Experimental Investigation of Electrostatic Fire Accidents After Aircraft Landing and Preventive Measures

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This work is an experimental investigation to determine the cause of electrostatic fire accidents after aircraft landing and to clarify the effects of various factors on the cause. This research work has conducted a series of ground simulation tests and actual flight tests under the fire and explosion environment conditions. The test results have indicated that the process of an aircraft landing run is the fundamental process of electrostatic charges generating in fuel tanks. After an aircraft comes to a stop, there is also a process of accumulation of electrostatic charges, while fuel charged with higher energy remains for a considerably long period, unable to dissipate. All kinds of unbonded conductors in the tank are electrodes for dangerous spark discharges. When an aircraft using RP-2 fuel flies 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 close to its chemical equivalent, thus possessing the condition of combustibles under which an electrostatic spark can cause fires and explosions. Some principles that should be followed in aircraft fuel system design are discussed.

Introduction

SINCE the 1960's, many electrostatic fire incidents during aircraft ground fueling have taken place. Many countries have been engaged in a number of research projects and analyses on the subject and have adopted several effective preventive measures. Recently, the number of electrostatic fire accidents several minutes after landing has steadily increased. This kind of fire accident research and analysis plays an important role in the prevention of accidents and the improvement of aircraft safety. For the completeness of the experimental investigation, a series of ground simulation tests and actual flight tests under fire and explosion environment conditions were conducted. If we want to ascertain whether fire accidents involving aircraft postlanding result from static electricity, then we must define the conditions under which these accidents occur, and conduct a number of studies on subjects such as the charging state on the fuel inside of aircraft fuel tanks, flammable vapor concentration in the tank, dangerous electrostatic igniting sources, etc. In order to prevent aircraft from electrostatic fire accidents after landing, measures should be adopted from all areas, such as prevention of flammable fuel/air mixtures and the charging of fuels, dissipation of dangerous electrostatic discharges, etc. Accordingly, some principles that should be followed in aircraft fuel system design are discussed.

Features of Electrostatic Fire Accidents

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

1) They take place only in aircraft with antisloshing nylon fabric separators installed inside the fuel tanks. The schematic drawing of an aircraft fuel tank is shown in Fig. 1.

2) They take place after aircraft landing and engine shutdown within 2–5 min.

3) There is 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, for example, these accidents usually take place from May through August.

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Experimental Investigation of the Causes

Approaches

To investigate the cause of electrostatic fires, one must study the conditions that cause them. Fires and explosions of this origin occur[1]:

1) When there is a state where electrostatic charges are easily generated;

2) After static electricity is generated, its leakage is minimal, and an insulating state remains able to accumulate electrostatic charges;

3) When something exists and serves as the electrode for discharges;

4) When electrostatic discharge energies are high enough to ignite flammable gases; and

5) When electrostatic sparks can cause ignition, but only for flammable gases near the chemically equivalent concentration.

In experimental investigations to ascertain whether fire accidents involving aircraft postlanding result from static electricity, we must define whether the given conditions have been met when these accidents occurred.

Study of Charging in the Fuel Tank

The electrostatic phenomenon comes under the combined influence of a multiplicity of factors. Therefore, the study of

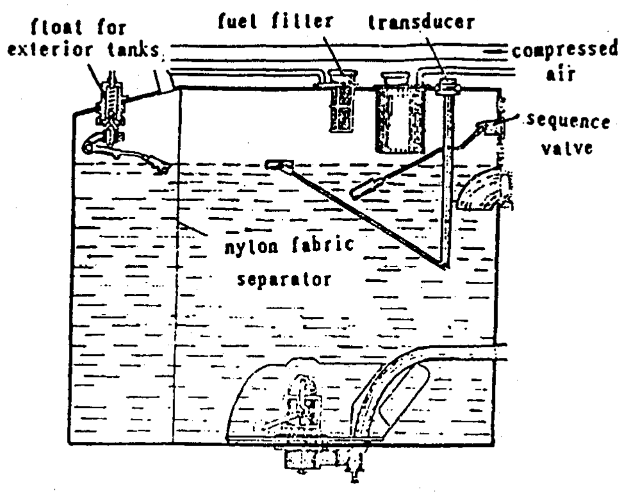

Fig. 1 Scheme of an aircraft fuel tank.

the causes of electrostatic fires has to be conducted under the conditions in which these fires take place. Static electricity is the simultaneous coexistent phenomenon of electrostatic field and discharge. The configuration of the fuel tank, materials, and parts installed inside the tank may all 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 conditions of actual accidents. Aspects of the study include the states of electrostatic generation, leakage, and accumulation.

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) Fuel rubbing against the walls of the tank and the nylon fabric separator, or fuel filtering through the separator during aircraft maneuvering, flight, and running;

3) Various floats on the fuel surface.

The results of the flight and ground simulation tests have shown that when the fuel is sloshing in the tank and is rubbing against the tank walls and nylon fabric separator, or filtering through the separator, the potential for the ground on the fuel surface reaches a maximum that is 5.7 times larger than when the fuel is pumped through a pipe into the tank, and 47 times larger than when various floats are on the fuel surface. When the fuel is rubbing against and filtering through nylon fabric separators, the potential for the ground on the fuel surface is 39 times larger than 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 facilitate the generation of electrostatic charge inside a fuel tank? Through the use of an electrostatic measuring device installed on aircraft, from engine start, flight, and landing to engine shutdown and right afterward for the duration of 5 min, the change of the level of charge on the fuel has been recorded. All the curves from the record are shown in Figs. 2–7.

As seen in Figs. 2, 4, and 5, in the process of aircraft operation including maneuvering flight, the charging on the fuel surface would change rapidly. In the process of landing, even charge polarity reversal phenomenon would appear. Figure 3 illustrates that in the process of level-flight, the level of charge on the fuel is low and the amplitude of charge is narrow. While flying in the air, there are generally positive charges on the fuel surface. As shown in Fig. 6 and 7, after engine shutdown, the level of charge on the fuel quickly tends toward a stable value that will basically have no change after a duration of 5 min. Figure 7 shows that the charging of the fuel after engine shutdown does not correspond mainly with the charging in the flight but with the 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 and sometimes covered with electroconductive rubber usually place negative charges on a fuel, and the maxima of the level of the charge measured are 6.28×10^{-6} and 4.45×10^{-6} C/m^2, respectively. Both greatly exceed the standard[2] of the safe level of charge for a fuel of 1×10^{-6} C/m^2. The separator, made of natural silk and polyester fiber blend fabric with electroconductive fiber in it, allows the level of charge on a fuel to reach 3.41×10^{-7} C/m^2.

From the preceding test results, the following conclusions can be made:

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 degree of sloshing.

2) The flight model that 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.

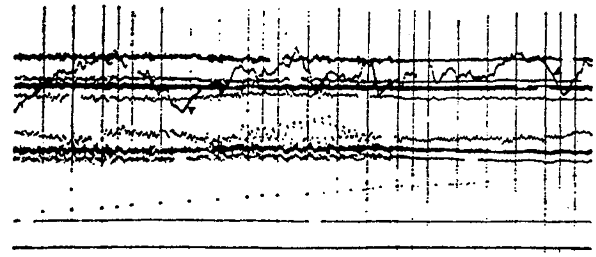

Fig. 2 Electrostatic buildup inside aircraft fuel tank at takeoff.

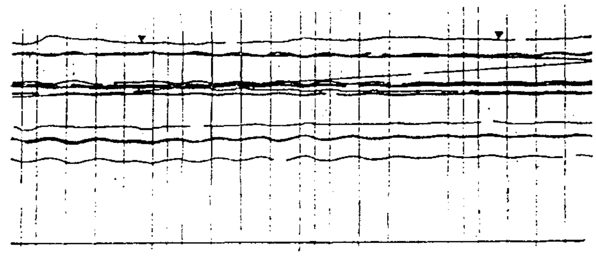

Fig. 3 Electrostatic buildup inside aircraft fuel tank at level flight.

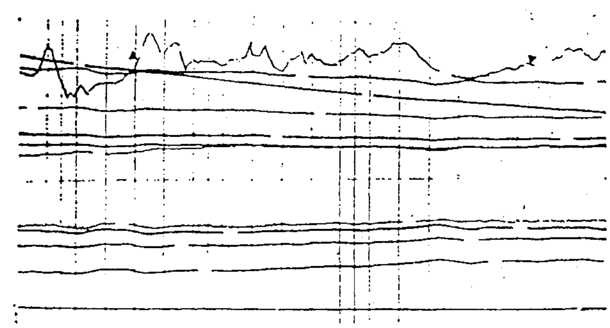

Fig. 4 Electrostatic buildup inside aircraft fuel tank at maneuvering flight.

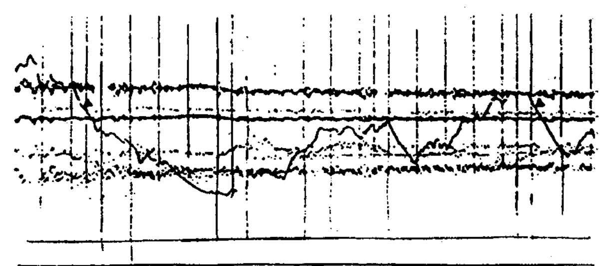

Fig. 5 Electrostatic buildup inside aircraft fuel tank at landing.

Electrostatic Leakage in the Fuel Tank

We know that if the fuel is charged with static electricity, like any other material its charges will sooner or later relax or dissipate. There are two ways for charge relaxation to happen: 1) the charge will be neutralized with electrons or ions in the air; or 2) the charge will leak to the ground through some insulators, such as the charged insulator, the container and its supporters, and then dissipate. As stated, basically no charge leakage happens on the fuel surface in the tank after aircraft landing. This is because the aircraft fuel tank is a closed container pressurized with the air from the engine without any electron/ion bearing fresh air to neutralize electrostatic charges after engine shutdown, and because the aircraft fuel tank is made of rubber material with high volume resistivity (above 10^{12} Ω-cm) and the tank bay is made of surface-anodized aluminum alloy plate with high resistivity. Consequently, the leakage resistance from fuel to ground is very high according to ground measurements, its value between tank walls, tank bay, and ground being more than $10^{12}\ \Omega$. Thus, there exists an insulating state for the electrostatic charge to be accumulating sufficiently.

Effect of Environmental Factors

Tests showed that external environmental conditions (locality, weather, etc.) 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 the coming of a typhoon and associated cold currents is 12 times higher than that after their coming, which may be a phenomenon related to atmospheric electric fields. Meteorological observation[3] has shown that every type of precipitation will sometimes receive a positive charge, sometimes a negative charge. However, the rainfall with positive charge is more dominant than that with negative charge, resulting in a quantity of purely positive charges transferred down upon the earth. Rainstorm and precipitation brought in with a typhoon 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 the tank. The effect of environmental factors is a very complicated problem that we have scarcely examined, and clarification requires long-term electrostatic observations.

The Study of Flammable Vapor

The energy required for a spark discharge to ignite a 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 at a minimum. The minimum ignition energy for the flammable mixtures of each hydrocarbon is generally in the range of 0.2–0.3 mJ. When the concentration of a flammable vapor approaches its upper or lower limit, the ignition energy will increase according to an exponential function, and when the fuel vapor concentration is in the vicinity of the lower limit, the energy requirements will be in the range of 5–6 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 aircraft fuel tanks varies with 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 an analysis and measurement with a gas chromatograph. The results show that after the aircraft with antisloshing nylon fabric separators installed inside of fuel tanks flies in hot weather, the fuel vapor concentration in the tank is about 0.5–5%, which is just in the flammable concentration range of 0.5–7.2% for RP-2 fuel. The chemical equivalent concentration of RP-2 fuel is about 3.5%. Therefore, during this kind of flight in hot weather, it is possible to produce a flammable vapor near its chemical equivalent concentration in the fuel tank. This is one of the major causes of accidents with marked seasonal occurrence.

The Study of Ignition Sources

There are usually three types of discharges[4] in the fuel tank. The first one involves a corona discharge from the fuel surface to the sharp point of some grounded projection. The second is a streamer discharge from the fuel surface to the area of some grounded projection (with curvature radius larger than 6 mm), and the third is a spark discharge from some unbonded conductors in the tank. Which type of discharge actually occurs in fuel tanks relates to 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 tank usually occur as short bursts. Each burst is made up of discharge energy from 4–11 μJ. Also, due to their low energy, corona discharges are generally considered nondangerous. The streamer discharge from fuel surface to grounded projection can occur at large gaps (over 2.5 cm). Due to the resistivity of fuel, charges would relax to null at the place where discharge occurs but still remain in other places. Consequently, the energy of streamer discharge is much lower than that of spark discharge, which can occur between unbonded conductors in fuel tanks at a small gap width (about 2 mm). Spark discharges are a type of high energy discharge that can relax accumulated charges instantaneously and, hence, is considered the most dangerous.

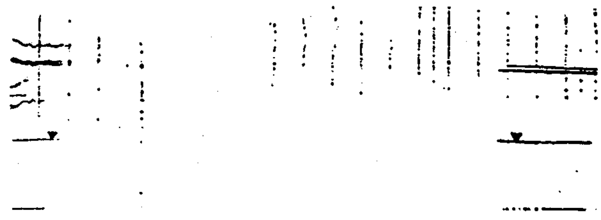

Fig. 6 Electrostatic buildup inside aircraft fuel tank at engine shutdown.

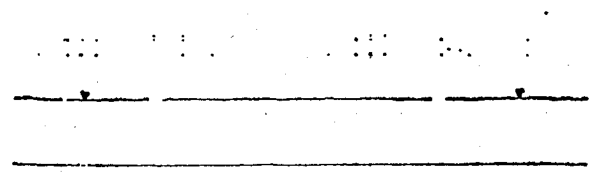

Fig. 7 Electrostatic buildup inside aircraft fuel tank at post engine shutdown.

It is noteworthy that there are some mechanisms in the tank for controlling the fuel-usage sequence and measuring the quantity of fuel with their pickup members floating on the fuel surface. These mechanisms generally consist of rotating shafts, and are made of aluminum alloy material, in view of the resistivity of the anodized aluminum alloy surface and the fuel. Under certain conditions, there may be a nonconducting 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 become "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," like high-temperature-melted micropits, have been found. Figure 8 shows the appearance of micropits. They have a resemblance to those formed in the ground test of a "spark discharge" from high voltage and small current (shown in Fig. 7). Results of analysis have shown that there really exist dangerous spark discharges inside of the fuel tank and that the electrodes for discharges are two unbonded conductor parts.

Preventive Measures

The prevention of electrostatic hazards requires a comprehensive search for preventive measures 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 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

Fig. 8 Appearance of micropits from spark discharge on the wreckages.

fuel from being in electrostatic hazards, measures aimed at eliminating or limiting related main factors that can create the two conditions should be adopted. Prevention of electrostatic hazards is a problem that must be considered by everyone involved in 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.

Prevention of Producing Flammable Mixtures

To prevent the production of flammable fuel/air mixtures, methods such as the inverting of the vapor space of the tank, the use of a high flash-point fuel, etc., are proposed in the design of aircraft fuel systems. Inverting the vapor space of the tank would be an ideal measure for either preventing electrostatic fires and explosions or preventing lightning strikes. However, this measure would result in an increase of aircraft weight and complexity of operation and maintenance. With the understanding that the prerequisite is to meet the requirements of engine performance and aircraft tactical performance, it appears that the use of high flash-point fuel to prevent the production of flammable mixture in the tank should also be adopted. But it must be pointed out that the lower limit of flammability of a fuel under dynamic conditions has to be extended downward. Consequently, the measures to prevent the production of flammable mixtures should be selected only after the aircraft tactical performance, maintenance, reliability, economics, etc., have been comprehensively considered.

Prevention of Static Electricity

Measures to prevent fuel from generating static electricity attempt to control electrostatic generation. They are the most ideal for the prevention of electrostatic hazards. However, most of them are difficult to realize in practice.

Prevention of the Charging of Fuels

The measures to prevent the charging of fuels attempt to make objects free of stored charge 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; and 3) use of electrostatic neutralizing technique.

Increasing the electric conductivity of the fuel is an effective measure to reduce the charging of fuel. However, for fuel tanks made of materials with high volume resistivity and fuel tank compartments made of aluminum 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 the tanks, it is necessary to make fuel tanks from a material with volume resistivity less than 10^6 Ω-cm. The surface of fuel tank compartments made of aluminum alloy material should not be anodized. The electrostatic leakage resistance between fuels, airframe, and ground must meet the requirements of ≤ 10 Ω. Installation of a charge relaxation device in the tank can safely eliminate electrostatic charges stored on a fuel, but, since the fuel surface inside the tank is changeable, the installation and operation of the charge reducer are hard to realize. Electrostatic neutralizing technique is a measure that acts on the principle of using different positions of material in electrostatic charges generated after contacting with and separating from the fuel to make electrostatic charges actually neutralized, thus greatly reducing the level of charge on a fuel. If the materials are appropriately selected, the level of charge on the fuel surface would be lower than the safe charging value.

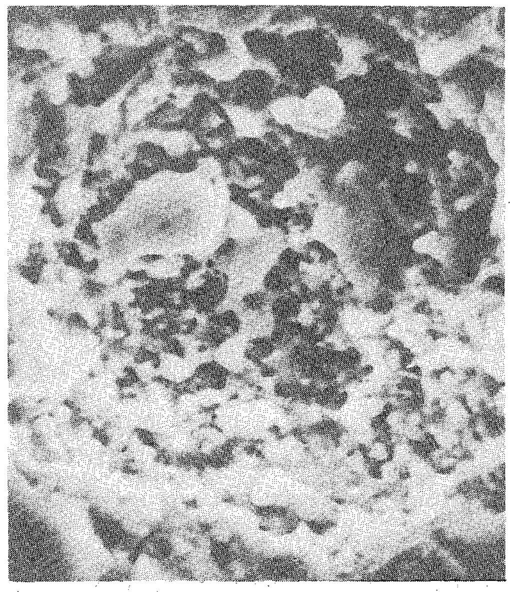

Fig. 9 Appearance of micropits from spark discharge on the test piece.

Dissipation of Spark Discharges

Dissipation of dangerous electrostatic discharges is a measure to prevent the electrostatic discharge. This measure is a complementary one, in case the measure to prevent the fuel from generating static electricity and charging fails. As spark discharge is the most dangerous type of electrostatic discharge, it should be the main target of prevention in the design of aircraft fuel systems and accessories. Design requires that good performance of electric bonding between metal parts be 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 to 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 an actual situation.

Conclusions and Suggestions

1) The cause of electrostatic fire accidents involving postlanding aircraft lies in the fact that there exist the following conditions of electrostatic ignition:

a) The state of landing run is a state of electrostatic charging that is easy to generate inside of aircraft fuel tanks.

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

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

d) While fuel rubs against nylon fabric separators and filters through nylon fabrics, the level of charge on the fuel surface exceeds the safe charging standard by a large margin.

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

2) Environment (locality and weather) may have an important effect on fuel charging in the tank. More research into the essence of this factor needs to be done.

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

a) The adoption of conductive material with volume resistivity lower than 10^9 Ω-cm as fuel tank material may be necessary. Also, it may be necessary to avoid the use of high volume resistivity material (higher than 10^9 Ω-cm) to make mechanisms in the fuel tank.

b) The surface of the fuel tank compartment made of aluminum alloy material should not be anodized.

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

d) Unbonded conductors should not be allowed in the fuel tank.

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

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