



EXPERIMENTAL AIRCRAFT FUEL TANK VAPOUR/AIR EXPLOSIONS USING JET A AND JET A / GASOLINE BLEND FUELS

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ABSTRACT

The potential of a fuel tank explosion is a well-known hazard in the aircraft industry. In this study, an investigation of a lab scale aircraft fuel tank in a flight situation at varying initial pressures of 400 - 1,000 mbar (equivalent to altitudes of 0 - 22,300 ft) and at variable temperatures was conducted in a 100-litre cylindrical test rig. A standard Jet A fuel and with a type Jet B fuel (which in this case was a Jet A with 10% of gasoline by mass) were used. Their flashpoints were measured to be 45°C (Jet A) and 20 °C (Jet B). In the simulated fuel tank explosions ignition occurred when the fuel liquid temperature was much higher than the flash point - 71 – 107 °C depending on initial pressure (altitude) for Jet A and 57 – 95 °C for the more volatile Jet B. The resulting maximum explosion overpressures were high, ranging from 0.7 to 5.8 bar, much higher than typical design strengths of aircraft fuel tanks, and much stronger than anticipated overpressures on the basis of ignition at or close to the lower flammability limit (LFL). It is postulated that these pressures are due to the distance between the liquid fuel surface and the ignition point and the formation of a vapour cloud with decreasing concentration with height above the fuel (being at LFL at the ignition point) and hence an overall concentration much higher than LFL. This demonstrated that severe explosions are fuel tanks are likely and the assumption that the explosion will be a near lean limit event is not safe. The work also provided explosion severity index data which can be used in design of suppression and venting systems for the mitigation of aircraft fuel tank explosions and provided other quantitative data to help manage this explosion risk appropriately.

Keywords: Aircraft fuel tank, Vapour-air explosions, Jet a fuel, Jet b fuel, Flashpoint

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The existence of flammable fuel vapours in the ullage of aircraft fuel tanks is well known in the aircraft industry (Colwell *et al.*, 2002; Clems, 2004; and Cheney 2004). Most aircrafts have flammable fuel/air vapours in the fuel tanks which upon ignition present a risk of explosion (Clems, 2004; Kazemi, 2006). Explosion is defined as an increase in volume and release of energy, it is usually associated with a sudden increase in temperature and pressure capable of causing damage to life and property. According to Bjerketvedt *et al.*, (1997), the prerequisite elements for an explosion are: fuel, oxidiser, and an ignition source.

The most common civil aircraft fuels are Jet A-1 or Jet A which are very similar kerosene-based fuels with a flashpoint higher than 38°C and boiling points of -47 and -40 °C respectively (IATA, 2015). Jet B fuel is mainly used in commercial operations where lower temperatures necessitate the use of lower flash point fuels for engine starting or as an alternate fuel. However, Jet A, being the less volatile fuel, has been strongly promoted since the early 1950s in the belief that it was safer in ground handling operations and in crash situations (Colwell *et al.*, 2002; and Clems, 2004). Jet A fuel could be converted to Jet B fuel by simply adding gasoline fuel thereby reducing the flash point temperatures of Jet A fuel. The jet fuels are complex kerosene-based hydrocarbon mixtures comprising of up to 260 aliphatic and aromatic hydrocarbon compounds (Shepherd *et al.*, 2000).

Generally, fuel tanks are vented to air in order avoid a vacuum from being created when the fuel is pumped out to the engines. All the aircraft fuel tanks have air above the fuel mostly Jet A or Jet B fuels whose pressure falls when the aircraft ascends. This phenomenon forms a crucial part of why a flammable vapour-air mixture is formed (Aerospace, 1997). The major causes of the ignition of fuel in a commercial aircraft's fuel tanks could be attributed to sources such as in-tank electrical wiring, fuel pump motor wiring, electric motor of fuel pump, static electricity build-up due to fuel circulation and lightning (Knezevic, 2018).

Historically, there has been several aircraft accidents involving fuel tank explosions which brought concerns in the fundamental safety strategy applicable to fuel systems of large commercial airplanes. The basic safety approach remains preventing the presence of ignition (Cheney, 2004). An overview of the past fuel tank explosions indicating the operational phase and source of ignition are summarised in Appendix A (Cheney, 2004; FAA, 1998a; FAA, 1998b; Carol, 2009; and Andrews, 2009). Also shown in Appendix A is the numbers of fatalities and hull losses indicated against each accident. Consequently, it could be deduced that aircraft fuel tank explosion can occur both on ground (sea level) and in-flight (altitude). However, the accident at altitude produced more fatalities than at sea level.

Early studies on aviation fuels flammability and by extension aircraft fuel tank explosions were conducted by Coward and Jones (1952), Zabetakis and Richmond (1953), Zabetakis (1965), Kosvic *et al.* (1971), Nestor (1967), Ott (1970), and Kuchta and Clodfelter (1985). Following the TWA Flight 800 Centre Wing Tank (CWT) explosions on 17 July 1996, the National Transport and Safety Board (NTSB) and Federal Aviation Authority (FAA) in the United State of America made both short term and long-term recommendations to enhance the safety efficiency of the aircraft fuel tank systems across the globe. The two organizations sponsored research to study fuel tank vapour characteristics in CWT for various in-flight conditions. However, there are limited studies in this regard (Sagebiel, 1997; Shepherd *et al.*, 1997; Woodrow and Seiber 1997; FAA 1998a, FAA 1998b, Summer, 1999; and NTSB, 2000). Also, most recent studies on aircraft fuel tank explosions focused more on preventive methods rather than the actual hazards assessment of the explosion itself. Equally, the studies were conducted based on the aircraft position at sea

level (on ground) and not at varying altitudes as the case of real aircraft scenarios (Yan *et al.*, 2015; Shao *et al.*, 2017; and Shao *et al.*, 2018).

ASTM D1655 (2020) requirements for Jet A properties include distillation temperature, flash point, and net heat of combustion. Of these properties, flash point is the measurement related to the relative flammability hazard of fuels in ground handling and flight storage and transfer. The flash point is defined as the lowest temperature, corrected to 101.3 kPa of pressure, at which the application of an ignition source causes the vapour of a liquid sample to ignite momentarily under specified conditions of testing (Summer, 2000). The agreement between lean flammability limit and the associated vapour concentration at the measured flash point for various fuels was highlighted by Andrews (2009) particularly for single component liquids. The flash point is a useful characteristic of aviation fuel; it is used in scientific measurements or predictive hazard assessment when evaluating the flammability hazards of combustible liquids. A temperature below the flash point of a fuel will lead to a non-flammable fuel vapour-air mixtures at standard atmosphere even though, a flammable mixture can be formed at reduced pressures. The minimum legal flash point for aviation kerosene is 38°C at 1 atmosphere, but, the range of flash point according to Mallard (1994) can be up to 63°C and sometimes an upper flash point for a range of kerosene is 66-70°C especially for military aircraft (Keating, 1993). The aim of this paper was to conduct experimental studies in lab scale aircraft fuel tank vapour/air explosions using Jet A and Jet B fuels at different pressures and temperatures, representing different flight conditions. The explosion characteristics such as maximum explosion pressure and explosion index were determined and these can be used for the design of appropriate explosion protection systems.

METHODOLOGY

FLASHPOINT CLOSED CUP TEST EQUIPMENT

In this work, a Pensky-Martens Closed Cup (FP IP34 ASTM D93) shown in Figure 1 was used to determine the flashpoint of the aviation kerosene used for the experiment. Thirteen (13) samples of Jet A fuel were collected from Leeds/Bradford Airport. In one of the samples, 10% by mass of gasoline aged for 24 hours to reduce its volatility was added in order to have different flashpoint and explosion results. This blend of gasoline and Jet-A fuels made up a Jet-B fuel which is an aviation fuel characterized with low flashpoint.

The apparatus consisted of the test cup, test cover shutter stirring device, heating source, ignition source device, air bath and top plate. Using the Pensky-Marten's apparatus, a 50 ml sample of Jet-A fuel was heated with a 3.2 mm diameter of flame in a 130 ml vessel closed cup. At a regular temperature interval of 1°C, the cup was opened momentarily and a pilot flame was dipped into the vapour space above the surface of the fuel. The temperature at which the first ignition occurred was taken to be the flashpoint. Each sample of the fuel was tested at least twice in order to get an accurate flashpoint.

From the Pensky-Martens method for determining closed flash point, a formula from ASTM D93 (2003) was used to calculate the corrected flash point for the prevailing ambient pressure at the test time, as given in Equation 1.

Corrected flashpoint (°C) = $C + 0.025 (1013 - P)$
where:

Eq. 1

C = Flash point obtained during the test in °C

P = Barometric pressure for the day in mbar.

Table 1 shows a summary of the tests for flashpoints, corrected flashpoint conducted in this work for both Jet A and Jet B fuels.

CYLINDRICAL TEST EXPLOSION RIG

A cylindrical test explosion rig was used to conduct experimental studies of an aircraft fuel tank explosion. The rig measured 0.48 m in internal diameter and 0.5 m in height, giving the rig a volume of 0.098 m³ (98 litres). Figures 2 and 3 show the picture and schematic diagram of the explosion rig used, respectively. Four thermocouples located inside the rig were used to measure the air and liquid temperatures. The lowest thermocouple was inserted in the liquid fuel and was used to measure the fuel temperature. The remaining three thermocouples were placed at 30 mm, 130 mm and 300 mm above the fuel surface to measure the air temperature. The thermocouple that measured the fuel temperature was connected to a temperature controller which derived its power from a 240 V mains supply via a variable power controller. An electrical mat heater heated the fuel in a 160 mm diameter tray from the underneath of the tray and was connected to a temperature controller. The remaining three thermocouples and a pressure barocel were connected to an "IOtech Data Logger" which generated data once in every 2 seconds to a personal computer.

A pressure transducer, a spark plug, a vacuum pump connecting pipe and a barocel connecting pipe were located on the vessel top lid. The pressure transducer was connected to a "Micro Link Fast Data Logger" which was capable of capturing data of 32 KBs in less than a second at 100 kHz rate. In this experiment, it was set to capture all the data in 15 seconds as the exact time of the explosion was not known. An ignition button and a computer (with wavecap and Famos software installed) in the control room were also connected to the micro link fast data logger. A spark plug of 15J (ignitor) was used as a source of ignition so as to cause an explosion provided that a flammable fuel vapour/air mixture was formed. The spark plug was 390 mm from the top lid which gave the tip of the plug 87 mm above the fuel surface. The barocel accurately measured the pressure inside the rig and was connected to an IOtech Data Logger. This measured the pressure increase due to fuel vaporization on heating. From this, the concentration of fuel vapour can be determined. Kerosene is flammable at 1% by volume with 10 mbar pressure increment at 1 bar and 5 mbar increments at 0.5 bar. A vacuum pump was used to evacuate the air inside the rig thereby reducing the pressure in the rig to simulate an aircraft fuel tank at various altitudes.

EXPLOSION TEST RIG PROCEDURE

The explosion rig was cleaned of residual fuel and dirt from the previous experiment. All the seals on the rig were checked to ensure that there would be no leakage. Sixty-eight (68) grams of fuel was weighed and poured into a fuel tray of 160 mm diameter and 20 mm deep which was placed carefully on the heating pad at the bottom of the rig in the centre of the 0.5 m diameter cylinder. The explosion vessel lid was lowered into place using an overhead support and was fastened securely and sealed, using bolts and a gasket. The spark plug, vacuum pump, and barocel and the pressure transducer which were located to on vessel lid were then connected to their respective circuits. The rig was then evacuated down to the desired initial pressure using a vacuum pump. The required initial pressure was measured

using the barocel which measured atmospheric pressure to 1/10,000 resolutions. The sample fuel was heated from underneath the rig by the mat heater. The fuel temperature was heated in 5°C increments. Once the fuel temperature was stabilized, all the valves to the rig were closed and the barocel was disconnected. This was to avoid damage to the barocel by the explosion overpressure.

The igniter was sparked once at the end of the 5-minute stabilisation period at the targeted temperature was reached. An explosion was indicated by a sharp rise in temperature as measured by the thermocouples and an increase in pressure as measured by the pressure transducer. If an explosion did not occur, the ignition button was pressed again. If there was still no explosion, the fuel was heated more to 5°C higher and tested again. After a successful ignition test, the explosion rig was left for an hour to cool and for the explosion vapours to escape. This was achieved using a vacuum pump to release the gases to the atmosphere. Table 2 gives a summary of tests conducted and the corresponding results obtained.

RESULTS AND DISCUSSION

FLASHPOINTS

The flashpoints of the Jet-A fuel were found to be in a range of 44-47°C and this is within the legally acceptable limits of Jet-A fuel flashpoint which is 38-70°C. For this experiment, there was only a small variation of 3°C flashpoint from the samples tested. The small variation in the flashpoint of the samples of aviation kerosene is due to the supplies from Leeds-Bradford Airport which comes from a single refinery source. For a mixture of Jet-B (a blend of Jet A fuel with 10% gasoline by mass), the flashpoint had reduced drastically to 20°C. This reduction in flashpoint was as a result of the volatile nature of the gasoline fuel which has a flashpoint of about -40°C or lower. The influence of gasoline in reducing the flashpoint of Jet-A as noticed in this experiment follows the trend of the experiments carried out by Shepherd and Perez (2008).

Figure 4 shows an experimental measured flashpoint of Jet A fuels by various researchers at standard atmosphere and at reduced pressures (Zabetakis and Richmond, 1953; Mullins, 1957; Nestor, 1967; Ott, 1970; Air Force, 1992; and Shepherd *et al.*, 1997). With the exception of the work of Shepherd *et al.* (1997), all the flashpoints measured were within acceptable range of 38-70°C. This is despite that the researchers used various types of testing methods. Also shown in Figure 4 are measured flashpoints of Jet A at various pressures (equated to altitude) as experienced in aircraft flight. There is a strong relationship between flashpoint and pressure from the studies shown, with a best fit line having a correlation coefficient (R^2) value of 0.83. When an aircraft ascends, the ambient pressure decreases and this allows more vapour to escape the liquid at lower pressures and thus flash point decreases with pressure. Notwithstanding, a flammable vapour can be formed at lower temperatures for low flashpoint fuels. For TWA flight 800, the residual fuel in the CWT that was fuelled in Athens was a legal fuel contrary to a report saying that it was illegal; rather, the fuel flashpoint was very close to the low limit of the range allowed and this made the fuel to be more volatile (Andrews, 2009). Generally, the fuel temperature in the aircraft tank is vital because it determines the amount of fuel vapour pressure produced at different altitudes. In the TWA flight the air conditioning units contributed in maintaining a relatively high temperature of the fuel in the central tank (NTSB, 2000), but in general the fuel temperature will drop with altitude. In this study although the pressure was changed to simulate the

change in altitude it was not possible to change the corresponding temperature. However, the change in temperature in the vapour space of the tank as the aircraft climbs would be slow due to thermal inertia but also due the fact that as the plane climbs the tank will be venting out rather than taking cold air in due to the pressure differences.

EXPLOSION TESTS RESULTS

Figure 5 shows a temperature-time and pressure-time profile at 1000 mbar initial pressure for the test using Jet A fuel only. From the commencement of the heating of the Jet A fuel, the fuel temperature (fuel t) and the air temperatures measured by the three thermocouples positioned at 30 mm (air30mm), 130 mm (air3) and 300 mm (air2) were nearly similar until about 50 s. Subsequently, the fuel temperature rose progressively whilst the air temperatures from the three thermocouples increased marginally. At about 1236 s, there was a sharp rise (spike) in both fuel and air temperatures which signifies an explosion at 107°C. The fuel temperature attained a maximum value of about 150°C and subsequently declined to about 130°C at nearly 1380 s. However, for the air temperatures, a peak temperature of over 200°C was realised prior to a sharp drop to below 40°C at about 1380 s. A similar profile for fuel and air temperatures was realised for other initial pressures for both Jet A and Jet B although at various magnitudes.

A vapour pressure could be indicated by the pressure trace over the experiment conducted. The pressure begins to rise slightly once the rig has been vacuumed down to the required pressure. This is as a result of the fuel vapour pressure. This pressure is taken as the percentage of the initial pressure which in turns gives the percentage by volume of the fuel present in the vapour space. Table 2 shows the fuel vapour concentration (% by volume of fuel) for all the tests carried out. The least pressure rise was that for 1000 mbar Test 1 with a fuel vapour concentration of 0.9%. However, there was high pressure rise resulting to a high fuel vapour concentration for the remaining tests conducted.

A pressure-time profile at 1000 mbar initial pressure upon ignition of Jet A fuel is given in Figure 6. A sudden increase in pressure is discernible at about 6 s reaching a maximum value of 3 bara at about 8 s thus realising an overpressure of nearly 2 bar. The sharp increase in pressure within 2 s led to a rate of pressure rise, dP/dt of 3.24 bar/s. According to Clancey (1975), an explosion overpressure of about 0.7 bar is severe enough to cause total possible damage of buildings. Stainless steel, aluminium alloys, or other fuel-resistant materials are used to make fuel tanks for commercial aircraft and are required to withstand an internal pressure of 0.24 bar (Knezevic, 2018). The pressure rise shown in Figure 6 is about 9 times higher than the design pressure of the tank and therefore the tank would fail unless other protection measures are available such as explosion suppression or venting.

For TWA Flight 800, an explosion which corresponds to an initial pressure of 600 mbar at an altitude of 13,600 ft. This suggests that a peak pressure of 4.8 bar would have occurred under stoichiometric mixtures (i.e., $0.6 \text{ bar} \times 8 = 4.8 \text{ bar}$). The CWT for B747 is designed to have a high structural strength which is 2 m high when the plane is level and 6.5 m depth when the plane is in a high banking manoeuvre and this will lead to a static depth pressure at the bottom of the fuel tank to be 0.17 and 0.5 bar respectively (Andrews, 2009). So, the structural strength of a fuel tank could withstand an overpressure of about 0.5 bar. The relationship between maximum explosion overpressure (normalized by the initial pressure) and the initial pressure for both Jet A and Jet B fuels is shown in Figure 7. It is evident that maximum explosion overpressure increased with an increase in initial pressure (decrease in altitude). This

follows a similar trend from the earlier researchers of aircraft fuel tank explosions (Sagebiel, 1997; Shepherd *et al.*, 1997; Woodrow and Seiber 1997; FAA 1998a, Summer, 1999; NTSB, 2000; Shepherd and Perez 2008). Also in the present work, the magnitude of explosion overpressure is higher for Jet B fuel when compared with that of Jet A fuel. The variation in explosion overpressure is wider with an increase in initial pressure. For 1000 mbar and 400 mbar initial pressures, the maximum explosion overpressure for Jet B fuel is 4.9 bar and 0.67 bar respectively. These overpressures are 2.4 and 1.8 times higher than those obtained from Jet A fuel respectively. This severity could be attributed to the lower flashpoint of Jet B fuel compared to Jet A fuel and this necessitates the need for more safety measures in handling aircraft using Jet B fuel on the ground.

The present experiments were intended to cause ignition at the lowest fuel temperature at which point the concentration would have been just inside the flammable range and therefore a low relative pressure increase would have expected and that should have been similar for all mixtures. In fact, Figure 7 shows that most of the tests showed similar pressure increases 2 to 3 times the initial with the exception of Jet B at 1 bar initial pressure which resulted in a maximum pressure ratio of almost 6, The results suggest that the ignition in the experiments is not achieved until higher concentrations (richer than the lean limit) are reached and case of Jet B at 1 bar initial pressure the concentration must have been approaching stoichiometric.

In Figure 8 the ignition temperatures of the two fuels are plotted against altitude (initial pressure). They are compared in the same plot against the flash point data of Jet A at different pressures (same data as in Figure 4). It is clear that the ignition temperatures from the experiments are much higher than the flashpoint temperature. The ignition temperatures for Jet A ranged from 71 to 107 °C compared to corresponding flashpoints of approximately 25 to 45 °C. The pattern was consistent and repeatable the fuel ignition temperature in these tests was much higher than the flashpoint.

The most likely cause of this phenomenon would be the position of the ignitor relative to the fuel surface. The fuel vapours are much heavier than air so would expect to vapours to spill over the container vessel and start filling up the “tank” from the bottom up with decreasing vertical concentration gradient. So, the fuel would ignite when the concentration of the flammable vapour and the ignitor tip, 87 mm above the fuel surface, was just inside the lower flammability limit (LFL) with rest of the mixture below that being at higher concentrations than the LFL. This would explain the high overpressures and high maximum pressure ratios reported in this work.

These observations also mean that the general assumption that fuel will ignite when near its flashpoint, hence near the LFL and thus an explosion would be weak and the overpressures would be low, is unsafe. The results clearly show that much stronger explosions are possible, with significantly higher potential damages and this is likely to be dependent on the location and timing of the ignition.

The maximum rate of pressure rise $(dp/dt)_{max}$ is useful in calculating the explosion severity factor otherwise known as deflagration or explosion index index, K_G in bar m/s. The $(dp/dt)_{max}$ in closed vessel is influenced by the fuel composition, fuel / air mixture, volume and shape of the enclosure, ignition source size, energy and position and heat losses during flame propagation (NFPA68, 2018). The K_G is dependent on $(dp/dt)_{max}$ as well as the volume of the explosion enclosure. This is mathematically expressed as in Equation 2,

$$K_G = (dp/dt)_{\max} V^{0.33}$$

Eq. 2

Figure 9 shows the relationship between initial pressure and the calculated K_G for both Jet fuels. For every increase in initial pressure, there is an increase in K_G leading to a maximum values of about 1.6 bar m/s for Jet A and 7 bar m/s for Jet B at 1000 mbar initial pressure.

In comparison with the work of Cashdollar *et al.* (2000), the $(dp/dt)_{\max}$ and K_G in the present experiment are low and this is typical of the lean mixture near the flammable limit due to lower flame temperature and also due to heat losses from slow buoyant flames near the limits. Also, the vessel shape and volume have an influence on the peak pressure rise for a near stoichiometric mixture due to the flame contacting the wall before burning all the mixture, this led to heat losses and a lower vessel's temperature and pressure. For instance, a flame in a cylindrical vessel as in the case of the present experiment will move outwards under near adiabatic conditions. But, before all the mixture is burnt, the flame will touch the sides of the vessel thereby causing heat losses. Therefore, only a spherical vessel as in the case of Cashdollar *et al.* (2000) with a central ignition will be close to adiabatic conditions for stoichiometric mixtures. However, the flame will be distorted near the flammability limits where the flame rises under buoyancy so that the flame will touch the vessel's wall of the sphere before it has burnt all the mixture.

The implication of these trends is that fuel tank explosions are more severe on the ground than in flight. However, in reality aircraft fuel tank explosions in-flight recorded more fatalities than on the ground. The K_G parameter is used in the design of explosion vents and/or suppression systems in order to keep the explosion overpressure below the strength of the containing vessel (the fuel tank in this case). Detailed consideration of these design strategies may show that that the risk or consequence reduction is not sufficient and alternative strategies such fuel tank ullage inerting may be more appropriate.

CONCLUSION

The present experiments highlighted the danger of fuel-air explosions from aircraft fuel tanks using Jet A and Jet B fuels. This was demonstrated using a 100 L cylindrical test rig at variable initial pressures. The flashpoints of the Jet-A fuel were found to be in a range of 44 - 47°C whilst the gasoline enriched Jet B had a much lower flash point at 20 oC,. In the simulated fuel tank scenarios, for a range of 400 mbar to 1000 mbar initial pressure (equivalent to 22,300 ft – 0 ft altitude), flammable fuel vapour/air explosions for Jet A occurred within 71 - 107°C fuel temperatures while for Jet B the equivalent ignition temperature range was 57-95 oC. The resulting maximum explosion overpressures were high ranging from 0.7 to 5.8 bar, in all cases much higher than typical design strength values of fuel tanks. If the vapours had ignited when the concentrations were just inside the flammable range (at LFL or just above that) then much weaker explosions would have been expected. High liquid fuel temperatures at the time of ignition, compared to the flash point temperature confirm that a large part of the vapour cloud inside the tank was at much higher concentrations than LFL.

It was postulated that the reason for these observations was that a stratified vapour/air mixture was formed between the bottom of the tank and the point of ignition with decreasing concentration gradient. At the point of ignition, the concentration might have been at or near LFL but the rest of the cloud layer was at higher concentrations

resulting in significantly higher pressures than anticipated. This needs to be investigated further and verified but the results demonstrate the severe explosions in fuel tanks are likely and the assumption that the explosion will be a near lean limit event is not safe.

The work also provided explosion severity index data which can be used in design of suppression and venting systems for the mitigation of aircraft fuel tank explosions. Alternatively, the severity of the explosion pressures would suggest a preventive strategy such as continuous space inerting may be a more appropriate strategy, if feasible. This work provides some quantitative data to help manage the explosion risk appropriately.

COMPETING INTEREST

The authors declare that they have no competing interests.

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List of Table

Table 1: Summary of flashpoint tests results

Sample	Initial Pressure (mbar)	Flash Point (°C)	Corrected Flash Point (°C)	Fuel Type
(-)	(-)	(-)	(-)	(-)
1	981	45	45.8	Jet A
2	981	43	43.8	“
3	981	45	45.8	“
4	981	44	44.8	“
5	981	43	43.8	“
6	981	46	46.8	“
7	981	44	44.8	“
8	981	45	45.8	“
9	981	46	46.8	“
10	981	43	43.8	“
11	981	18	18.8	Jet B
12	981	21	21.8	“
13	981	19	19.8	“
Zabetakis and Richmond (1953)	1013	45	-	Jet A
Zabetakis and Richmond (1953)	628	35	-	“
Zabetakis and Richmond (1953)	182	25	-	“
Mullins (1957)	1013	47	-	“
Mullins (1957)	628	37	-	“
Mullins (1957)	182	15	-	“
Nestor (1967)	1013	48	-	“
Ott (1970)	1013	48	-	“
Air Force (1992)	1013	54	-	“
Shepherd et al. (1997)	1013	35	-	“

Table 2. Summary of experimental work and results (Jet B is Jet A + 10% gasoline).

Test (-)	Fuel (-)	P _i (mbar)	Alt (ft)	T _{ig} (°C)	t _{ig} (sec)	P _m (mbar)	P _m /P _i (-)	F _{vc} (%)	dp/dt (bar/sec)	K _G (bar m/s)
1	Jet A	1000	0	107	1236	3064	3.1	0.9	3.24	1.494
2	Jet A	600	13,600	85	3022	1548	2.6	6	0.745	0.3437
3	Jet A	500	17,200	79	1044	1218	2.4	25	0.346	0.1595
4	Jet A	400	22,300	71	793	778	2.0	5	0.334	0.1540
5	Jet B	1000	0	95	1316	5873	5.9	2.9	15.52	7.1558
6	Jet B	600	13,600	72	811	2115	3.5	2.6	3.3198	1.5306
7	Jet B	500	17,200	60	758	1201	2.4	2.5	0.2868	0.1322
8	Jet B	400	22,300	57	716	1073	2.7	3.3	0.6118	0.2821

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- Figure 8.** Fuel tank ignition temperatures as a function of altitude and comparison to the flash point.
- Figure 9.** Comparison between mixture reactivities for Jet A and Jet B fuels at various initial pressures.



Figure 1



Figure 2

Aviation Fuel Tank Rig Schematic 484mm Dia *500mm height

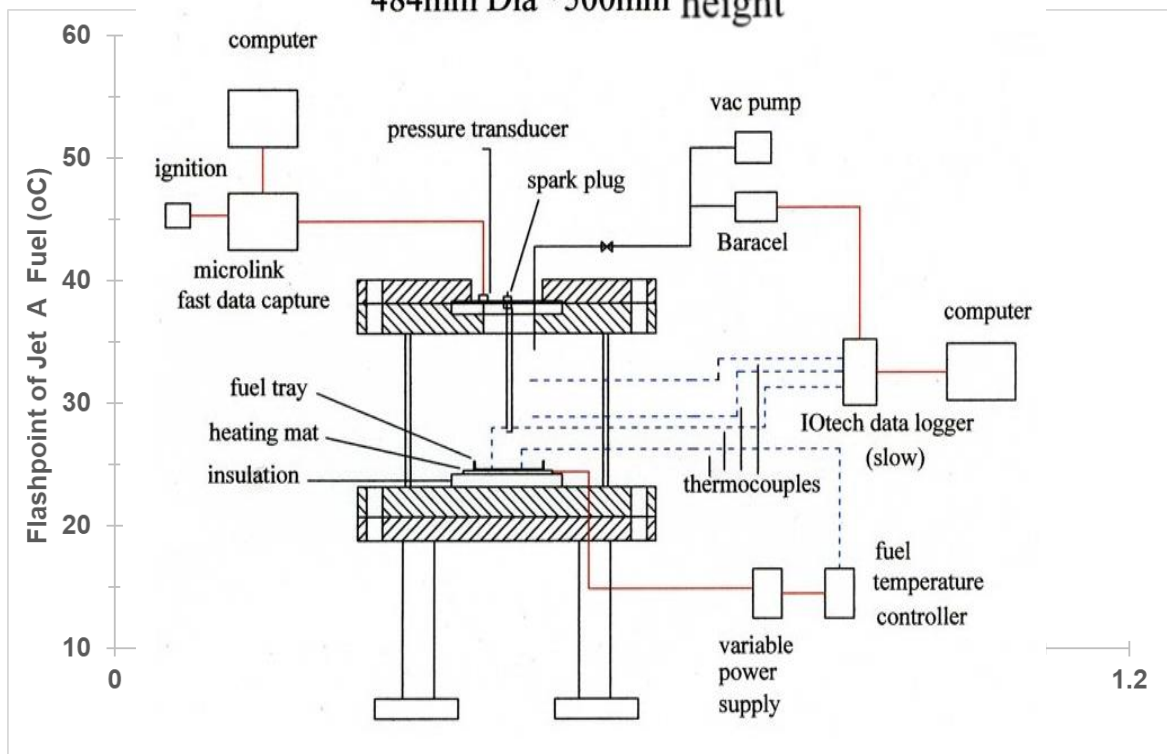


Figure 3

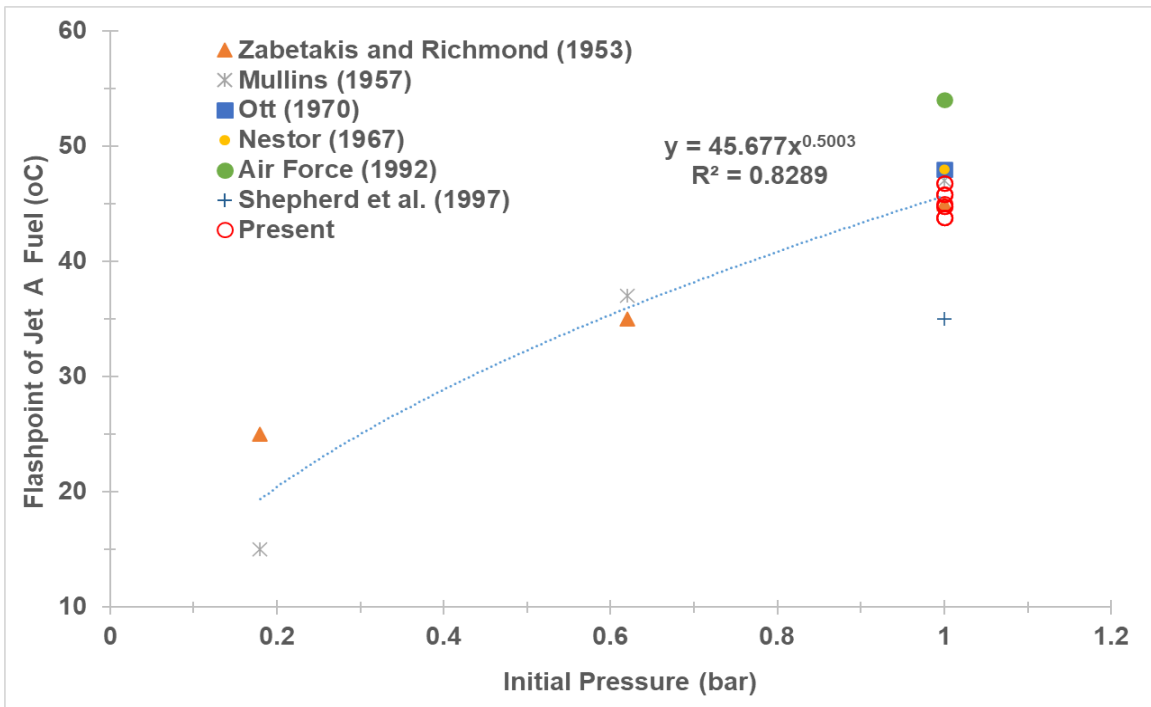


Figure 4

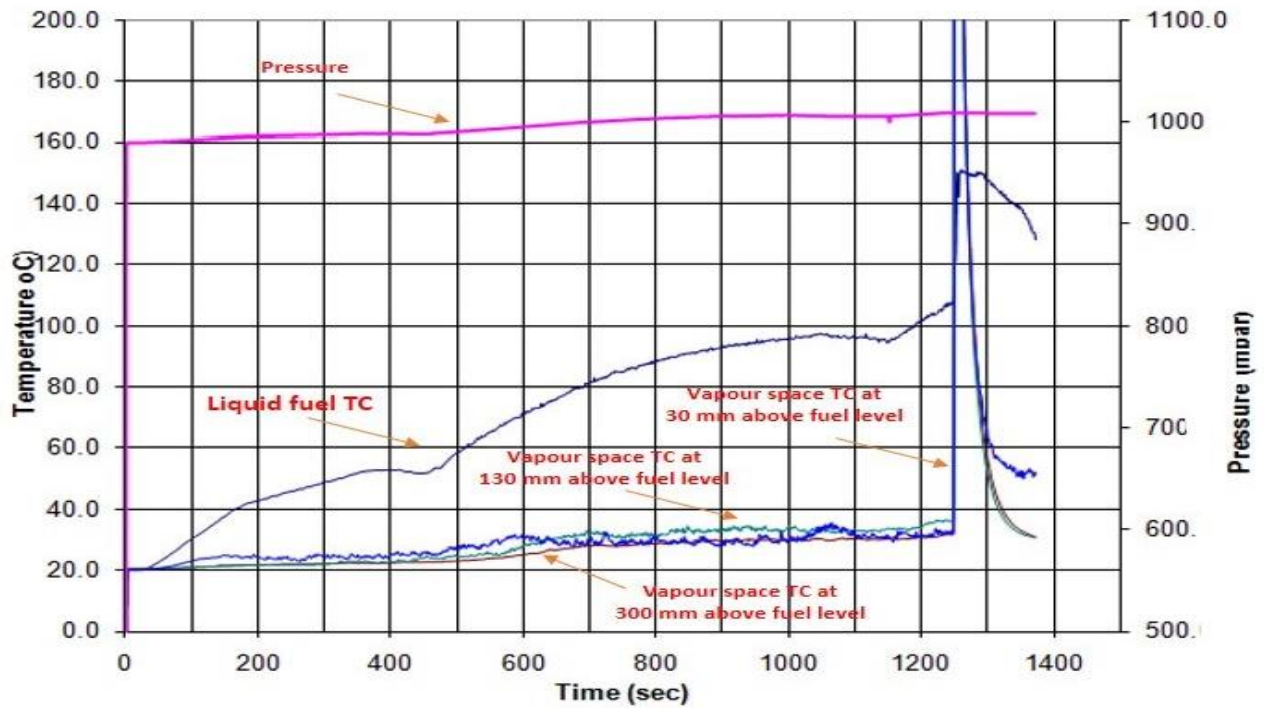


Figure 5

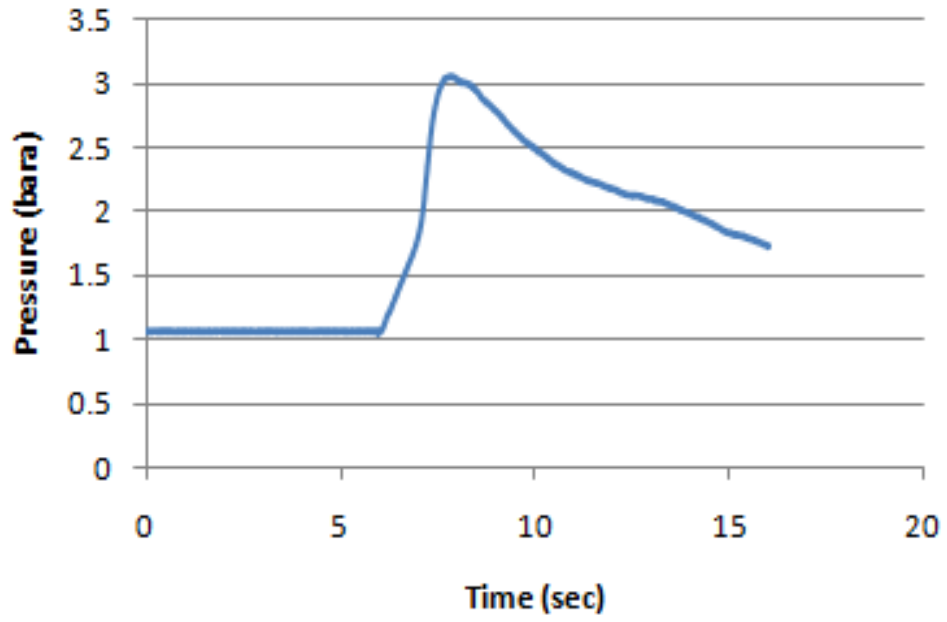


Figure 6

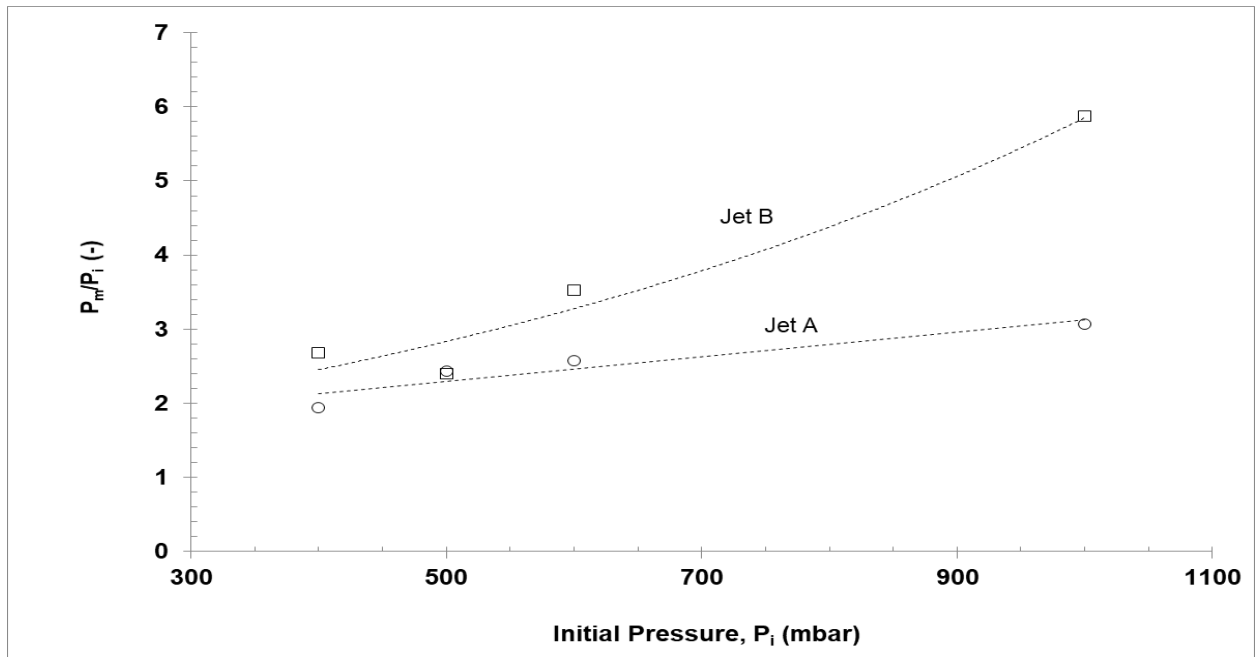


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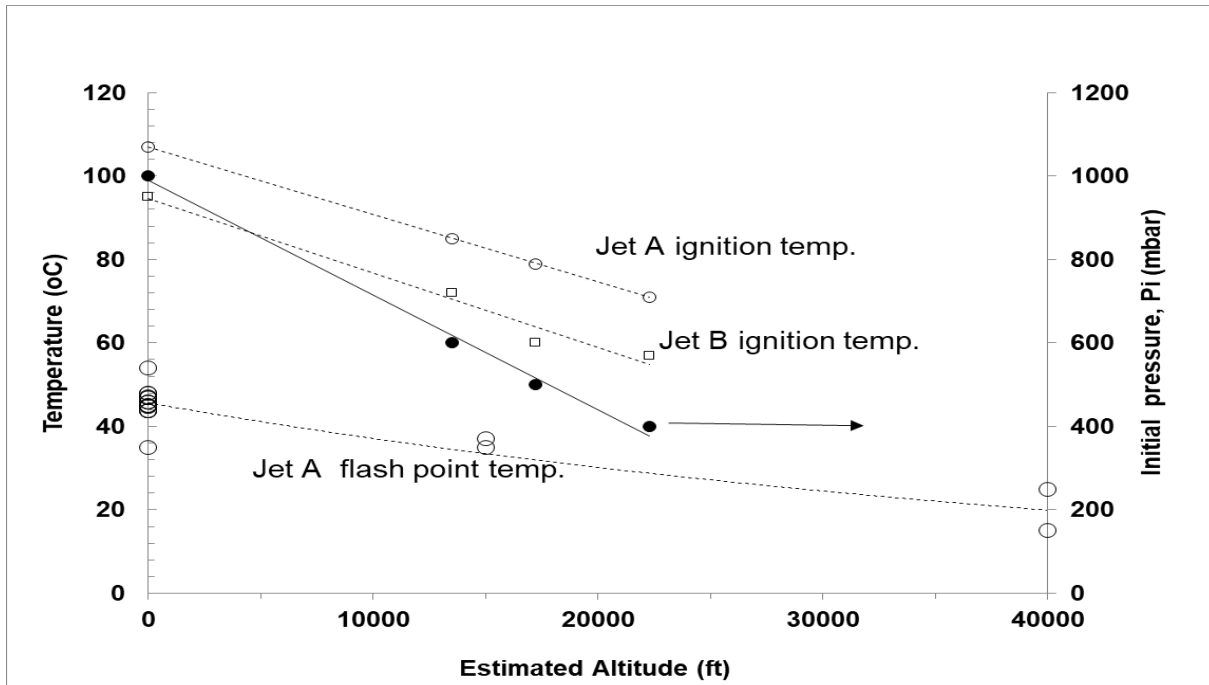


Figure 8

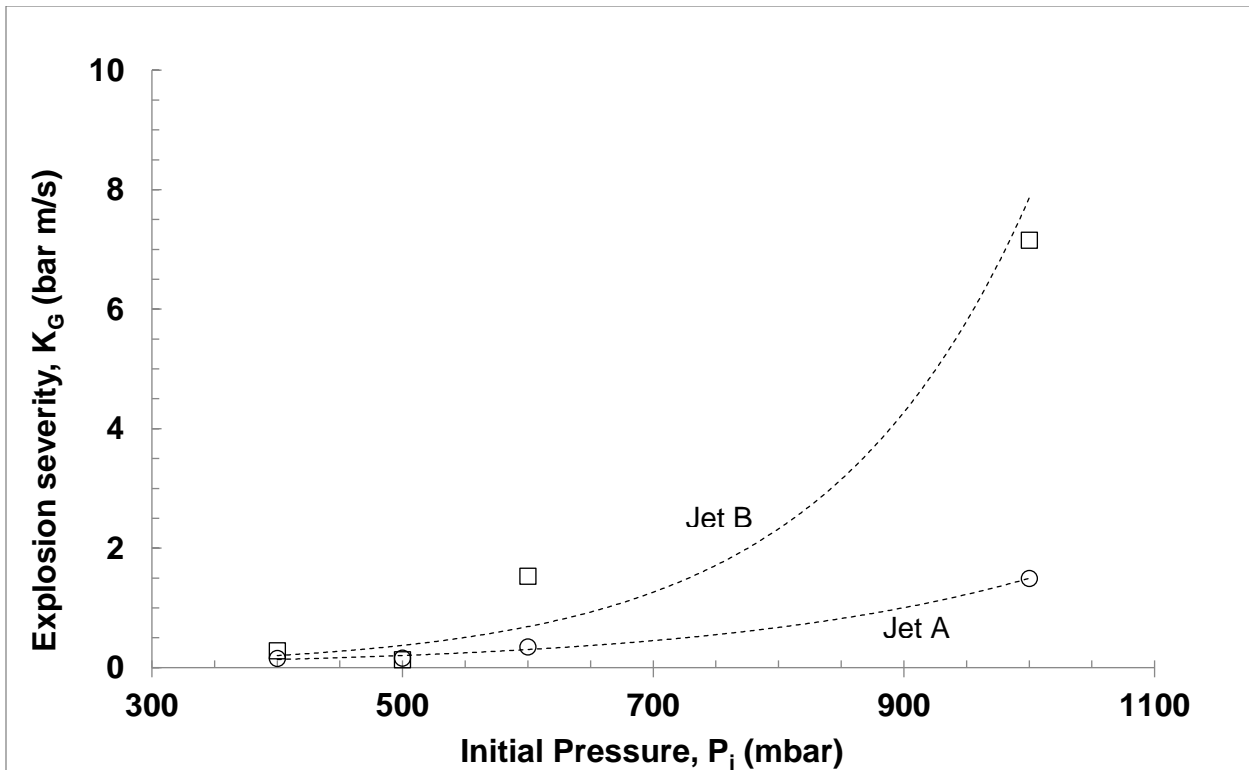


Figure 9

APPENDIX

APPENDIX A. Overview of aircraft fuel tank explosions accidents.

Year	Plane	Location	Inflight	Ground Ops	Ground Maint.	Refueling	Lightning	Overwing Fuel inflight	Static Discharge	Sabotage	Unknown	Death	Hull Loss
1959	B707	OSO	x								x	4	Yes
1963	B707	Elkton	x				x					81	Yes
1964	B707	Taiwan	x									1	No
1965	B707	San Francisco		x								0	Yes
1968	B727	Minneapolis			x				x			0	No
1970	DC-8	Toronto	x					x				106	Yes
1970	B727	California				x			x			0	No
1973	DC-8	Toronto				x			x			0	No
1974	DC-8	Travis AFB			x						x	1	Yes
1976	B747	Madrid	x				x					17	Yes
1982	DC-9	Air Canada			x						x	0	yes
1983	S-T108	New York		x							x	2	No
1983	S- TRP	New York	x								x	1	Yes
1989	B727	Avianca	x							x		107	Yes
1989	Beech Jet	Jackson MS				x			x			0	No
1990	B737	Philippine	x								x	8	Yes
1992	B707	Marseille	x					x				UN	Yes
1996	B747	New York	x								x	230	Yes
2001	B737	Thailand		x							x	1	Yes
2004	DC-54B	Alaska		x							x	0	No
2005	C-130 H	Iraq	x							x		10	Yes
2006	B727	Bangalore		x					x			0	No