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Electrical Ignition of Fuel-Air Mixture in Aircraft Fuel Tanks

Abstract.
The fuel system, electric equipment of fuel tank and wiring, fuel flammability, mechanisms of electrical ignition and possibility of explosion of fuel-air mixture as a result of arcing and/or static electricity in fuel tanks of commercial aircraft has been analyzed. Approximate equations for minimum ignition energy (MIE) in fuel tanks have been derived. Examples of explosions of fuel tanks include the air crash of Boeing 747-131 TWA 800 on June 17, 1996 and explosion of Boeing 727-200 at Bangalore Airport on May 4, 2006. Although probability of explosion of fuel in the wing tanks due the electric short circuit, arcing or static electricity is low, this problem should be always carefully considered in examinations of air crashes.

Streszczenie.
Przedstawiono analize ukladu paliwowego, wyposazenia elektrycznego i przewodow zbiornikow paliwa, zapalnosci paliwa, mechanizmow zaplonu elektrycznego oraz mozliwosci wybuchu mieszanki paliwo-powietrze na skutek luku elektrycznego lub ladunkow statycznych w samolotach pasazerskich. Zostaly wyprowadzone zaleznosci do obliczen przyblizonych minimalnej energii zaplonu w zbiornikach paliwa. Do wybuchow zbiornikow paliwa doszlo podczas lotu Boeinga 747-131 TWA 800 17 czerwca, 1996 oraz podczas postoju Boeinga 727-200 na lotnisku w Bangalore 4 maja 2006. Chociaz prawdopodobienstwo wybuchu oparow paliwa w zbiornikach paliwa na skutek zwarcia instalacji, luku elektrycznego czy tez ladunkow statycznych jest niskie, problem ten powinien byc zawsze dokladnie rozwazony podczas badan wypadkow lotniczych.
(Zaplon elektryczny mieszanki paliwo-powietrze w zbiornikach paliwa samolotow)

Keywords: aircraft, air-fuel mixture, electrical wiring, electrical equipment, explosion, fuel system, fuel tank
Słowa kluczowe: samolot, mieszanka paliwo-powietrze, przewody elektryczne, wyposazenie elektryczne, wybuch, uklad paliwowy, zbiornika paliwa

Introduction

Civil transport aircraft use the wing structure as an integral fuel tank to store the fuel (Fig. 1). In larger aircraft, the fuel is also stored in the structural wing box within the fuselage (Fig. 2). The primary components of the wing box are spars, ribs, stringers and skin panels. Fuel tanks for aircraft are made usually of aluminum alloy, stainless steel or other fuel-resistant materials [18]. The wing skin the seams of which are sealed constitutes the walls of wing fuel tanks.

Metal fuel tanks are required to withstand an internal test pressure of 24 kPa (3.5 psi) without failure or leakage [18]. Fuel tanks located within the fuselage are required to withstand rupture and retain the fuel underneath the inertia forces during emergency landing, i.e., $4.5g$ downward, $2.0g$ upward, $9.0g$ forward, and $1.5g$ sideward [18].

The mixture of fuel vapor and air that accumulates above the surface of fuel in the tanks in the so called *ullage*[1] always must be regarded as a potential explosion hazard. The *fuel air mixture* can be ignited amongst other as a result of static electricity build-up due to fuel circulation or arcing of electrical components, e.g., pumps, wiring, measuring probes, level sensors, etc. Most known explosions of fuel-air mixture are:

1. in the center wing tank (CWT) of Boeing 747-131 over Atlantic Ocean, flight TWA 800 from New York to Paris on June 17, 1996 [23];
2. in the left wing fuel tank of Boeing 727-200 belonging to Malaysian Transmile Airline at Bangalore Airport, India on May 4, 2006 [25].

According to Federal Aviation Association (FAA) the fuel tank explosion rate is 1 in 100 million of flight hours. According to Association of European Airlines (AEA) this rate is even lower, i.e., 1 in 140 million of flight hours.

Fuel system of passenger aircraft

The aircraft fuel is stored in the CWT, wing fuel tanks, aft fuel tanks and sometimes in horizontal stabilizer fuel tank, e.g., Boeing 747-400. Fig. 3 shows a fuel tank architecture of a typical passenger aircraft with two wing fuel tanks, one CWT and one aft auxiliary tank.

A CWT has its shape close to a rectangular cube (Fig. 2). A typical wing tank is irregular, long and shallow [15]. The fuel is in direct contact with the outside skin. The interior of a wing fuel tank is shown in Fig. 4. Depending upon the aircraft configuration and the degree of control, the aft tank may be used as means of controlling the aircraft center of gravity (CG) [15]. The vent surge tanks (Fig. 3) are located near each wing tip in a semi-isolated location. These surge tanks function as fuel collectors for relatively small amounts of fuel which may be trapped in the climb vent line during flight maneuvers and climb attitudes, or during thermal expansion of the fuel. Each surge tank is vented to atmosphere.

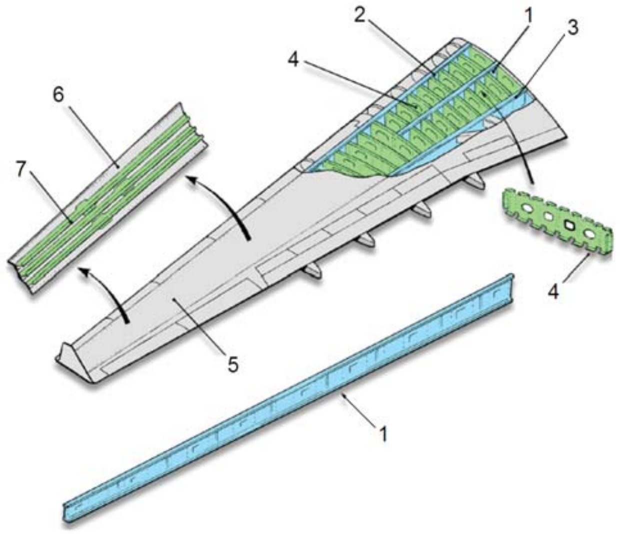

Fig. 1. Construction of wing box of a commercial aircraft. 1 – center spar, 2 – front spar, 3 – rear spar, 4 – rib, 5 – skin panel, 6 – underside of skin panel, 7 – stringers [10].

Each tank can feed fuel to its own engine, e.g., Boeing 727-200. Additionally, it is possible to crossfeed from any tank to any combination of engines. However, it is not possible to crossfeed tank-to-tank in flight.

Fuel pumps are driven by 115/220-V induction motors and/or 28 V DC brush motors. A flange mounted motor and pump constitute one integral unit. The feeding cables in fuel tanks are in aluminum conduits (tubes). It is required that wire bundles carried in conduits through fuel tanks be wrapped with an additional protective layer of teflon. Accidental arcing in wiring system that delivers electric input power to fuel pump motors can ignite the *fuel-air mixture* in the wing

[1] space between the fuel surface and upper wall of the tank.

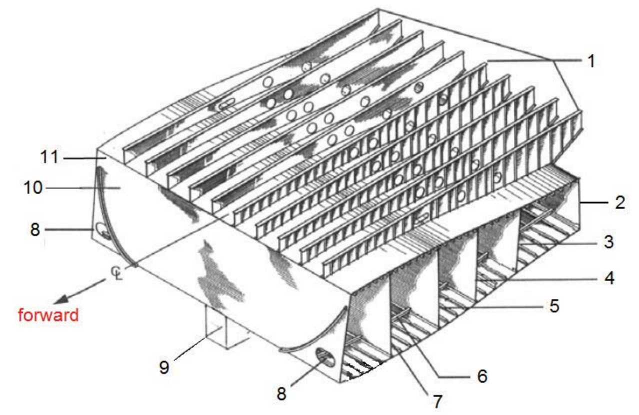

Fig. 2. Construction of the Boeing 747-100 wing center section and CWT. 1 – floor beams, 2 – rear spar, 3 – spanwise beam 1, 4 – center spar, 5 – spanwise beam 2, 6 – intercoastal, 7 – spanwise beam 3, 8 - vent opening, 9 – keel beam, 10 – front spar, 11 – ring cord [24].

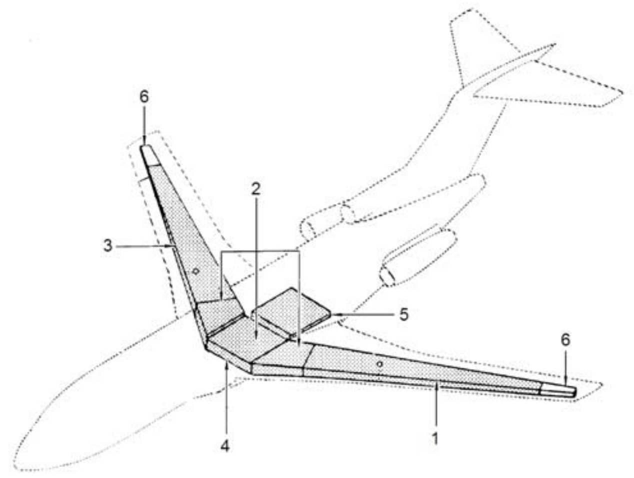

Fig. 3. Fuel tank configuration of a commercial air craft (Boeing 727). 1 – wing tank No 1, CWT No 2 (three sections), 3 – wing tank No 3, 4 – integral tank, 5 – aft auxiliary tank, 6 – vent surge tank [2].

tank [7, 9, 13, 15, 16, 20, 25, 26].

In general, there are two types of fuel pumps on typical aircraft [15]:

1. Fuel *transfer pumps* which perform the task of transferring fuel between the aircraft fuel tanks to ensure that the engine fuel feed requirement is satisfied;
2. Fuel *booster pumps* also called *engine feed pumps*, which are used to boost the fuel flow from the aircraft fuel system to the engine;

Most passenger aircraft use fuel Jet A-1. Jet A-1 is a *kerosene* grade of fuel suitable for nearly all aircraft turbine engines. This is a *complex mixture of hydrocarbons* consisting of paraffins, cycloparaffins, aromatic and olefinic hydrocarbons with carbon numbers predominantly in the C9 to C16 range [6]. It is produced to a stringent internationally agreed standard. Characteristics of aviation turbine engine fuels Jet A and Jet A-1 are given in Table 1.

A thin layer of fuel on the bottom of a tank needs minimal heat input to the tank walls to reach the temperature exceeding the flash point and form combustible vapors in the ullage.

Electric equipment and wiring of fuel tanks and wings

The CWT is generally categorized as hazardous tank due to the proximity to external heat sources, e.g., air conditioning units (Fig. 5) [5, 15]. It requires *tank inerting* with the aid of nitrogen-enriched air from the on-board inert gas generating system. The left and right wing tanks are categorized as non-hazardous as there is mostly no proximity of high-energy heat sources, as for example, air conditioning systems [15]. However, *are they really non-hazardous?*

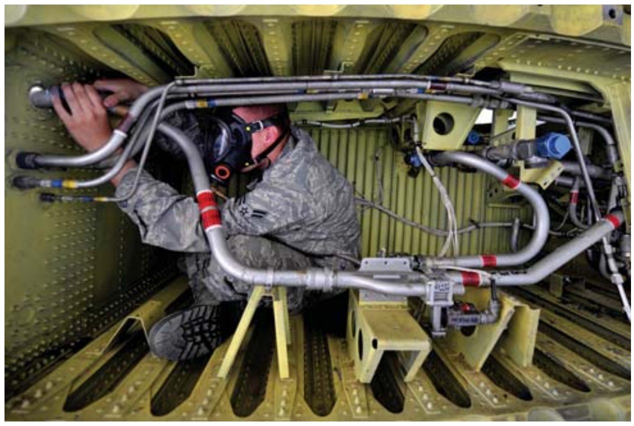

Fig. 4. Inside the wing of the C-130 Hercules transport aircraft [14].

Table 1. Characteristics of fuels JET A and Jet A-1 [6]

Parameter	JET A	JET A-1
Density at 15^{o}C, kg/m^3	775 to 840	775 to 840
Flash point, ^{o}C	38	38
Auto-ignition temperature, ^{o}C	210	210
Freezing point, ^{o}C	-40	-47
Open air burning temperature, ^{o}C	260 to 315	260 to 315
Maximum burning temperature, ^{o}C	980	980
Electric conductivity, $\times 10^{-12}$ S/m	1.0 to 20.0	1.0 to 20.0
Electric conductivity if conductivity improver is added, $\times 10^{-12}$ S/m	50 to 450	50 to 450
Gravimetric energy content, MJ/kg	42.8	42.8
Volumetric energy content, MJ/kg l	35.3	34.7

As it has been mentioned, in-tank electric wiring is necessary to feed the electric motor-driven fuel pumps submerged in the fuel. Electric wiring and electric equipment always create a potential hazard of short-circuit (SC) and arcing. In addition, a static electricity can be generated due to fuel circulation in a tank and between tanks. An example of electrical fire in the wing area that caused extensive damage to an aircraft wing and could have led to loss of the aircraft is shown in Fig. 6 [22].

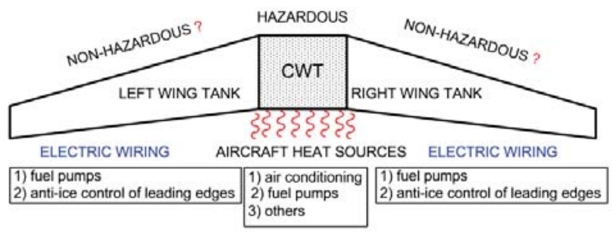

Fig. 5. Hazardous and non-hazardous fuel tanks of a commercial aircraft [5].

Traditional approach to ice removing includes pneumatic de-icing boots, thermal antiicing systems and glycol based fluid (to protect wing surfaces). Most civil aircraft use hot

Fig. 6. In-flight electrical/hydraulic fire in an aircraft wing area [22].

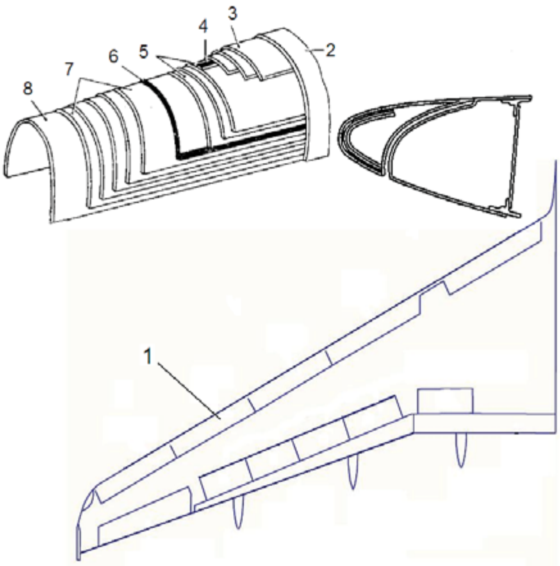

Fig. 7. Exemplary conctruction of wing leading edge anti-ice system: 1 – slat, 2 – outer skin, 3, 5, 7 – thermal glass insulation, 4 – thermal “knife”, 6 – heating element, 8 – inner skin.

bleed air for anti-ice control of outer wing leading edges [15]. The wing leading edge slat section is equipped with anti-ice control system, typically with hot air ducts. These ducts take form of pipes with holes to allow air to heat the inner surface of leading edges. The hot air flow to the outer wing leading edges is controlled by the wing anti-ice valve [15]. In aircraft with tail-mount engines an electric resistive heating for anti-ice of the wing leading edge slats (Fig. 7) is more reasonable, as the turbofan engines are located far away from the wings. The electric heating elements require wiring. The electric power consumption by electric anti-ice systems is in the range of tens of kilowatts.

Modern anti-ice and de-ice technologies include electro-expulsive methods, electro-impulsive methods, electromechanical expulsion, ultrasonic methods and application of shape memeory alloys [8]

Fundamental definitions

Ignition is usaully considered to be a vapor-phase combustion reaction with the evolution of heat and emission of light that may or may not be visible to the naked eye [11]. Such reactions are most often associated with the rapid oxidation of a combustible in air or oxygen. *Electrical ignition* can occur as [11]:

(a) a thermal process, in which excesive surface heating (e.g., abnormal electric heating of wing leading edges) is produced by the resistance R to current flow I in an electrical circuit during the time t, (the energy $E = I^2Rt$);

(b) electrostatic sparks that are formed when the electrical charge of a conductor is sufficient to bridge the gap to another conductor or insulator (the energy $E = 0.5CV^2$ where C is the capacitance of charged conductor and V is the potential difference);

(c) brake sparks when current-carrying conductors are abruptly separated, e.g. when an electric switch is open (The energy is $E = 0.5LI^2$ where L is the inductance.

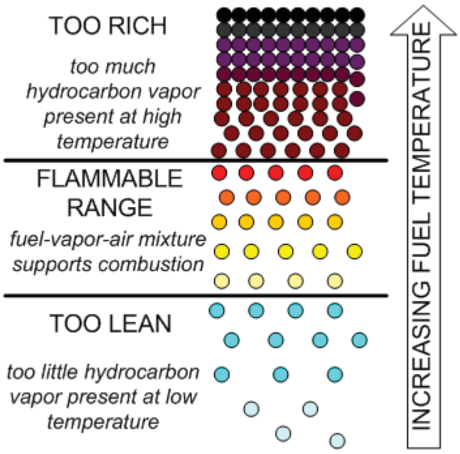

Fig. 8. Flammability concept for fuel vapor-air mixture [13].

The *flash point* of the fuel is the minimum temperature at which sufficient vapor is released by the fuel to form a flammable vapor-air mixture near the surface of the liquid or within the vessel [7]. For Jet A and Jet A-1 fuels the flash point is 38^{o}C (Table 1). It has been found that fuels in tanks or pools can propagate flames at temperatures below those established by the flash point [7].

There is a definite concentration range over which mixtures of each hydrocarbon in air will burn [13]. This is called the *flamable range* (Fig. 8). Not all fuel-air mixture can be ignated. The composition of the fuel-air mixture in the vapor space is dependent on the fuel type, temperature and physical state, i.e., vapor or mist [13]. Sloshing of the fuel in the tank is the mechanism that is typically associated with mist formation [7].

Flammability limits are experimentally determined upper and lower flammability boundaries of fuel concentration between which the fuel-air mixture only burns [1]. The upper (UFL) and lower (LFL) flammability limits in the air depend on initial temperature and pressure [1]. Thus, there is a limiting minimum and maximum *fuel-to-air* ratio. Below the LFL, the fuel-air mixture is too lean to burn. When UFL is exceeded, the vapor space mixture is too rich in fuel to be flammable. When considering only equilibrium conditions, the particular fuel-to-air ratio, which can exist is determined by the temperature and pressure of the system. The temperature determines the quantity of the fuel by controlling its vapor pressure, and the altitude determines the quantity of air. Therefore, by a suitable combination of temperature and altitude, under equilibrium conditions, the ullage of a fuel tank can be made either flammable or nonflammable [16].

As stated in Table 1, Jet A and Jet A-1 fuels under static conditions are typically not flammable under 38^{o}C. Small amount of fuel in the tank that forms a very thin liquid layer across the bottom surface is more dangerous than the full fuel tank. Any heat input into this fuel layer can rapidly raise

Table 2. Hazard and causes of fuel ignition in tanks

Hazard	Cause
In-tank electrical wiring	hot wires SC induced currents chemical damage mechanical damage
Fuel pump motor wiring	wear of teflon sleeving wear of wire insulation SC electric arcing
Electric motor of fuel pump	interturn SC phase-to-phase SC phase-to-housing SC hot spots arcing on terminals
Pump dry-running (there are fuel lubricated bearings)	Sparks generated due to mechanical friction
Adjacent systems, e.g., electric anti-ice system	electric arcing external to the fuel tank hot surface ignition explosion within the adjacent area
Static electricity build-up due to fuel circulation [13, 17]	ESD from fuel surface to tank walls
Lighting [3, 19]	ESDs within the fuel tank electrical arcing between components (inadequate distance between components)

its temperature to above the flash point of the fuel, thus forming combustible vapors in the ullage.

There are many factors that determine how and how much this heat transfer affects the fuel tank temperature and the flammability of the ullage space. These factors include the operational environment, flight operations, condition of the aircraft, the amount and temperature of fuel loaded in the tank, and other variables. In many cases, the fuel temperature is sufficiently high that the *fuel-air mass ratio*, i.e.,

$$k_{fa} = \frac{m_{fuel}}{m_{air}} \tag{1}$$

in the ullage space is above the LFL ($k_{fa} > 0.03$). In eqn (1) m_{fuel} is the mass of fuel and m_{air} is the mass of air.

Another important parameter characterizing a fuel tank is the so called *fuel loading* or *mass loading*, i.e.,

$$k_{ml} = \frac{m_{fuel}}{V_{tank}} \tag{2}$$

where V_{tank} is the volume of the fuel tank. For a full fuel tank the mass loading is equal to the density of the fuel (approximately 800 kg/m^3), for a half-full tank, it is equivalent to half of the density and so on [7].

The environmental parameters of temperature and altitude which will affect the flammability of the tank ullage, are illustrated by the so called *flammability envelope*. Traditional flammability envelopes have been available for many years [7]. The envelopes shown in Fig. 9 together with ignition energies, were derived by British Aerospace in the 1970's [7]. It should be noted that the flammability limits are not specification requirements, which include instead flash point, vapor pressure, and distillation of the particular fuel type.

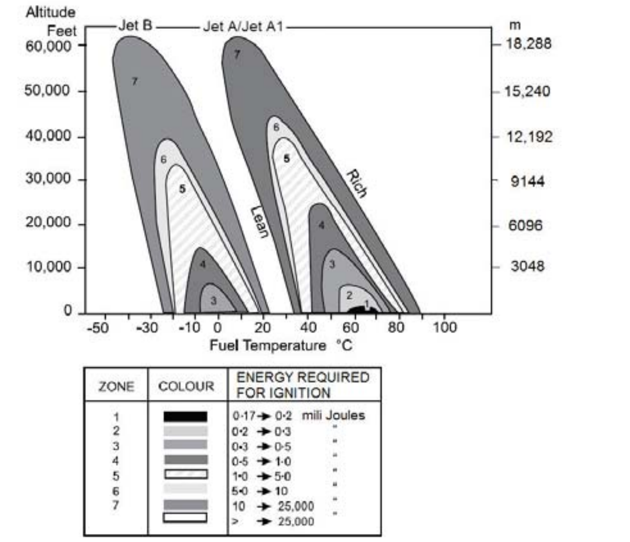

Fig. 9. Flammability envelopes and estimated minimum electrical ignition energies for Jet A/Jet A-1 and Jet B fuels. Source: British Aerospace [7].

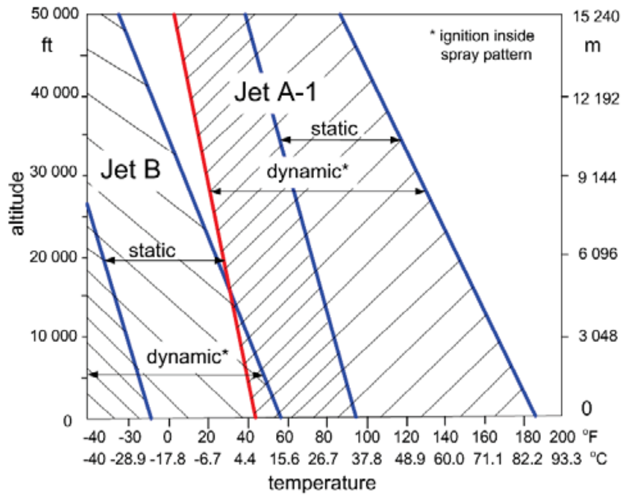

Fig. 10. Static and dynamic flammability envelopes for Jet A-1 and Jet B fuels [16].

Under dynamic conditions (pressure and temperature transients), the flammability envelope extends towards lower temperatures, as shown in Fig. 10 [16]. The dynamic flammability envelope for Jet A-1 fuel shows, that the flash point at low altitudes is as low as 4 to 5^{o}C.

Auto-ignition or *ignition temperature* (Table 1) is the temperature at which the material will ignite on its own without any outside source of ignition. Auto-ignition is sometimes called *hot-surface ignition*. The fuel is in direct contact with the outside skin. For example, at the end of 3-hour gate hold, the skin temperature of the bottom of the CWT can reach a maximum temperature of $93°$C [7]. Existing research [7, 11] indicates that hot surface ignition of fuels similar to Jet A can occur at temperatures ranging between $210°$ and $300°$C.

Electric ignition of aircraft fuel

Table 2 lists sources and causes of fuel ignition (explosion) in the tanks. A brief description of mechanisms of spark innitiations due to electric effects are given below.

Short circuit and electric arcing

An *electric arc* is an electrical breakdown of a gas which produces a continuously moving forward plasma discharge that results from a current through normally nonconductive media such as air. An electric arc is the form of electric discharge with the highest current density. The maximum current through an arc is limited only by the external circuit, not by the arc itself.

Arcing can also occur when a low resistance channel (foreign object, conductive dust, moisture, etc.) forms between objects with different potential. The conductive channel then can facilitate formation of an electric arc. The ionized air has high electrical conductivity approaching that of metals, and can conduct extremely high currents, causing a short circuit (SC) and tripping protective devices (fuses, circuit breakers). Similar situation may occur when a lightbulb burns out and the fragments of the filament pull an electric arc between the leads inside the bulb, leading to overcurrent that trips the breakers.

A *short circuit* (SC) is an electrical circuit that allows a current to travel along an unintended path with an impedance tending to zero. Electric arcs result from SCs that can develop from poor electrical contacts or failure of insulation. The electric arc is widely recognized as a very high level source of heat. The temperature of metal terminals are extraordinarily high, being reliably reported to be $20\ 000$ K [12].

Streaming electricity and electrostatic spark ignition

When a liquid is flowing, there is a transfer of electrons from one surafce to another as they flow past each other. The origin of the charge that forms the basis of the streaming potential stems from the chemical reactions taking place at the interface between the wall material of the pore (pipe) and the aqueous solution flowing through it.

The volume charge developed in the liquid is transported by the flow, resulting in a streaming current or charging current being carried by the liquid (Fig. 11). If the walls of the flow system are insulated or floating, the flow electrification process also leads to an electrostatic charge accumulation (ECA) and the generation of high electrostatic surface potential at liquid - solid interfaces. The lower the electric conductivity of the liquid, the stronger the ECA. Aircraft fuels have very low electric conductivity (Table 1).

The phenomenon of charge generation by low-conductivity liquids flowing in pipes and ducts is well known in petroleum industry. It is also known to occur in forced oil cooled power transformers. A number of explosions and fires have been attributed to discharges initiated in fuel tanks and handling equipment due to accumulation of charge generated by flow electrification.

Electrostatic discharge

Electrostatic discharge (ESD) is a single-event, rapid transfer (1 ns to 1 ms) of electrostatic charge between two objects, usually resulting when two objects at different potentials come into direct contact with each other. The ESD can also occur when a high electrostatic field develops between two objects in close proximity.

Electrostatic charge build-up occurs as a result of an imbalance of electrons on the surface of a material. Such a charge build-up develops an E electric field.

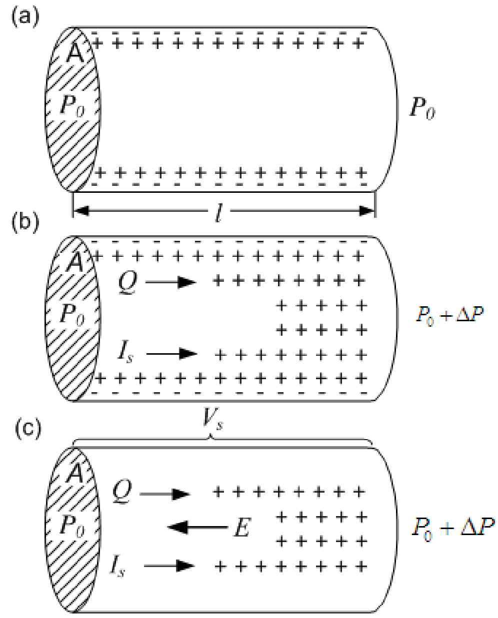

Fig. 11. Streaming potential and electricity: (a) a metal pipe with length l and cross section A, filled with a liquid (negative charge accompanied by partly mobile positive counter charge is present at the stationary pipe wall); (b) a pressure difference ΔP causes a flow Q, transport of charge and streaming current I_s; (d) the charge polarization causes an E electrostatic field and thus a conduction current, I_c (in a conductive liquid). Owing to the field, a streaming potential V_s is present over the pipe [17].

Electrical overstress

Electrical overstress (EOS) is typically defined as an over voltage or over current event with a duration exceeding 100 to 1000 ns and nominal durations of 1 ms that occurs while the device is in operation. It is typically differentiated from the ESD, which has a shorter duration (1 ns to 1 ms). Events that can lead to EOS damage include voltage spikes, lightning strikes and any temporary and unexpected connections to power or ground.

EOS events typically induce failures either due to dielectric breakdown (excessive voltage) or thermal runaway from Joule's heating (excessive current). In addition, some research has indicated that current-induced and field-induced degradation mechanisms complement one another and both are required to fully explain breakdown behavior over a wide range temperature.

Thermal overstress

Thermal overstress (excess heat) can be caused by EOS. When a device is subjected to more than its rated current or voltage and it exceeds the power dissipation defined by its safe operating area, EOS occurs. ESD can cause thermal overstress, too.

Minimum ignition energy in fuel tanks

On the basis of the report [7] the *minimum ignition energy* (MIE) in fuel tanks as a function of the altitude h_a can be approximately expressed as

$$E_i(h_a) = 10^{-3} exp[f(h_a)] \tag{3}$$

where

$$f(h_a) = \left[\frac{2.067 \times 10^{-4} h_a - 1.395}{(1 - h_a/2.043 \times 10^4)^{0.5}} \right] \quad (4)$$

and h_a is the altitude. Including the fuel temperature T_f, the MIE can be expressed as a function of two variables h_a and T_f, i.e.,

(5)
$$E_i(h_a, T_f) = 10^{-3} exp \left[f(h_a) + +a \left(\frac{9(T_f - T_{min})}{5} + 32 \right) \right]$$

where the minimum temperature of flash point

$$T_{min}(h_a) = T_{fp} - 5.55 - \frac{5}{9}(0.00492 h_a - 32), \quad (6)$$

the proportionality coefficient

$$a(h_a) = 2.841 \times 10^{-7} h_a + 6.73 \times 10^{-3}, \quad (7)$$

and T_{fp} is the temperature of the flash point. In the above equations the altitude h_a is in meters, temperatures T_f, T_{fp}, T_{min} in centigrades, and the MIE E_i is in Joules. Eqns (3) and (5) have been derived from equations given in [7]. Approximations (3) and (5) can be used for altitudes up to about 16 800 m $= 55\,000$ ft.

For example, for the flash point temperature $T_{fp} = 38°$C, fuel temperature $T_f = 10°$C at the altitude $h_a = 100$ m, the MIE $E_i = 11.98$ J. For $T_f = 20°$C at the same T_{fp} and h_a, the MIE $E_i = 6.48$ mJ. If the $h_a = 1000$ m, the MIE $E_i = 2.03$ J at $T_f = 10°$C and MIE $E_i = 2.53$ mJ at $T_f = 20°$C ($T_{fp} = 38°$C). Comparison of calculations with test results on the basis of eqns (3), (4), (5), (6), and (7) is given in Figs 12 and 13.

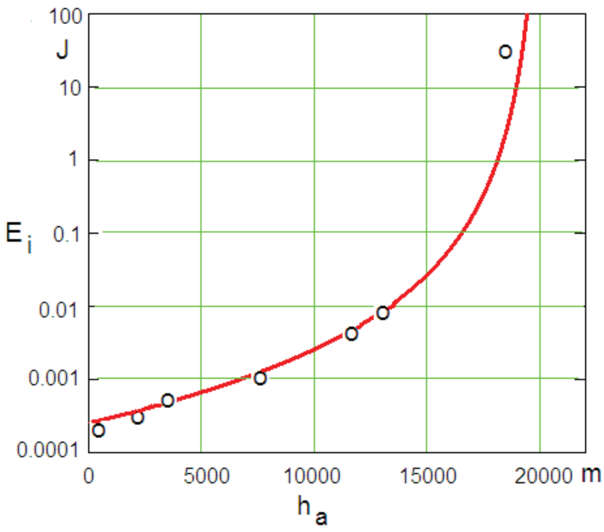

Fig. 12. Comparison of eqn (3) with test data for variation of the MIE with altitude. Experimental data from Bristish Aerospace [7].

Design of fuel tanks

Since the introduction of kerosene fuel for civil aircraft use in the late 1940's, the aircraft designers have been aware that the ullage would contain a mixture of fuel vapor, or mist and air, which could be ignited in the presence of a spark, flame, or hot surface.

To prevent tank explosions, designers have always assumed a flammable vapor exists in the fuel tanks and

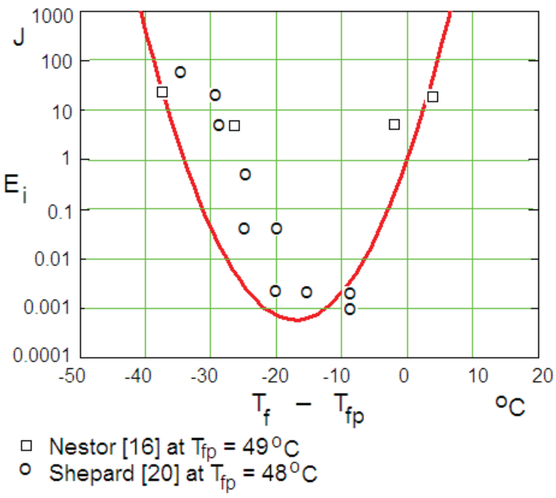

Fig. 13. Comparison of eqn (5) with test data for variation of the MIE with the temperature $T_f - T_{fp}$ of JET A fuel at $h_a = 4270$ m (14 000 ft) altitude. Exparimental data from J. Nestor [16] and J.E. Shepard [7, 20].

adopted standards to preclude ignition sources from the fuel tanks. The following are some of the design measures taken to satisfy that philosophy [7]:

A. Surface temperatures inside the tanks, under normal and failure conditions, are kept at least 10°C below the minimum necessary to ignite a fuel-air mixture. Pump motors are kept cool by an integral passage of circulating fuel. The motors have a temperature fuse, which cuts the electrical supply before an unsafe surface temperature is reached. In addition, the pumps and other similar equipment inside the tanks, are designed and tested to explosion-proof standards. Bleed air pipes or electric heating elements in the wing leading edges are frequently routed close to fuel tank walls. In such a case, heat-sensitive detector wires are installed to protect fuel tanks from overheat.

B. Electrical components and wiring within a fuel tank are designed to handle 1500 V AC which is well in excess of the voltage available on the airplane (115/200 V).

C. Electrical energy applied to any component in the fuel tank is limited to a value that is 10 times lower than the MIE necessary to ignite a fuel-air mixture. The MIE for hydrocarbon vapors is about 0.25 mJ.

D. The flow of a *hydrocarbon type fuel* through pipes, valves, filters, etc., causes the ECA in the fuel, which, if relaxed sufficiently fast, could allow the accumulation of hazardous potential levels inside a receiving tank. Therefore, it is necessary to avoid very high rates of fuel flow in the refueling system and control distribution of the fuel in the tanks. In addition, meticulous attention is paid to electrical connection of all metallic parts to dissipate the charge. The use of special additives in the fuels to increase the fuel electrical conductivity is required in some countries.

E. It is not allowed to bundle 28 V AC wires and 28 V DC wires (automatic fuel shut off valve).

F. Power limitation devices should be incorporated to minimize power into a fuel tank to eliminate hot spots.

A major consideration of fuel system safety is protection against the affects of lightning [2,4,9]. When an aircraft is struck by lightning, a pulse of high current flows through the aircraft from the entrance to the exit points. Protection against this phenomenon is provided in a number of ways (well bonded structure of aircraft, thick wing skin panels, proper location of tank vents, etc.).

Examples of explosions of fuel tanks

In older (and also many new) types of passenger aircraft, electric wires belonging to different electric circuits are laid in common bundles [4, 7, 23, 24, 26]. It is economical solution, which reduces the cost of electrical wiring. On the other hand, ageing and deterioration of insulation, wire overheating, SC or electric arcing in one electric circuit can make damage to insulation and SC of wires belonging to other electric circuits. Thermal protections are sometimes not reliable.

Fuel explosion in CWT

The most known fatal accident is explosion of fuel-air mixture in the CWT of Boeing 747-131, flight TWA 800 on June 17, 1996 due to SC in a bundle of electric wires (Fig. 14). Burst of the CWT led to destruction of the aircraft over the Atlantic Ocean [23, 24].

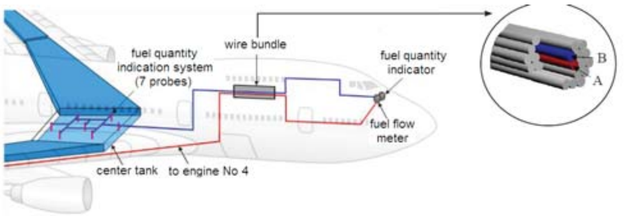

Fig. 14. Wiring configuration on the Boeing 747. Investigators suspect that high voltage from the fuel flow meter A passed to the fuel quantity indication system (FQIS) B because of a SC in the wire bundle [23].

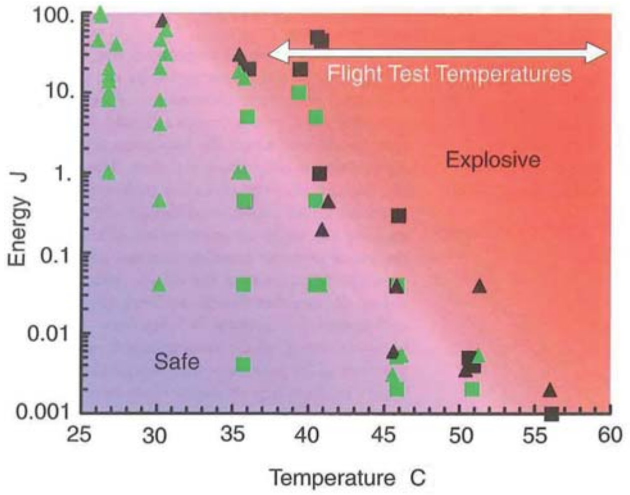

Fig. 15. MIE E_i versus fuel temperature T_f at pressure of 0.585 atm to ignate a sample of Jet A fuel-air mixture according to J.E. Shepard [21]. The green data points represent samples that did not ignite, the black points exploded. The squares are test simulating 0.189 m^3 (50 gallon) of fuel and the triangles represent a quarter-fuel tank.

In the case of TWA-800 the CWT had a capacity of 49.98 m^3 (13 200 gallon) and only contained 0.189 m^3 (50 gallon) of fuel Jet A. This corresponds to a fuel loading $k_{ml} \approx 3$ kg/m^3. The MIE E_i versus fuel temperature T_f at pressure of 0.585 atm is visualized in Fig. 15 [21].

Other recorded fuel explosions in the CWT or auxiliary tanks include [19]:

- Boeing 727, Taiwan, September 17, 1967, fuel Jet A, during ground maintenance, rupture of the CWT, the precise source of ignition could not be determined;
- Boeing 727, Minneapolis, MN, USA, May 3, 1970, fuel Jet A, during refuelling, heavy muffled explosion of the CWT, it is presumed that ignition resulted from a static discharge within the CWT;
- Boeing 727, Minneapolis, MN, USA, December 23, 1970, fuel Jet A, during refuelling, muffled explosion, combustion of the fuel vapor as a result of static discharge internal to the CWT;
- Beechjet 400, Washington DC, USA, June 6, 1989, fuel JP-4/Jet A mixture, during refuelling, fuel surged out of the filler opening, hissing noise followed by a bang, electrostatic charge has been built-up in the aft tank;
- McDonnell Douglas DC-9, Monteral, Canada, June 2, 1982, Jet A-1, at parking, over-pressure in the forward auxiliary fuel tank, the most probable source of sparks igniting the fuel vapor-air mixture was the transfer pump power supply harness;
- Boeing 737-300, Manilla, Philippines, May 11, 1990, Jet A, at parking, explosion and burning of the CWT, electrical failure was the source of ignition of the fuel-air mixture in the CWT;
- Boeing 747-100, New York, USA, July 17, 1996, Jet A, during climbing, inflight explosion in the CWT, flammable fuel vapor-air mixture due to fuel temperature $T_f = 45°$ at the altitude of 4200 m;
- Boeing 747-400, Bangkok, Thailand, March 3, 2001, Jet A, parking at the gate, empty CWT exploded as a result of ignition of fuel vapor-air mixture.

Fuel explosion in left or right wing tanks

Explosion in the left wing fuel tank took place on May 4, 2006 in Boeing 727-200 belonging to Malaysian Transmile Airline at Bangalore Airport, India, as the airplane was being repositioned for ground maintenance [25]. Explosion destroyed the structural integrity of the left wing. Investigators have found damaged electrical installation and electrical arcing in aluminum tube with 115-V AC cable feeding the fuel pump motor in the left wing tank (Fig. 16). Fuel pump motor wires have melted through the aluminum conduit, exposing the fuel vapors to ignition energy.

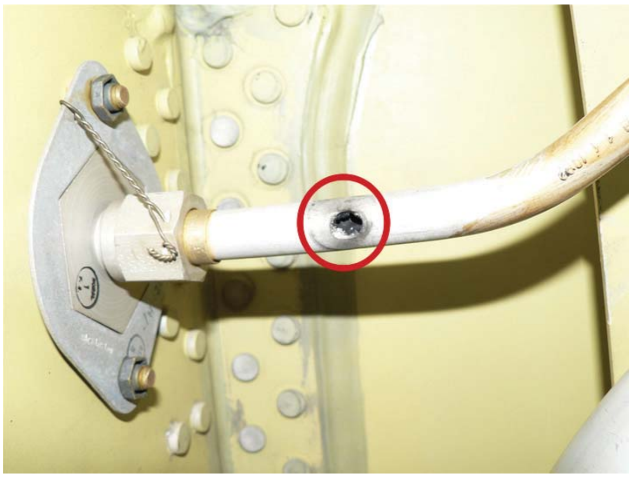

Fig. 16. Evidence of electrical arcing of the wiring inside the exploded left wing fuel tank of Boeing 727-200, Transmile Airlines, Bangalore, May 4, 2006 [25].

The evidence of fuel explosion in the left or right wing tanks has been found also in the following incidents [19]:

- Mc Donnel Douglas DC-8, Toronto, Canada, June 21, 1973, JP-4/Jet A mixture, during refuelling, fuel tank explosion blew of pieces of the right wing top skin and spar structure, ignition of fuel vapor-air mixture in the wing tank vent system;
- Mc Donnel Douglas DC-8, Travic AFB, CA, USA, March

23, 1974, JP-4, during ground maintenance; after removal inoperative fuel boost pump in the left wing fuel tank and installation of a different boost pump an explosion occured in the left wing center section, no conclusive evidence of an ignition source was established.

The above incidents do not include wing tank explosions due to lighting strike events, i.e.,

- Boeing 707, Elkton, MD, USA, December 8, 1963, Jet A/JP-4 mixture, descent for the approach to Philadelphia airport, left wing reserve tank on fire;
- Boeing 747-IIAF, Madrid, Spain, May, 9 1976, Jet A/JP-4 mixture, descent for the approach to Madrid airport, explosion and separation of the left wing.

Conclusions

Electrical equipment installed in the CWT and wing tanks (fuel pumps, fuel probes, level sensors, wiring) that routinely operate in the fuel vapor environment or partially sumberged in the fuel are potential source of electric sparks or arcing. Streaming electricity and ECA is another dangerous source of electric sparks.

The CWT is in direct contact with high energy heat sources as air conditioning system, so it is regarded as more flammable than left or right wing fuel tanks. The analysis of accidents shows that CWTs and fuselage mounted tanks experience considerably more explosions than wing tanks, since they are more vulnerable to explosions in the presence of ignition sources.

Although probability of explosion of the fuel in the left or right wing tanks due the electric SC, arcing or static electricity is low, this problem cannot be neglected. Malaysian Transmile Airline Boeing 727-200 explosion at Bangalore Airport, India is an evident proof that such incident can happen [25].

A substantial heat dissipation in the wing tanks can be due to abnormal operation or failure of electric resistive heating system of wing leading edges. The power consumption is in the range of tens of kWs.

Electromagnetic interference from radio frequency sources external to fuel tanks do not produce enough energy to ignite the fuel-air vapor in the tank. Also, electromagnetic interference from personal electronic devices plays no role in igniting the fuel-air vapor in the tank [24].

The MIE E_i to ignite the fuel depends on the fuel-air mass ratio k_{fa} (1), flash point T_{fp}, fuel temperature T_f, and pressure (altitude h_a). The MIE E_i can be estimated on the basis of experimental data or predicted using eqns (3) and (5).

A fuel-air mixture explosion in a fuel tank is capable of generating sufficient internal pressure to break apart the tank [24].

Until recently, insufficient attention has been paid to the condition of aircraft electrical wiring, resulting in potential safety hazards [24].

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