing flammable mixtures should be selected only after the aircraft tactical performance, maintainability, reliability, economics, etc. have been comprehensively taken into consideration.

2. Prevention of static electricity generated by the fuel

   The measures to prevent fuel from generating static eletricity are with the purpose of trying hard to control the electrostatic generation, and they are the most ideal ones for the prevention of electrostatic hazards. However, most of them are difficult to be realized in practice.

3. Prevention of the charging of fuels

   The measures to prevent from charging of fuels are to make object without any stored charge in it and to safely eliminate all the electrostatic charges already generated. In the design of aircraft fuel systems, it may be necessary to adopt the following measures to prevent fuels from charging: (1) increasing the electric conductivity of the fuel; (2) installation of charge reduction devices; (3) use of eletrostatic neutralizing technique.

Practice hasproved that, in the process of fuel storage, transportation, and transfer-fueling operation, to increase the electric conductivity of the fuel is an effective measure to reduce the charging of fuels. However, for aircraft fuel tanks made of materials with high volume resistivity and fuel tank compartments made of aluminium alloy with anodized surface, the electrostatic charges of the fuel in the tank are hard to dissipate. In order to reduce the level of charge on the fuel in aircraft tanks, it is necessary to make fuel tanks from a material with volume resistivity less than $10^9$ Ohm·cm, and the surface of fuel tank compartments made of aluminium alloy material should not be anodized. The electrostatic leakage resistance between fuels, airframe, and ground must meet the requirements of $10^8$ Ohm or under.

Installation of charge relaxation device in the tank can safely eliminate electrostatic charges stored on a fuel. But, since the fuel surface inside of the tank is changeable, the installation and operation of the charge reducer are hard to realize.

Electrostatic neutralizing technique is a measure which acts on the principle of using different positions of material in electrostatic charging sequence and different polarities of electrostatic charges generated after contacting with and separating from the fuel to make electrostatic charges mutually neutralized, thus greatly reducing the level of charge on a fuel. This measure, using the charging character of material itself, can bring the reduction of fuel charging into effect for a longer duration. If the composing materials are appropriately selected, the level of charge on the fuel surface would be lower than the safe charging value (under $1\times10^{-6}$ Coulumb/$m^2$).

4. Dissipation of dangerous electrostatic discharges

Dissipation of dangerous electrostatic discharges is a measure with the purpose of preventing the electrostatic discharge known as one of the hazard causes. This measure is a complementary one, in case the measure to prevent fuel from generating static electricity and charging fails. Spark discharge is a type of the most dangerous electrostatic discharge, it should be considered as the main target of the prevention in the design of aircraft fuel systems and accessories. While in designing, it requires that good performance of electric bonding between metal parts should be surely secured. As for the place (along rotating shafts) where the electric bonding performance is hard to maintain, it is necessary to change the material of metal parts or their configuration to turn the dangerous spark discharges into other less dangerous discharges, or change the medium of discharge space to transform discharges in fuel vapor space on the fuel surface into discharges in liquid fuel under the fuel surface, thus greatly increasing discharge breakdown strength and disabling discharge from occurring in actual situation.

Static electricity is a very complicated phenomenon. Preventive measures of electrostatic hazards require not only a comprehensive consideration of all sides, but also a long-term and continuous monitoring of the effectiveness of various preventive measures of electrostatic hazards. Practice has proved that such kind of accidents can be effectively prevented after all the above-indicated comprehensive measures have been adopted for aircraft on which post-landing electrostatic fires can take place.

CONCLUSIONS AND SUGGESTIONS

1.The cause of electrostatic fire accidents involving post-landing aircraft lies in the fact that there exist the following conditions of electrostatic ignition:

(1) The state of landing run is also a state of electrostatic charging which is easy to generate inside of aircraft fuel tanks.

(2) The high volume resistivity of fuel tank material and the high insulativity of anodized surface of fuel tank bay can make the fuel charging inside of the tank in a fully accumulated and insulated state after aircraft landing.

(3) All kinds of unbonded conductors in the tank are electrodes for dangerous spark discharges.

(4) While fuel rubbing against nylon fabric separators and filtrating through nylon fabrics, the level of charge on the fuel surface exceeds the safe charging standard by a big margin.

(5) While aircraft using RP-2 fuel and flying in hot weather, the concentration of flammable vapor produced in the space above the fuel surface inside of the tank will, under certain conditions, come to near its chemical equivalent, thus possessing the condition of combustibles under which an electrostatic spark can cause fires and explosions.

2. Environment ( locality and weather ) would have an important effect on fuel charging in the tank. But it remains to further probe into the essence of this factor.

3. In order to prevent aircraft from taking electrostatic fires after landing, the following principles should be followed in the design of aircraft fuel systems:

(1) To adopt conductive material with volume resistivity lower than $10^9$ Ohm.cm as fuel tank material may be necessary . Also, it would be necessary to avoid the use of high volume resistivity material(higher than $10^9$ Ohm cm) to make mechanisms in the fuel tank.

(2) The surface of fuel tank compartment made of aluminium alloy material should not be anodized.

(3) Since the dimensions of a fuel tank is larger and the adoption of anti-sloshing measure becomes necessary, the use of conductor materials is required. If conductor materials are not allowed, then other different materials able to generate static electricity with opposite polarity in a fuel have to be selected and coordinated properly.

(4) Unbonded conductors are not allowed in the fuel tank.

(5) The use of fuels being unable to produce any flammable gas in the tank under conditions of aircraft operation, or fuels with the minimum amount of ignition energy larger than that required by a flammable vapor are recommended.

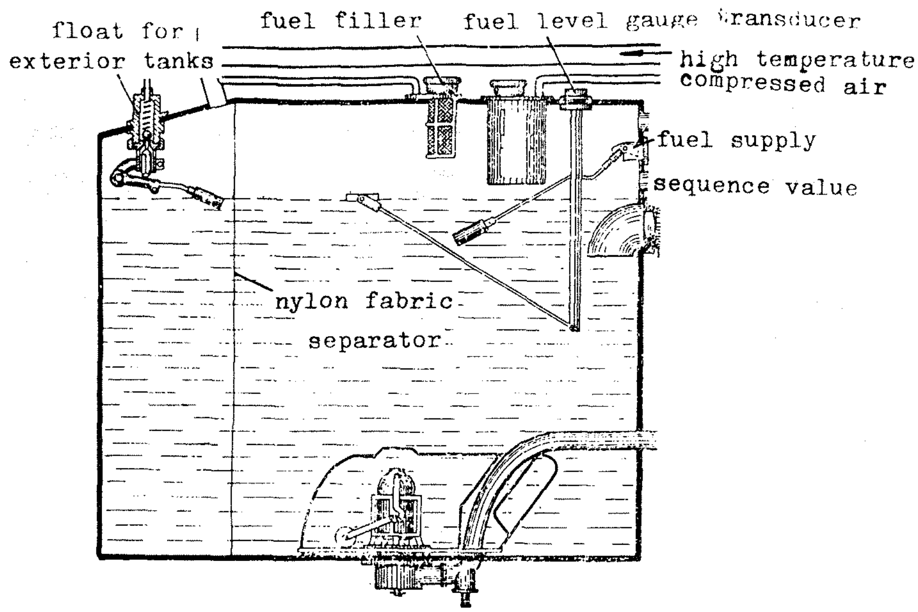


Fig.1 The scheme of aircraft fuel tank

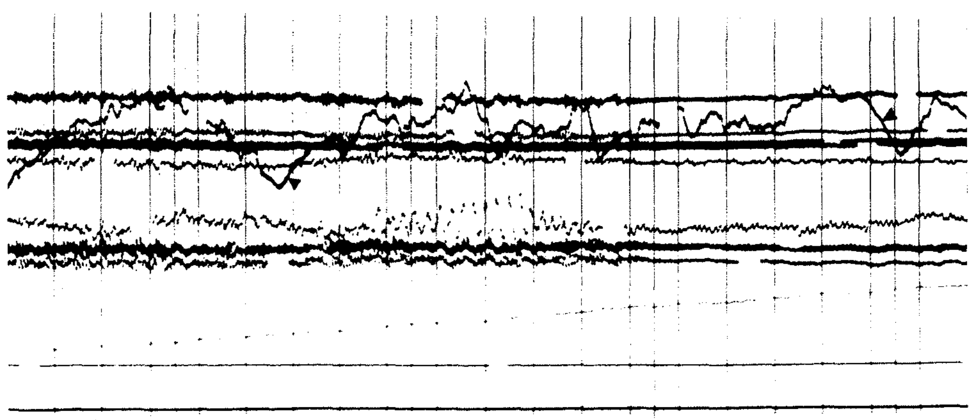

Fig. 2 The electrostatic build-up inside of aircraft fuel tank at taking-off

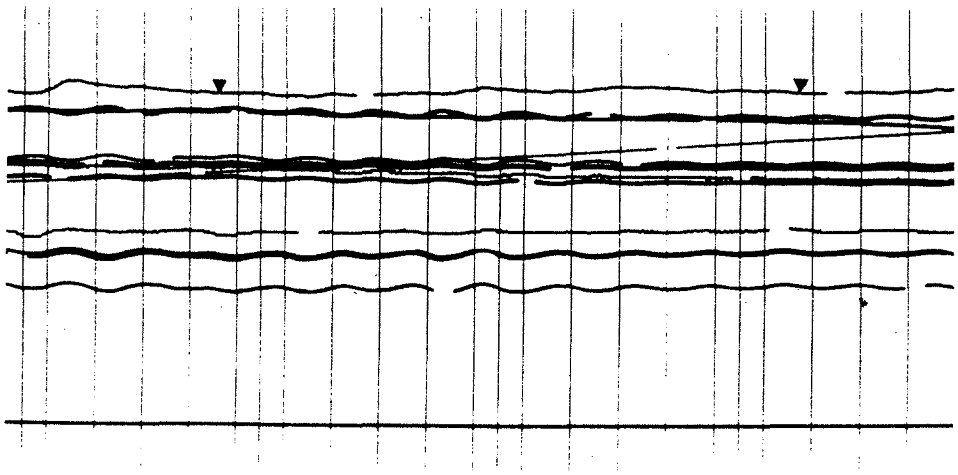

Fig.3 The electrostatic build-up inside of aircraft fuel tank at level flight

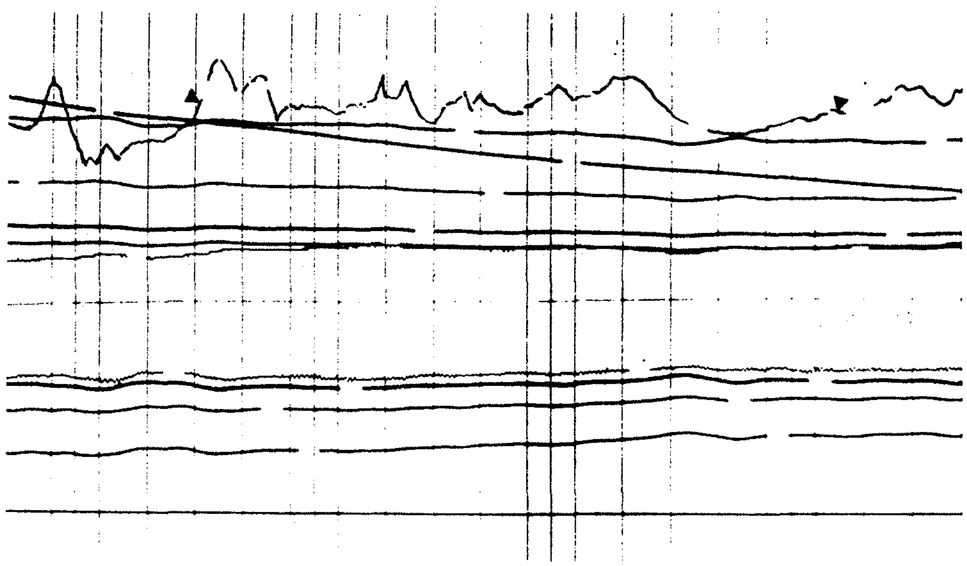

Fig. 4 The electrostatic build-up inside of aircraft fuel tank at maneuvering flight

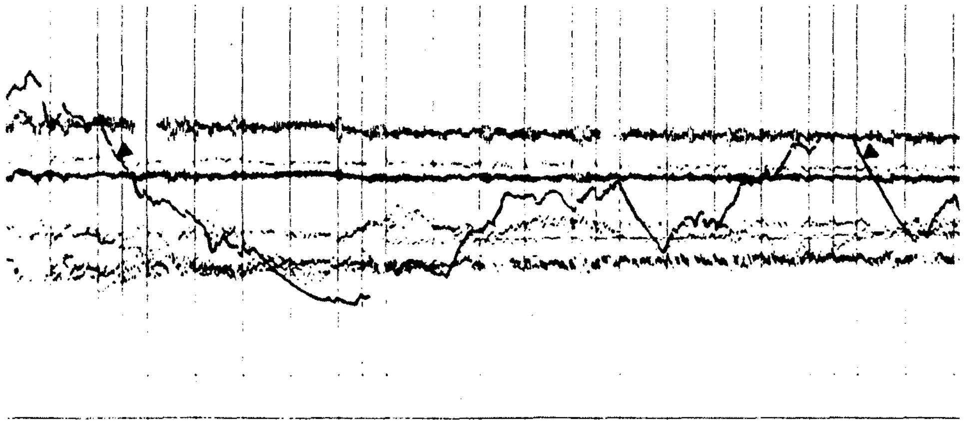

Fig. 5 The electrostatic build-up inside of aircraft fuel tank at landing

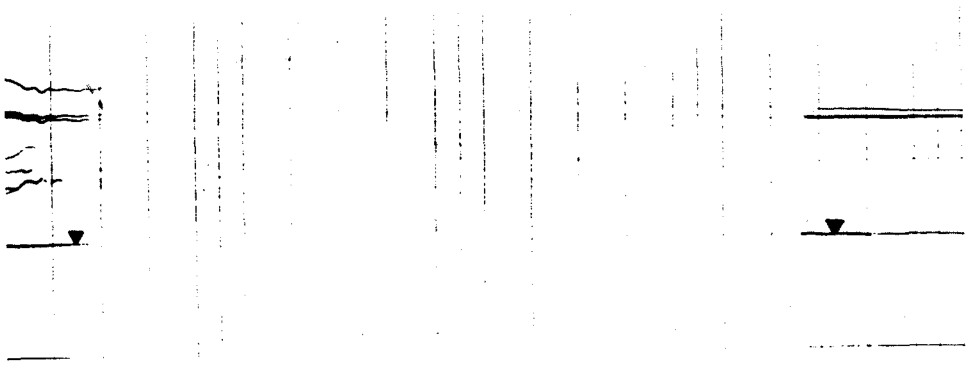

Fig.6 The electrostatic build-up inside of aircraft fuel tank at engine shutdown

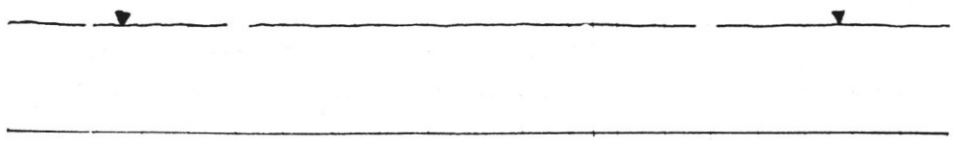

Fig.7 The electrostatic build-up inside of aircraft fuel tank at post engine shutdown

Fig. The appearance of micro-pits from spark discharge on the wreckages

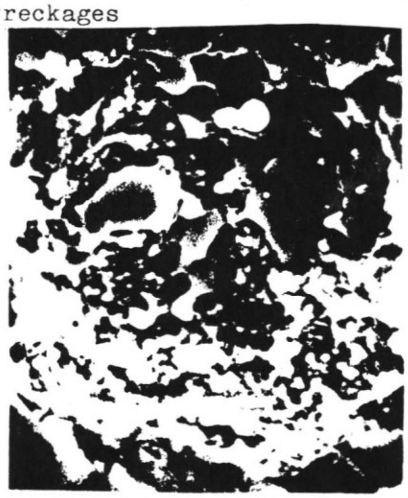

Fig. 9 The appearance of micro-pits from spark discharges on the test piece