Aviation Rulemaking Advisory Committee

Service History/Fuel Tank Safety Level Assessment

Task Group 1

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Service History and Safety Assessment

at 1 July 1998

Summary

Task Group 1 was initially charged with providing "An analysis of the threat of fuel tank explosion due to internal and external tank ignition sources for the major fuel system designs making up the transport fleet, including transport airplanes with heat sources adjacent to or within the fuel tanks."

This was interpreted as a requirement to carry out a detailed analysis of previous tank explosion events, and to carry out a flammability review of the current range of fuel system designs and tank configurations. A further task was then added to prepare a safety analysis to evaluate the safety impacts of any proposed (design) changes recommended by the other groups. Task Group 1 successfully discharged each of these responsibilities, although the detailed flammability review was transferred to (and discharged by) Task Group 5.

Review of Service History

A review of the records of the last 40 years of transport airplane operations worldwide revealed a total of 16 tank explosions relevant to this study. Analysis of these events showed that the fuel tank location was a major factor. In comparing explosion events in integral wing tanks with those located in or adjacent to the fuselage (known as "center tanks"), it was found that the rate of center tank events was considerably higher than one would expect. It was also found that whereas corrective actions to prevent recurrence of the wing tank events were in place, the exact ignition sources in the two most recent center tank events have not been identified, and do not yet have proven remedies.

It was concluded that flammability reduction measures which would reduce the rate of center tank explosions down to the level attained by wing tanks should be investigated.

Safety Assessment

Top-level functional hazard analyses (FHA's) were performed for each option to identify the significant failure conditions these options might bring to the airplane. It was noted that whereas some of the options exhibited relatively benign failure conditions, others had the potential to cause Hazardous or Catastrophic events. However, it was concluded that proper design techniques were available to reduce the frequency of these latter failure conditions to levels consistent with the requirements of FAR/JAR 25.1309. The only exception to this statement was the Explosion Suppression option, where it was not clear that the technology was sufficiently mature to permit identification of all its potential failure modes with confidence.

Contents

1. Introduction

This report describes the work carried out by Task Group 1 to accomplish the tasks outlined below.

The objectives for Task Group 1 were derived from the Terms of Reference for the Fuel Tank Harmonization Working Group (FTHWG), as published in the Federal Register on 23rd January, 1998. Those Terms of Reference included a task to provide:

"An analysis of the threat of fuel tank explosion due to internal and external tank ignition sources for the major fuel system designs making up the transport fleet, including transport airplanes with heat sources adjacent to or within the fuel tanks."

This task was assigned to Group 1, and was further developed at the first Working Group meeting in Washington D.C. into the following three sub-tasks:

(1) Carry out a **detailed analysis of previous tank explosion events**, in order to determine whether any further information could be gained regarding the contributory effects of fuel type, tank location, system design philosophy, environment etc. on the incidence of tank explosions.

The objective was to better identify those circumstances in which there is an increased likelihood of explosion, such that these could be minimized in the future, and also to identify configurations/circumstances where the risk had been shown to be low such that these could be used to guide design practice in the future.

(2) Carry out a **flammability review of the current range of fuel system designs and tank configurations** by first creating a matrix of major types of fuel tank configurations, and then to assess the flammability levels currently existing within a representative selection of those fuel tanks.

However, it became clear during early discussions that members of Task Group 5 (Fuel Vapor Reduction) already possessed the analytical tools to complete this task. It was therefore agreed that Group 1 should compile the **tank configurations matrix** and pass it to task Group 5, which would then carry out flammability analyses.

The objective of this work was to define those configurations most at risk if an ignition source were present, such that these areas received particular attention when considering future rule changes or aircraft modifications.

(3) Prepare a **safety analysis to evaluate the safety impacts of any proposed (design) changes** recommended by the other groups.

The aim was to provide a consistent means of assessing the safety effects of each of the options, and to indicate the level of complexity such systems might require in order to meet any new rules regarding flammability and meet existing rules governing system failure conditions (e.g. JAR/FAR 25.1309).

2. Working Practices

Group 1 comprised four members. Two came from a propulsion design and certification background with aircraft manufacturers. The third member was an airline fleet engineering manager who participated in the TWA800 accident investigation, and the final member came from the propulsion certification office of the FAA.

The group discharged its various tasks through the individual efforts of its members, and held regular reviews of its progress through data exchange, through dedicated task group meetings, and through presentations and reviews of its work in front of the full Working Group on a monthly basis. In addition, because of the relationship and inter-dependence of the tasks of Groups 1, 5 and 8, these teams also held periodic joint meetings to exchange findings and ideas.

3. Review of Service History

The service history of the transport airplane fleet (including turbofan and turboprop airplanes) over the last 40 years was examined, and information regarding known instances of fuel tank explosion (other than those caused by post-impact crash events) was assembled. The starting point was the table of events contained in the FAA Notice on Fuel Tank Ignition Prevention Measures published in the Federal Register on April 3, 1997. The data sources used were accident and incident reports provided by investigating organizations, regulatory authorities, and original equipment manufacturers' safety-related databases. The level of details reported in the early events was sometimes limited dependent on the event location in the world and the type of event (whether it involved an internal or external ignition source).

3.1 Details of previous tank explosions

Appendix A contains a detailed description of each event and the findings of the investigating authority, followed by a description of the mitigating actions taken subsequent to the event to prevent its recurrence.

3.2 Analysis of previous tank explosion events

The 16 tank explosion events are summarized on Tables 1 and 2. They have been separated into Operational Events (i.e. those occurring on an airplane where passenger-carrying flight was intended), and Refuelling & Ground Maintenance Events. They are grouped by cause (Lightning, Engine Separation, Refuelling, Maintenance, etc.), and are then categorized by operational phase, ignition source, type of fuel tank involved, and fuel type. The mitigating actions taken subsequent to each event are summarized, and any recurring events are identified.

Table 3 gives details of the aircraft damage and lives lost due to tank explosions.

Table 1 - Summary of Operational Events

		1963 Lightning Elkton 707	1976 Lightning Madrid 747	1965 UCEF/Eng sep San Francisco 707	1970 Eng Sep Toronto DC-8	1990 Eng Sep New Delhi 747-200	1992 Eng Sep Marseilles 707	1989 Sabotage Bogota 727	1990 Unknown Manila 737-300	1996 Unknown New York 747
Operational Phase	Inflight	•	•	•	•	•	•	•		•
	On Ground Operations								•	
	Ground Maintenance									
	Refuelling									
Ignition Source	Lightning	•	•							
	Overwing Fire - Inflight			•	•	•	•			
	Static Discharge									
	Sabotage							•		
	Unknown								•	•
Tank Type	Main (Wing) = W Center = C	W	W	W	W	W	W	C	C	C
Fuel Type		JP-4 / Jet A	JP-4 / Jet A	Jet A	JP 4	Jet A	Jet A	Jet A	Jet A	Jet A
Mitigating action taken to minimize or prevent	Airplane Design Change	• Flow-thru' vent; surge tank suppression	• Improved bonding inside tank	• Redundant control of spar shutoff valve	• Spoiler Lockout Mechanism					• Flame Arrestors on Pump Inlets
recurrence of root cause	Hardware Inspection Requirements						• Mid-spar attach't repeat inspection		• 12 Service Bulletins	• 12 Service Bulletins
	Ground Support Equipment Change									
	Maintenance Program / Procedures Revised					•			•	•
	Operations Bulletin								•	
	Improved Airport Security							•		•
	None									
	Unknown									
Recurring Event			• Different cause							•

Table 2 - Summary of Refuelling and Ground Maintenance Events

		1970 Refuelling Minneapolis 727	1970 Refuelling Minneapolis 727	1973 Refuelling Toronto DC-8	1989 Refuelling Washington Beechjet 400	1967 Ground Maint. Taiwan 727	1974 Ground Maint. Travis AFB DC-8	1982 Parked Montreal DC-9
Operational Phase	Inflight							
	On Ground Operations							
	Ground Maintenance					•	•	•
	Refuelling	•	•	•	•			
Ignition Source	Lightning							
	Overwing Fire - Inflight							
	Static Discharge	•	•		•	•		
	Sabotage							
	Unknown			•			•	• Suspect dry running boost pump
Tank Type	Wing = W Rear Aux = RA Center = C Fwd Aux = FA	C	C	W	RA	C	W	FA
Fuel Type		Jet A	Jet A	JP-4 / Jet A	Jet A / JP-4	Jet A	JP-4	Jet A
Mitigating action taken to minimize or prevent recurrence of root cause	Airplane Design Change				• Installed conductive foam			
	Hardware Inspection Requirements							
	Ground Support Equipment Change		• "Anti-static" filters introduced					
	Maintenance Program / Procedures Revised			• (probable outcome)		•	•	• (probable outcome)
	Operations Bulletin							
	Improved Airport Security							
	None	•						
	Unknown							
Recurring Event			•					

From Tables 1 and 2, certain patterns and trends emerge:

- There are 8 wing tank events, and 8 involving center or fuselage tanks
- In the wing tank events, 5 out of 8 involved the use of wide-cut fuel (JP-4/Jet B)
- In the wing tank events, 5 out of 8 occurred in flight
- All the wing tank events involved external ignition sources - there are no known wing tank explosions due to internal ignition sources in 520 million hours of flight operations
- There were only 2 explosions due to lightning strike, with 396 million flight hours accumulated since the last event in 1976
- All the center tank events involved the use of Jet A/Jet A-1 fuel
- In the center tank events, 6 out of 8 occurred on the ground
- There are 9 operational events, and 7 refuelling and ground maintenance events

From the data, there appears to be a difference in the respective safety levels of wing tanks and center tanks.

All the wing tank events have been due to known, external ignition sources (lightning strikes, over-wing fire, refuelling, maintenance error) - there are no known internal ignition sources in 520 million hours of commercial transport fleet operation that resulted in a tank explosion. Corrective actions to prevent recurrence of these wing tank events have been in place for many years, and have been demonstrated to be effective.

By contrast however, in the two most recent center tank events the exact ignition sources have not been identified. Whilst corrective actions to identify and eliminate potential ignition sources are now being put in place, the investigation of flammability reduction is warranted since the efficacy of these actions has yet to be proven.

Over the years, center tanks have accumulated considerably fewer operating hours than wing tanks (for example, a B-737 has two wing tanks and one center tank, and therefore accumulates wing tank hours at twice the rate of center tank hours). Since the equipment in wing and center tanks is very similar, i.e. there are similar types and numbers of potential ignition sources, one would expect there to be significantly fewer center tank events than wing tank events. Actually the numbers of events are equal. This indicates that center tanks are significantly more susceptible to explosion than wing tanks.

It might be argued that the reason for this disparity is that components in the wing tanks are more often submerged than those in the center tanks, which often operate almost empty. However, this may be an over-simplification. There are several pieces of equipment inside wing tanks which routinely operate in the vapor space, such as fuel quantity probes and wiring, and partially submerged boost pumps. There is still considerable potential for the existence of ignition sources within the ullage of wing tanks. This being the case, if center tanks are experiencing considerably more explosions than might be expected relative to wing tanks, it must be that center tanks are significantly more <u>flammable</u> than wing tanks. Reducing the flammability in center tanks down to wing tank levels would be a worthwhile goal.

In the last 20 years (when Jet A has been the predominant fuel), there have been five tank explosion events involving center/fuselage tanks, and two wing tank events (which were both exceptional ones - see Appendix A, Event nos. 3 & 4). The continuing incidence of center tank explosions (all of which involved Jet A fuel) indicates that these tanks have not yet reached the safety level attained by wing tanks, and that action to further reduce the flammability levels in center tanks should be considered.

Table 3 summarizes the numbers of fatalities and degree of aircraft damage resulting from all the events. As discussed earlier, the Manila B-737 and New York B-747 events are the only ones for which the corrective actions have not been proven in subsequent airline service. In any cost/benefit analyses performed elsewhere in this study, it is recommended that only those lives lost in these last two events should be counted, since formal or informal cost/benefit analyses have already been performed on the earlier events when the decisions were taken regarding the follow-on actions from those events. A total of 238 lives were lost in the two most recent events.

Table 3 - Aircraft Damage and Fatalities

Operational Events	**No. of Events**	**No. of Fatalities**
Hull loss with fatalities	6	539
Hull loss	2	
Substantial damage	1	
Non-Operational Events		
Hull loss with fatalities	1	1
Hull loss	2	
Substantial damage	4	1
Totals	16	541

3.3 Service History Conclusions

This study identified and analyzed 16 known instances of fuel tank explosions (other than those following impact with the ground) over the last 40 years of transport aircraft operations worldwide. The following conclusions have been drawn:

- There is a close relationship between the incidence of explosions in wing tanks and the use of wide-cut fuel.
- Wing tanks operating with Jet A type fuel have demonstrated an acceptable safety record.
- In comparison, center tanks and fuselage-mounted tanks are more vulnerable to explosion in the presence of ignition sources.
- Apart from the two most recent events (1990/Manila & 1996/New York), the causes of all the other events have been addressed by actions designed to prevent or minimize their recurrence.

It is recommended that action to further reduce the flammability levels in center tanks should be considered.

4. Fuel Tank Configurations

An extensive survey of fuel system and fuel tank configurations was conducted for the commercial transport aircraft fleet. A tabular summary was compiled for 68 different aircraft types or models, including large, medium and small turbofan aircraft, regional jets, business jets and turboprop aircraft. This described the aircraft in terms of size and range, and characterized the wing and tank configurations, the fuel capacity and presence of adjacent heat sources for each aircraft fuel system.

On completion, it was passed to Task Group 5 to facilitate selection of suitable candidate aircraft types on which to perform flammability analyses.

5. Safety Assessment

5.1 Objectives

As stated earlier, the third task assigned to Group 1 was to assess the overall aircraft-level safety implications of carrying out the modifications being investigated by the other Task Groups. Clearly, since some of these modifications involve technologies which are currently not fully mature or proven in a commercial airline environment, rigorous and detailed safety analyses down to component level could not be carried out with confidence. However, the safety assessments described below do allow some useful comparisons to be made regarding the safety impacts of the various options relative to each other. They also provide an indication of the complexity or levels of redundancy which such systems may require in order to meet the certification requirements of FAR 25.901(c) and JAR/FAR 25.1309.

5.2 Analysis Methods

A top-level functional hazard analysis (FHA) was performed for each option. This typically looks at the effects of the system not operating when required, and operating when not required, and identifies the severity of these failure conditions (using the guidance contained in Advisory Circular AC 25.1309-1A).

For each system being analyzed, Group 1 made extensive use of the more detailed knowledge of the individual task group “responsible” for that system.

The following options were the subject of safety assessments:

- Filling the ullage space with inert gas
- Filling the tank with foam
- Purging fuel vapor from the tank
- Raising the flash point of the fuel
- Reducing the heat input into the fuel

Due to the lack of commercial aircraft operational experience with explosion suppression systems, the technology was not considered sufficiently mature or well-understood to merit carrying out an analysis of its safety implications.

5.3 Analyses

For each of the “explosion protection” systems analyzed below, the condition where they failed to operate when required was classified as Minor since loss of the protection system on its own does not significantly reduce airplane safety. Clearly, loss of protection coupled with an ignition source in a flammable atmosphere would be considered a Catastrophic event. This combination of failures is the case which would actually set the required reliability (availability) of the protection system.

5.3.1 Gaseous inerting

The gaseous inerting system is assumed to be one which actively replaces the oxygen component of the air inside the tank(s) such that the resulting fuel vapor/gas mixture is too rich to be flammable. Further, it is assumed that this requires the tank to be closed from the atmosphere to prevent dilution of the inerting agent and re-oxygenation of the ullage.

The gaseous inerting system has the following functions:

(1) To keep the oxygen concentration inside the tank below the level which will support combustion

(2) To keep the tank differential pressure within limits

(3) To prevent leakage of inert gas into the passenger cabin or flight deck

The functional failures are documented below.

Function: (1) To keep the oxygen concentration inside the tank below the level which will support combustion

Functional Failure	**Failure Condition** **Effect on (A) System, (B) Aircraft, (C) Occupants**	**Classification**	**Probability Requirement**	**Safety Design Implications**
Fails to prevent ullage volume becoming flammable	(A) Explosion possible if ignition source present (B) None unless ignition source present (C) None unless ignition source present	Minor	N/A	Loss of protection returns tank to pre-mod condition, i.e. only vulnerable to explosion if flammable atmosphere <u>and</u> ignition source present
Operates inadvertently during tank maintenance	(A) Oxygen concentration inside tank depleted (B) None (C) Asphyxiation of maintenance personnel	Hazardous	1×10^{-7} per hour	May require system inhibition interlocks as well as explicit maintenance procedures

Function: (2) To keep the tank differential pressure within limits

Functional Failure	**Failure Condition** **Effect on (A) System, (B) Aircraft, (C) Occupants**	**Classification**	**Probability Requirement**	**Safety Design Implications**
Allows tank differential to exceed maximum positive limits	(A) Wing over-pressure deformation (B) Loss of structural integrity (C) Multiple loss of life	Catastrophic	1×10^{-9} per hour	Need dual-redundant vent valves, and an over/under-pressure relief valve
Allows tank differential to exceed maximum negative limits	(A) Wing under-pressure deformation (B) Loss of structural integrity (C) Multiple loss of life	Catastrophic	1×10^{-9} per hour	Need dual-redundant vent valves, and an over/under-pressure relief valve

Function: (3) To prevent leakage of inert gas into the passenger cabin or flight deck

Functional Failure	Failure Condition Effect on (A) System, (B) Aircraft, (C) Occupants	Classification	Probability Requirement	Safety Design Implications
Transfers inert gas into cabin	(A) Possible loss of tank inerting (B) None (unless pilots incapacitated) (C) Incapacitance/death of some occupants before oxygen masks deployed	Hazardous	1 x 10^{-7} per hour	Consider N_2 detector in cabin

5.3.2 Foam

The foam "system" is assumed to comprise multiple small blocks of highly porous material which completely fill the tank interior, with negligible voids. It prevents gross over-pressure or explosion within a tank by limiting the extent of any vapor/air ignition to a small local detonation, preventing it propagating throughout the tank.

The foam "system" has the following functions:

(1) To prevent ignition of the fuel vapor/air mixture from causing a tank explosion

(2) To allow free movement of fuel within the tank and into the fuel delivery system to the engine(s)

The functional failures are documented below.

Function: (1) To prevent ignition of the fuel vapor/air mixture from causing a tank explosion

Functional Failure	Failure Condition Effect on (A) System, (B) Aircraft, (C) Occupants	Classification	Probability Requirement	Safety Design Implications
Fails to protect against ignition propagating into tank explosion	(A) Explosion possible if ignition source present in flammable atmosphere (B) None unless ignition source present (C) None unless ignition source present	Minor	N/A	Loss of protection returns tank to pre-mod condition, i.e. only vulnerable to explosion if ignition source <u>and</u> flammable atmosphere present

Function: (2) To allow free movement of fuel within the tank and into the fuel delivery system to the engine(s)

Functional Failure	Failure Condition Effect on (A) System, (B) Aircraft, (C) Occupants	Classification	Probability Requirement	Safety Design Implications
Interruption of fuel flow to the engine(s)	(A) Blockage of fuel supply to engine(s) (B) Possible multiple engine power loss requiring forced landing (C) Serious injury/death of some occupants	Hazardous	1×10^{-7} per hour	Life limits for foam. Increased/redesigned filtration and increased frequency of filter inspections
Inability to transfer fuel out of a tank	(A) Fuel trapped within a tank (B) Loss of range requiring diversion (C) None	Major	1×10^{-5} per hour	

5.3.3 Ullage sweeping

An ullage sweeping system is one which the fuel vapor is purged from the tank ullage using forced ventilation, making the ullage too lean to be flammable.

The ullage sweeping system has the following functions:

(1) To keep the fuel vapor concentration inside the tank below the level which will support combustion

The functional failures are documented below.

Function: (1) To keep the fuel vapor concentration inside the tank below the level which will support combustion

Functional Failure	Failure Condition Effect on (A) System, (B) Aircraft, (C) Occupants	Classification	Probability Requirement	Safety Design Implications
Fails to prevent ullage volume becoming flammable	(A) Explosion possible if ignition source present (B) None unless ignition source present (C) None unless ignition source present	Minor	N/A	Loss of protection returns tank to pre-mod condition, i.e. only vulnerable to explosion if flammable atmosphere <u>and</u> ignition source present

5.3.4 High flash-point fuel

This option uses fuel whose flash point has been raised from the current minimum value of 100°F to a significantly higher value (say 120°F). It prevents a fuel tank explosion by maintaining the flash point above the highest temperature attainable inside a fuel tank.

High flash fuel has the following functions:

(1) To prevent formation of a flammable vapor/air mixture within the operating temperature envelope of a fuel tank interior

(2) To provide a fuel suitable for aircraft gas turbine engine operation

The functional failures are documented below.

Function: (1) To prevent formation of a flammable vapor/air mixture within the operating temperature envelope of a fuel tank interior

Functional Failure	Failure Condition Effect on (A) System, (B) Aircraft, (C) Occupants	Classification	Probability Requirement	Safety Design Implications
Allows formation of a flammable vapor/air mixture inside the tank	(A) Explosion possible if ignition source present (B) None unless ignition source present (C) None unless ignition source present	Minor	N/A	Loss of protection returns tank to pre-mod condition, i.e. only vulnerable to explosion if flammable atmosphere <u>and</u> ignition source present

Function: (2) To provide a fuel suitable for aircraft gas turbine engine operation

Functional Failure	Failure Condition Effect on (A) System, (B) Aircraft, (C) Occupants	Classification	Probability Requirement	Safety Design Implications
Fuel causes engine malfunction	(A) Flameout (B) Possible multiple engine power loss requiring forced landing (C) Serious injury/death of some occupants	Hazardous	1×10^{-7} per hour	Rigorous engine/airframe compatibility testing required, possibly with controlled service introduction & fleet leader program

5.3.5 Heat reduction

This option is intended to minimize the heat added to the fuel once it is onboard the aircraft by insulating, ventilating or otherwise physically separating heat sources from fuel tanks. The intent is to prevent raising the fuel vapor above its flash point.

The heat reduction option has the following functions:

(1) To prevent the fuel vapor inside a tank being raised above its flash point

The functional failures are documented below.

Function: (1) To prevent the fuel vapor inside a tank being raised above its flash point

Functional Failure	Failure Condition Effect on (A) System, (B) Aircraft, (C) Occupants	Classification	Probability Requirement	Safety Design Implications
Allows fuel temperature to rise above its flash point	(A) Explosion possible if ignition source present (B) None unless ignition source present (C) None unless ignition source present	Minor	N/A	Loss of protection returns tank to pre-mod condition, i.e. only vulnerable to explosion if flammable atmosphere and ignition source present

5.4 Safety Assessments Conclusions

The top-level safety analyses above indicate that some of the options under consideration could exhibit undesirable failure conditions. However, it is considered that all of these systems could be designed with sufficient integrity to meet the requirements of FAR 25.1309 such that the overall safety of a given fleet of airplanes was not compromised. For some of the options, meeting those requirements would require greater system complexity and (possibly) more onerous inspection and maintenance requirements than the options with benign failure conditions. A comparison of the relative merits of these options is therefore primarily an economic consideration, since all of the options could be made equally safe.

Appendix A - Details of previous tank explosions

Appendix A contains a detailed description of each event and the findings of the investigating authority, each followed by a description of the mitigating actions taken subsequent to the event to prevent its recurrence. The 16 events have been grouped initially into broad categories which characterize their circumstances, i.e. engine separation events, lightning strike events, ground maintenance events, refuelling events, “others” and those where the cause remains unknown.

Engine Separation Events

1.	Date:	**28 June 1965**	Flight phase:	**Takeoff climb**
	Aircraft:	**Boeing 707**	Tank type:	**Main reserve tank**
	Location:	**San Francisco**	Fuel type:	**Jet A**

<u>Summary of Event</u>

Approximately 39 seconds after takeoff No.4 engine experienced an uncontained engine failure resulting in separation of the engine from the wing. The loss of the engine resulted in mechanical damage to the wing and a severe fire. The fire triggered a low order explosion in the No.4 reserve tank which resulted in the loss of the lower wing skin, lower stringers, and spar chord flanges. The loss of these components resulted in the loss of wing integrity which allowed the outer wing panel to fail and separate from the wing. The ensuing fire was extinguished by the closing of the main fuel shutoff valve either by the first officer or the flight engineer.

There was evidence of fire on the separated wing section, on the remaining wing around the point of separation, and on the No.4 engine. Fire was observed by ground witnesses, passengers and crew members, and photographed, in color, from the ground and by a passenger. The flight crew was alerted to the fire when an intermittent fire warning was observed while they were going through the engine shutdown procedure following the failure of the No.4 engine. The first officer then actuated the fire selector lever for the No.4 engine and discharged both fire extinguisher bottles to the engine. The fire was observed streaming from the right wing. Fuel was still streaming from the No.4 tank area after landing until the fire department plugged the hole in the bottom of the tank. The area around the fuel spill and the wing stub were foamed as a preventative measure while the passengers were disembarking from the aircraft.

<u>Analysis</u>

A disk failure resulted in an explosive failure of the No.4 engine and its separation from the wing due to high vibration and out of balance oscillation of the rotating parts of the engine. The right outer wing received so much damage to the lower load-bearing skin and associated structure that capability of the wing to sustain in-flight loads were reduced below the loads imposed, and the outer wing panel separated from the wing. Fuel from the engine fuel line was then being pumped directly into the airstream. This fuel was ignited by an undetermined source shortly after the engine separated and resulted in an explosive separation of a portion of the lower wing skin. It is believed that dangling wires from the engine separation sequence ignited the fuel. The fire was sustained by the continued supply of fuel through the engine fuel line until the flight engineer or the first officer shutoff the main fuel supply either by activating the fuel shutoff valve to the closed position or actuating the fire selector handle.

The disintegration of the third stage turbine disk cut the engine in two pieces and threw turbine debris into the wing inboard of the engine pylon. The two engine sections, each supported by only one mount on the strut, began to oscillate and separated from the wing in approximately four seconds. The strut failures were caused by the oscillation, possibly coupled with mechanical damage from flying engine parts. The engine fuel line pulled from the strut closure rib when the engine separated from the wing. Fuel was pumped through this line for an estimated 99 seconds at a rate of approximately 30,000 pounds per hour, until the fuel valve was shut off by the action of either the first officer or the flight engineer. A second fuel source was the fuel line on the forward face of the main spar which had a loosened fitting that leaked and supplied fuel for a fire over the strut center spar between the front spar and the nacelle closure rib. A third possible flammable fluid source was the ruptured slat hydraulic line on the inboard gap cover area.

The source of the ignition cannot be determined, but the possible sources included the engine exhaust, hot turbine parts, or arcing from exposed electrical leads. The latter is the most probable source because there was an appreciable time lapse between observation of the fuel spray and ignition. The fuel sources wetted much of the upper wing surface before ignition occurred.

The fact that No.4 main tank was full of fuel probably prevented more extensive fire damage to that area of the upper wing surface because the fuel acted as a heat sink. The fire in this area reached temps ranging from approximately 870 - 1165°F, based on damage caused to the metal.

The damage to the right outboard wing section top and bottom skin and ribs could only have been caused by an over-pressure in the reserve tank. This is demonstrated particularly by the manner in which the lower skin separated from the aircraft. The entire panel was forced straight down, taking the attaching flanges of both spars with it. This is plainly the result of a low order explosion. The source of ignition for this explosion could not be determined but could have been auto-ignition, burn through, or hot surface ignition from a localized hot spot.

The final separation of the wing followed the explosion in the reserve tank. The wing separation is not believed to have been simultaneous with the explosion. The indications of yaw and vertical oscillation on the flight recorder readout and the location of the wreckage on the ground indicate that the wing section remained on the aircraft approximately 10-11 seconds after the separation of the lower skin panel.

The heat damage to the wing structure was not considered to have been a major factor in the wing failure. Rather, the loss of lower skin panel, stringer, mid spar chord flanges reduced the load carrying capability of the wing below that required to support a 1 “g” condition, thus leading to the failure.

Laboratory tests of the fuel samples taken from the six remaining fuel tanks on the aircraft revealed no significant deviation from the specification established for Jet A turbine engine fuel. It was estimated that the fuel temperature in the tanks at the time of the accident was between 70-80°F. The flammability limit of Jet A fuel was reported by the FAA to be from 90-170°F. Ambient temperature prior to the flight were recorded as 77°F.

<u>Mitigating Actions Taken:</u>

Airplane design change were made to incorporate redundant wiring paths to close spar and engine high pressure valves when the fuel shutoff or fire handle switch is activated. Engine assembly procedures were modified to ensure proper running clearances.

There has been no recurrence of an engine uncontained failure leading to separation of the wing since design changes.

2. Date: **July 1970** Flight phase: **Go-around**

Aircraft: **McDonnell Douglas DC-8** Tank type: **Wing tank**

Location: **Toronto** Fuel type: **JP-4**

Over the threshold of runway 32 at about 60 feet agl, the first officer deployed, instead of arming, the ground spoilers causing a rapid descent until striking the ground. The captain tried to compensate by applying full power and rotating the airplane to initiate a go-around. However, the airplane hit hard at 18 feet per second, number 4 engine separated and number 3 engine partially separated. Somewhere in the sequence of the engine separation from the wing, leaking fuel that may have been ignited by dangling wires causing some explosions. The airplane continued with go-around while trailing fuel and fire. Airplane climbed to 3,100 feet and commenced a turn for a second approach. The right wing separated above the number 3 engine, the airplane rolled over and struck the ground . The airplane crashed 2.5 minutes following touchdown and approximately 8.5 miles from runway 32. The FAA has reported that JP-4 fuel was being used. Ambient conditions were reported as warm and sunny.

Mitigating Action Taken:

As a result of this accident, the FAA issued an airworthiness directive (AD) requiring placard warnings against in-flight deployment of ground spoilers by DC-8 operators. Following a non-fatal accident some three years after this crash, the FAA issued another AD requiring that all aircraft of the type be fitted with spoiler locking mechanisms to prevent such an occurrence.

3. Date: **7 May 1990** Flight phase: **Landing**

Aircraft: **Boeing 747-200** Tank type: **No 1 wing tank**

Location: **New Delhi, India** Fuel type: **Jet A**

A 747-200 operating a flight from London to New Delhi landed at Delhi at 0915 local time. The flight crew reported there were no problems experienced with the No. 1 engine during the London-Delhi flight. Touchdown and engine transition to reverse thrust were reported as normal. Shortly after the engines reached full reverse, all No. 1 engine indications apparently went to zero. The flight crew was not aware of the nature or extent of the problem at this point as there was no engine fire warning. Another 747, which had landed five minutes earlier, advised the 747-200 they had a large fire on the left wing in the area of No. 1 engine. The crew reportedly pulled the No. 1 fire handle and discharged the fire extinguisher. The tower also noted the fire and alerted the aircraft and the airport fire department. The fire department was already aware of the situation and had four fire engines on the scene within two minutes of first noting the fire. The fire was reportedly extinguished within eight minutes of the first report.

All 175 passengers and 20 crew members were evacuated using the five main deck slides on the right side of the aircraft. All five slides deployed normally and were used. There were no reported injuries of anyone on board. The aircraft apparently touched down between one and two thousand feet from approach end of the runway. Weather was clear and dry with little or no wind and the temperature was 35°C. First evidence of the No. 1 engine inlet cowl contacting the runway was at three thousand feet. Spatters of molten aluminium were first noted at above five thousand feet from approach end. The aircraft stopped ten thousand feet from approach end slightly to left of center. The No. 1 engine was in a near vertical position. The engine had rotated around the mid spar attach points with the nose cowl resting on the runway and the exhaust plug and engine tail pipe jammed against the wing lower surface. The No. 1 strut upper link forward attach fuse pin was sheared. Pieces of fractured fuse pin remained in the upper link forward clevis fitting and associated strut attach lug. The aft end of the diagonal brace was detached from its associated fitting on the lower wing skin and the associated fuse pin was completely missing, and could not be found. Failure of these two strut attach points allowed the front of the engine to drop, contacting the runway. All equipment in the No. 1 strut sail boat area was destroyed by impact with strut aft bulkhead, engine exhaust pipe, tail cone and subsequent fire.

The No. 1 engine fuel supply line separated at the wiggins fitting between strut bulkhead and wing front spar. All wire bundles to the engine appeared to have been broken due to tension caused by the strut rotating to a vertical position. All leading edge flaps and leading edge fiberglass panels severely burned inboard and outboard of No. 1 strut. The outboard end of the outboard trailing edge flap was severely burned. The outboard flap track fairing was totally consumed by fire. The inboard end of the outboard aileron was severely burned. The outboard spoilers 1 and 2 and the trailing edge fiberglass panels inboard and outboard of the No. 1 strut was severely burned. The left wing tip was drooping down outboard of the No. 1 strut at about 15 degrees. There was evidence of extreme heating and warping of upper wing skin above the No. 1 strut. The upper wing skin was pulled loose from the forward and aft spar webs outboard of the No. 1 strut. Vent stringers were split open longitudinally. All upper wing skin rivets were pulled through the skin in the area of the surge tank. The lower wing skin was scorched in area of surge tank.

Analysis

In brief summary, the fuel from the ruptured fuel line and hydraulics in the strut were ignited by the hot engine and exhaust, followed by auto ignition of residual fuel in the reserve and surge tanks due to external heating. Fuel supply to the fire was terminated prior to the aircraft coming to rest and flammable wing and subsystem material continued to burn until extinguished by ground personnel.

Following forward strut pin failure and engine dropping nose down:

- Fuel is discharged at approximately 100 gpm into air stream prior to engine spar valve closure due to fuel line separation from front spar coupling. Fuel is washed under and possibly over wing and into leading edge cavity due to both forward speed of aircraft and due to thrust reverser air from engine.
- Due to engine exhaust/tailpipe being rotated up which forced diagonal brace into the hydraulic reservoirs in strut aft fairing, reservoir is crushed and 10 gallon (U.S.) hydraulic fluid is released.
- Fuel and/or hydraulic fluid is ignited on hot engine tail cone/nozzle.
- Hot engine exhaust gases and/or fuel fire heat the lower surface of reserve tank. Reserve tank is empty, but air is heated in excess of fuel AIT (auto ignition temperature). Residual undrainable fuel is approximately one U.S. gallon.
- Heated air or burning fuel vapor reaches surge tank through the reserve tank vent line. Fire initiates in surge tank due to residual fuel vapors and temperature in

excess of AIT for fuel. Hot front spar at surge tank due to leading edge fire could also have been the ignition source.

- Main tank No. 1, because of fuel acting as a heat sink, remains "cool".
- Wing leading edge receives fuel spray or mist due to engine thrust reverser air or free stream air dispersion. Prior to fuel shutoff, during landing roll, fuel attaches to flap torque tubes and interior flap surfaces, and subsequently burns. Resin binding agents in fiberglass honeycomb panels will burn when fed by heat of fuel fire. Fuel was shut off prior to the end of the landing roll as evidenced by soot being confined to aft portions of strut and aft part of core cowl.

Fire damage to aft end of engine is primarily to exterior cowling and exterior surface of nozzle. Inner steel nozzle does not appear fire damaged. This is considered a consequence of external fuel or hydraulic fluid falling or spraying on aft end.

An assessment of the cause of the wing overpressure has been made. This assessment, in conjunction with visual inspection of the damage indicates that an in-tank explosion occurred which destroyed the integrity of the torque box by separating the wing panels and spars from their internal support structure. Further damage occurred after the overpressure due to inertia loads imposed during landing rollout.

The engine separation was found to be due to a maintenance error when re-assembling the components of the strut linkages.

<u>Mitigating Action Taken</u>

Procedural changes were implemented at the specific airline to ensure existing instructions for engine retention hardware installation were properly followed.

4.	Date:	**31 March 1992**	Flight phase:	**Climb**
	Aircraft:	**Boeing 707**	Tank type:	**No 4 wing tank**
	Location:	**Near Marseilles, France**	Fuel type:	**Jet A**

As the aircraft was climbing towards flight level 330, both right engines separated from the wing. The No.3 inboard pylon fitting fractured and subsequently released the engine under power which then impacted the No.4 engine causing it to separate also. The crew succeeded in controlling the aircraft and landed gear and flaps down with the right wing on fire. The aircraft rolled off the runway to the left of centerline and all crew members evacuated the aircraft safely and the firemen extinguished the fire.

The trailing edge of the wing was totally burnt in the area between both engines. The inboard and outboard flaps had completely disappeared, revealing the burnt operating mechanisms. The inboard aileron was severely damaged. Moreover, the examination of the inboard wing box identified the marks of an inner explosion on fuel tank No.4. This explosion seemed to be at the origin of significant deteriorations affecting the wing stiffness. This explosion had caused the displacement of the inner ribs of this tank. The wing stiffness was particularly damaged on the front and aft spars. Thus, it appeared that the right wing was severely damaged first because of a fire and then because of an inner explosion at the fuel tank No.4.

Note: All right wing valves, transfer and shutoff valves operated normally, when tested. The shutoff valves were found in the fully closed position and the transfer valves were found in the open position which matched the cockpit switch positions. The fuel leakage on the leading edge of the wing near engine No.3 could not have been caused by a closing failure of the shutoff valve. Damage (collateral) of the piping following the pylon detachment could be the cause of the leak. The exact location of the leak could not be detected.

During all of the descent at speeds greater than 220 kt, it is probable that the fuel leak carried on without the fuel catching fire, as the conditions for ignition (depression of the upperwing, speed....) were not achieved and the vaporized fuel was not in contact with the electrical short-circuits of the damaged cabling loom located on engine No.3 leading edge. These conditions changed during the last turn as a consequence of the semi-extension of the flaps. The speed reduced (between 220 and 190 kt), the depression on the upper wing decreased and the turbulence increased. Then, it was possible that under the effect of the electric arcs of the short-circuits quoted above, the fuel ignited, as the conditions of the kerosene-air mixture became optimal for burning. The fire was violent as the condition of the upper wing demonstrated, particularly at the trailing edge. This intense fire had destroyed the trailing edge as well as the flaps and left evidence of overheating over the whole of aft part of the right fuselage side. The air traffic controller advised that the right wing was on fire at 08:33:28 hrs and the landing touchdown occurred at 08:35:35 hrs. Consequently, the right wing fire lasted for at least two minutes.

The accident report did not provide a good rationale for the explosion in the No.4 main tank. It is believed that during the intense fire the wing structure may have weakened and fire progressed to the air-fuel mixture in the tank.

Mitigating Action Taken

An airworthiness directive was issued to inspect the pylon/strut mid-spar fittings at 1500 hours or 600 cycles.

Lightning Strike Events

5. Date: **8 December 1963** Flight phase: **Holding**

Aircraft: **Boeing 707** Tank type: **Wing (reserve) tank**

Location: **Elkton, Maryland** Fuel type: **Jet A / JP-4 mix**

The flight was in a holding pattern at 5,000 feet awaiting an instrument approach to Philadelphia airport from Baltimore, when it was struck by lightning. Immediately thereafter, the aircraft was observed to be on fire. A large portion of the left wing separated in flight and the aircraft crashed in flames near Elkton, Maryland. The probable cause was lightning induced ignition of the fuel/air mixture in the No.1 reserve fuel tank with resulting explosive disintegration of the left outer wing and loss of airplane control.

Fuel onboard at the time of the accident was approximately a 68% Jet A / 32% JP-4 by volume mix. It was estimated that fuel temperatures were 42°F in the reserve tank and 46°F in the main tanks. Considering all factors it was concluded the fuel vapors in all tanks were within the flammability limits. Multiple lightning-strike marks were found on the left wing tip. Although much effort was expended, the physical evidence failed to disclose the precise mechanism of ignition which triggered the explosion in the left reserve fuel tank.

Mitigating Action Taken

A fire suppression system was installed on some airplanes which consisted of a light-triggered fire extinguishing system in the wing surge tank. Additionally, some airplanes had a flow-through vent system installed. An FAA Advisory Circular 20-53 was developed to define lightning strike zones.

Since incorporation of the above design changes and practices, there has not been a recurrence of a lightning strike event on the 707/720 model.

6. Date: **9 May 1976** Flight phase: **Approach**

Aircraft: **Boeing 747-IIAF** Tank type: **Wing tank**

Location: **Madrid** Fuel type: **Jet A / JP-4 mix**

The airplane was being operated as a military logistic flight to McGuire AFB with an enroute stop at Madrid, Spain. During descent for the approach at 6,000 feet, the airplane was struck by lightning which resulted in an explosion and separation of the left wing causing loss of control. Prior to the event, the crew requested ATC vectors around severe thunderstorm activity. The fuel onboard was a mixture of 58% JP-4 and 42% Jet A type.

At the time of the accident the weather was cloudy with rain and lightning, but good visibility. At least two witnesses reported seeing lightning strike the airplane. Parts from the left wing, including a section of the left wing tip, were the first found along the flight path wreckage.

Evidence of lightning strike, pitting and localized burn areas typical of lightning attachment were found on the left wing tip and on the vertical fin at the VOR antenna.

The fire centers were located in the wing tip, in the outboard end of No.1 fuel tank, and the outboard end of No.2 fuel tank. These fire centers were independent and not interconnected. There was no pattern to the fire, heat, and soot damage in the reserve tank. In the area of the No.2 tank, the fire, heat, and soot damage pattern on the inner part of the wing indicated that a fuel fire moved inboard behind the rear spar and along the trailing edge. At the wing root, the fire pattern extended fore and aft along the fuselage. The fuel for this fire obviously came from the No.2 tank from which the upper wing skin cover plank was gone.

Findings and Plausible Hypothesis

The aircraft was fueled with a mixture of JP-4 and Jet A fuels. Lightning struck the aircraft an instant before an explosion. The first wreckage on the ground contained a considerable number of parts of the left wing outboard of the No.1 engine. Damage to the wing in the area of the No.1 fuel tank is the result of a low order explosion. The ullage of the No.1 tank contained a flammable mixture of fuel and air. Pressures provided by the ignited fuel were sufficient to cause the damage. Three fires occurred in No.2 tank, No.1 tank, and the wing tip surge tank. The crushing or collapsing of the fuel tube in the No.1 tank required an application of pressure only available from an explosion. The pressure required to detach the stringers and skin from the wing were in the range of typical pressures developed by an explosion. The first deposit of wreckage formed a pattern of light objects downwind and heavy objects upwind, which is not compatible with gusting or turbulent wind conditions but is compatible with an explosion in calm or steady wind conditions. The H.F. antenna and wing tip edge were snapped off the wing by inertial loads developed by an oscillating outer wing. The loosening of the stringer/plank unit from the wing destroyed the aft wing box of the wing. Extreme engine oscillations developed as a result of the wing box damage. The loss of the rear box structure allowed the wing to twist torsionally and to deflect up and down about the rear spar. The first objects along the flight path were units from the inside of No.1 fuel tank. The three fire areas within the left wing contained electrical devices. The highest level of residual magnetic field was along the rear spar aft of the No.1 tank. A motor that operates a fuel valve normally mounted in this position was never found. Damage to the fuel tank access doors could only result from pressure from inside. No structural loads were applied to these doors. The 28Hz oscillations superimposed on the power line were in the area of the third harmonic of the wing oscillations (9Hz) which were attributed to engine fan rub in the early service history of the 747. The inertial damage to the extreme wing tip (H.F. antenna and coupler) could result only if the inboard section of the wing tip was still attached to inner wing. Throttle lever vibration in synchronization with the wing oscillations was observed during previous incidents. The damage to the wing tip cannot be caused by gust loads or aerodynamic loads. They were due to wing oscillations. The wing oscillations were the result of rear box failure. The deformation to rib WS 1168 was caused by pressure loads prior to its departure from the wing along with the jettison fuel line. The flight control difficulty mentioned on the CVR was probably related to the outer wing damage. The crossover vent duct for the forward outboard end of the No.1 tank was severely fire damaged, and the aft end was never recovered.

Fuel Tank Flammability Evaluation Results

Based on these calculations of the fuel and ullage conditions, the fuel/air mixture in portions of the ullage may be such as to permit ignition at the time of a descent through 10,000 feet.

Analysis

Consensus of the highly specialized investigation team was that an explosion occurred at or near the aft outboard corner of the No.1 Tank.

Conclusion from the Accident Report

After analyzing all of the available evidence, it is concluded that the most probable sequence of events which culminated with multiple structural failures and separation of the wing began with an ignition of the fuel vapors in the No.1 fuel tank. The damage to the structure in the area of the tank provided positive indications of an explosion. The possibility that the explosion was a secondary result of an initial structural failure caused by excessive aerodynamic forces developed during high velocity gusts and turbulence cannot be completely dismissed; however, the evidence and the probabilities of an aircraft encountering these unique environmental conditions make this hypothesis less supportable.

Mitigating Action Taken

A design change was incorporated that basically improved bonding (electrical grounding) where plumbing passes through the wing spar to further dissipate the voltage difference.

There has been no recurrence of a lightning strike related explosion to this model airplane or any other fleet airplane since this event in more than 246 million flights.

Ground Maintenance Events

7.	Date:	**17 September 1967**	Flight phase:	**Ground maintenance**
	Aircraft:	**Boeing 727**	Tank type:	**Center**
	Location:	**Taiwan**	Fuel type:	**Jet A**

The airplane was undergoing routine scheduled maintenance of the interior of the left wing tank. Both No.1 (wing) and No.2 (cheek tank) tanks had been drained and were open. Tank No.1 had been purged and No.2 tank was to be purged. A flash fire occurred followed in a few seconds by an explosion which ruptured the integral section comprising the RH end of tank No.2. An 8 ft. by 12 ft. section of upper wing structure was blown off. A small fire flared up in the damaged area which was quickly put out. There were 74 people in the immediate area. 16 persons were injured; five of these received serious injuries.

The precise source of ignition could not be determined. However, the following information was obtained in the ensuing investigation:

An explosion-proof light was illuminating the interior of the electronics compartment and was still functioning after the explosion. There was no evidence to indicate that it had been plugged in coincident with the event. All power was off the airplane, the ground power unit had been shutdown nearly two hours earlier, and the battery had been removed.

The lead man in charge of tank purging stated that purging with portable CO_2 bottles had been completed within tank No.1, and that the CO_2 equipment had been laid down, and that the crew had been instructed to open up the RH access door of tank No.2 before purging that tank. No checks had been made of explosive vapor concentration either internally or externally.

The tank purging procedure used is noted to be contrary to the procedure recommended in the OEM manual. One of the more severely burned mechanics, interviewed later in the hospital, was stated to have corroborated the above. The FAA personnel had come to the conclusion that tank No.2 was being purged through the LH access opening at the time. They based their assumption on the statement that the CO_2 equipment had just been laid down on a work stand, and that the most seriously burned mechanic was standing on a stand near the LH No.2 tank, not No.1.

It was noted that metallic parts in the CO_2 discharge assembly might produce a spark and also that the static electricity discharges from the fiber horn or nozzle on portable CO_2 bottles have been historically a cause of fuel fires.

A mechanic was filing a piece of light gage stainless steel, making a nut retainer, in a wheel well area. Another was making a layout on another piece of metal. The first man, who received burns on exposed skin areas, reported that he felt pain and ran from the area. He did not report noting the origin of the explosion.

The only ground leads specifically identified were connected to the RH landing gear, rather than to the grounding lug provided on a RH gear door, and to the rear fuselage. Whether or not ground leads were attached to the work stands, as recommended by the OEM, was not determined due to confused activities following the explosion. A large crew of workmen were reported to be cleaning (but not polishing i.e., using buffers or polishing compounds) with cans of solvent, brushes and cloths. After the explosion, several of the cans of solvent were noted to be on fire. Electrical outlets were non-explosion proof; however, none was reported as being used, at the time, except for the connection to the light in the electrical compartment.

No precautions had been taken to limit access or post warnings in the area. The FAA considers that any of the 74 men in the area might have created a spark which could have ignited fumes in the area.

<u>Mitigating Action Taken</u>

The CO_2 bottle flow rates were reduce and the discharge nozzles inspected and reworked. There is no known recurrence of this event for these specific causes.

8. Date: **23 March 1974** Flight phase: **Ground maintenance**

Aircraft: **McDonnell Douglas DC-8** Tank type: **Wing**

Location: **Travis AFB, California** Fuel type: **JP-4**

Upon arrival at Travis Air Force Base from a Military Charter flight, a routine maintenance “A” check was being accomplished including maintenance action in response to the flight crew reports of inflight mechanical irregularities that appeared on the previous two flight legs. One of the crew log reports was an inoperative No.1 fuel boost pump.

Access to the boost pump was made through the top of the wing. This was done by removing the No.1 main fuel tank access cover, located behind and slightly outboard of the number 2 engine pylon. Affected circuit breakers for the fuel system had been opened. The tank contained approximately 3,000 pounds of JP-4 fuel. The boost pump was partially submerged in fuel. The total fuel on the aircraft was 25,000 pounds. External power from a ground power unit was connected to the aircraft.

Removal and re-installation of a different boost pump was completed. An operational check of the pump was then attempted and failed. Two of three circuit breakers for the AC three phase pump opened and no boost pressure was noted. It is noteworthy that the same two circuit breakers had opened while enroute on a prior flight leg which resulted in a log book write up “No.1 main boost pump inop”. Maintenance replaced the fuel boost pump with the second pump to see if the malfunction could be cleared. Electrical power from an external power unit was reconnected after a “low fuel” warning signal was activated. Inspection of the newly installed fuel boost pump electrical connector was conducted.

At 2008 PDT an explosion occurred in the left wing center section. The upper wing surface between nos. 1 and 2 engines was blown forward and away from the airplane centerline some 250 feet from the airplane. A fire then began which engulfed the entire left wing, fuselage, and inboard right wing. Evidence from the recovered fuel boost pumps and connectors revealed no evidence of burning. The explosion resulted in hull loss, and one fatality.

The investigation also points to an external ground power unit that was supplying power to the aircraft while tank maintenance was being performed. It also mentions a flashlight which one of the mechanics on the wing had in his possession which had a broken “flasher” switch i.e. the switch that allows the user to momentarily activate the light without locking it on or off. Most of the recommendations from everyone involved focused on procedures to prevent another accident. No conclusive evidence of an ignition source was established.

<u>Mitigating Action Taken</u>

The mitigation action taken for this event has yet to be determined.

Refuelling Events

9. Date: **3 May 1970** Flight phase: **Refuelling**
Aircraft: **Boeing 727** Tank type: **Center**
Location: **Minneapolis** Fuel type: **Jet A**

The airplane was being refuelled using a single-point refuelling system. About 2,000 lbs of fuel had been loaded when a heavy muffled explosion occurred in the No.2 (cheek tank). A puff of gray smoke came from the LH wing tip vent. Fuelling was immediately terminated, all electrical power on the airplane was cut off, the APU was shutdown, and the aircraft was de-fuelled.

No injuries had occurred. No damage was apparent from an external check of the aircraft. The damage was largely confined to the secondary structure within the No.2 tank on the LH side of the airplane. When inspecting the tank, it was found that the structure above the top level of the fuel was heavily soot blackened. The ribs visible from the front spar access hole exhibited heavy deflection and distortion and the stringers were also damaged. Some pulled rivets were noticeable in the LH wing. The formed covers for the fuel boost pump were "hydro-pressed" down over both the RH and LH pumps, but no leaks had developed.

No faults in the electrical systems of the aircraft in and around tank No.2 were found. It is presumed, in the absence of any electrical sources, that ignition resulted from a static discharge within the No.2 tank.

Time of day was 8:28 am. Fuel temperature was 55°F. Flash point of samples was: Tank #1-118°F, Tank #2 - 120°F, Tank #3 - 110°F and the Storage tank from which the fuel was loaded was 127°F.

At the time of the event the following airplane systems were operating; the APU was operating and the LH pack was on to heat the cabin, All navigation lights on. No boost pumps were on.

The duration of the fuelling was approximately 5 minutes with the No.2 tank 31% full.

<u>Mitigating Action Taken</u>

No mitigating action taken since no root cause for an ignition source was found.

10. Date: **23 December 1970** Flight phase: **Refuelling**
Aircraft: **Boeing 727** Tank type: **Center**
Location: **Minneapolis** Fuel type: **Jet A**

The airplane was being refuelled using under-wing refuelling at the RH wing station. Approximately 3,000 pounds of fuel had been loaded when a muffled explosion was heard. Fuelling was immediately stopped and a minor leak was noticed coming from the area of the inboard boost pump in the LH wing. There was no fire and no injuries to any of the servicing personnel. Over-pressure damage to the aircraft's No.2 fuel tank was extensive but minor in nature.

The aircraft was being readied for its next departure. Besides the refuelling operations, other activity around the aircraft included baggage loading and de-icing operations. Some light snow was being stirred around by a wind that was blowing from the left to the right wing at 18 knots with gusts to 24 knots. The outside ambient temperature was +8°F.

After about 5 minutes of fuelling with kerosene type A (Jet A) , a harsh muffled explosion shook the aircraft with a large white cloud of smoke or vapor issuing from the LH wing root area and continuing for about 30 seconds. The outboard boost pump cavity access door was split in two with half flying across the apron and half still dangling from the opening. Fuel was leaking from the cavity area in a stream about the size of a pencil diameter. The fueller immediately dropped the "dead man" switch and closed both fuelling nozzles. The fire department was then summoned, and they hosed down the area.

Subsequent examination of the aircraft revealed minor exterior physical damage, most noticeable being the blown-off access door, collapsed and fractured number 2 tank LH fuel boost pump cavity housing, and popped rivet heads on the number 2 tank LH upper skin area. Interior physical damage was quite extensive within the number 2 fuel tank. Both the No.1 and No.3 tanks were undamaged. Evidence of soot deposits were found within the left and right hand surge tanks, the number 2 fuel tank, and at each wing tip fuel tank vent scoop area.

The investigation that followed the incident indicated that the probable cause of the explosion was delivery by the ground fuelling system of highly charged fuel into the airplane. However, the investigation was unable to pinpoint the exact source of ignition that triggered the combustion of the fuel vapor. The evidence is very strong, however, that the source of ignition was static discharge internal to the number 2 fuel tank.

Time of day was 6:18 am. Fuel temperature was 31°F. Flash point of samples was: Tank #1-119°F, Tank #2 - 118°F, Tank #3 - 124°F and the Storage tank from which the fuel was loaded was 121°F.

At the time of the event the following airplane systems were operating: APU, all navigation lights on, No.2 tank boost pumps on and all crossfeed valves open.

The duration of the fuelling was approximately 5 minutes with No.2 tank 32% full.

<u>Mitigating Action Taken</u>

The paper element filter separators in the ground refuelling equipment were replaced with filters that did not create electrostatic charging.

The has been no recurrence of a refuelling related event to this model since changes were made.

11. Date: **21 June 1973** Flight phase: **Refuelling**

Aircraft: **McDonnell Douglas DC-8** Tank type: **Wing**

Location: **Toronto** Fuel type: **JP-4 / Jet A mix**

The airplane was at the gate and a ground power unit was connected to the airplane's electrical system when a fuel tank explosion blew off pieces of the right wing top skin and spar structure. Burning fuel rapidly engulfed the right wing. The aircraft was destroyed and two ramp servicing personnel were seriously burned.

The aircraft was being fuelled with Jet B (JP-4), but examination of the left wing tanks revealed a fairly even mix of Jet A-1 and Jet B. Some Jet A-1 was already in the tanks. The ambient temperature was 76°F.

Shortly thereafter an explosion occurred in the right wing. A 20 foot long piece of wing upper skin covering the forward portion of number 3 alternate and number 4 main tank was blown high into the air and landed about 100 feet to the right of the aircraft. Flames erupted from the right wing and burning fuel was sprayed onto a man on a conveyor who leaped off toward the rear of the aircraft. This explosion was followed almost immediately by another which blew a 10 foot long piece of the upper wing skin from the aft section of the number 3 alternate tank to a position forward and to the left of the aircraft. The loss of this skin allowed the right wing to collapse, hinging from the bottom skin. Burning fuel ran from the ruptured number 4 tank and fuel manifold over the leading and trailing edges of the wing. The fueller under the right wing ran toward the front of the aircraft through the fire that now extended to the ground and he was doused with burning fuel. Both the refueller and the cargo handler were seriously burned. No passengers had boarded the aircraft. The nine crew members aboard evacuated through the loading bridge.

The findings of the Canadian Department of Transportation were that the initial explosion occurred in the number 3 alternate tank and that the fuel vapor was ignited in the wing vent system. The source of ignition of fuel vapor in the wing tank vent system could not be definitely determined, but was suspected to have originated outside the aircraft.

<u>Mitigating Action Taken</u>

It is believed that no direct action was taken since it appeared that ignition of the fuel vapor had taken place outside the aircraft adjacent to the vent outlet.

12. Date: **6 June 1989** Flight phase: **Refuelling**

Aircraft: **Beechjet 400** Tank type: **Aux Tank**

Location: **Washington D.C.** Fuel type: **JP-4 / Jet A mix**

The aircraft departed early in the morning from Jackson, Mississippi enroute to New Orleans. Early in the afternoon the airplane returned to Jackson and was refuelled with JP-4. At approximately 4:00 p.m. CST the airplane departed from Jackson enroute to National Airport in Washington, DC After arrival in Washington, the crew spent approximately one hour securing the airplane before departing for the hotel. Line service then began refuelling operations. Operations manager advised that the fuel truck was grounded to the airplane and also to the fuel ramp grounding point. Main wings were topped off first with Jet A fuel. Line personnel then began to service the aft tanks. Prior to service, there was approximately 200 pounds of fuel remaining in the tanks. After pumping five gallons into the aft tank through the aft filler port, line personnel reported hearing a hissing noise followed by a bang. Fuel surged out of the filler opening and covered the line service personnel. At this point, refuelling was terminated and the pilots were contacted. At the time of refuelling there were thunderstorms in the area at the time of refuelling. Shortly after the refuelling operations began, heavy rain began falling in the area of the airport.

Fuel was later noted dripping from the underside of the airplane. After the cabin interior seats were removed to gain access to the aft fuel tank, it was found to be torn loose from all 14 fuselage attach points. The tank had expanded significantly from internal pressure. The forward access panels on the tank were removed for internal viewing. The inside of the tank exhibited very heavy carbon deposits throughout the tank and especially on the upper surface of the horizontal support frames within the tank. These deposits indicate some type of fire or detonation occurred inside the tank.

The investigation concluded the most probable cause was that during refuelling of the interconnected fuselage and auxiliary tanks, an electrostatic discharge occurred which resulted from charged fuel entering the aft auxiliary tank from the fuselage tank. The fuselage mounted tank had a blue foam installed in the tank to protect against rotor burst threats. The foam being used at the time was determined to have low conductivity characteristics and was able to build up an electrostatic charge which subsequently discharged in the aft tank that did not have the protective foam installed.

Mitigating Action Taken

Final action resulted in an airworthiness directive to replace the blue foam with a more conductive foam and install additional bonding and grounding to the subject fuel tank.

Other - Parked in Hanger

13. Date: **2 June 1982** Flight phase: **Parked**

Aircraft: **McDonnell Douglas DC-9** Tank type: **Fwd Aux Tank**

Location: **Montreal** Fuel type: **Jet A-1**

While the airplane was parked in the hangar, it is believed that a fuel boost pump located in the forward auxiliary fuel tank had been left on and overheated, causing an over-pressure in the (de-fuelled) tank, and a subsequent fire which destroyed the aircraft. Structural analysis of the auxiliary tank did not show signs of an “explosion” but did show signs of rapid over-pressure in the tank. The residual fuel in the forward auxiliary fuel tank (estimated at 2.6-3 US gallons) was insufficient for pump priming; therefore there was no motor cooling which resulted in excessive fuel vapor generation within the tank. The exact source of ignition could not be determined during the investigation but out of the four electrically operated components in the auxiliary tank, three could be ruled out as spark producing agents. These are: the fuel quantity probes and the float switch which were not energized and the fuel pressure switch which was found in good condition and its electrical wiring is installed in a metal tube. The fourth item, the transfer pump power supply harness, is the most probable source of sparks. Examination of electrical assemblies on other aircraft indicated burned sockets and pins at the pump connector. The burn marks were the result of arcing. If a faulty connector has a secondary failure at the harness pressure seal, a spark could ignite a critical fuel vapor/air mixture. Considered a serious over-pressure event.

Mitigating Action Taken

No aircraft-related action was taken since this was treated as an industrial accident rather than an event affecting airworthiness.

14. Date: **11 May 1990** Flight phase: **Climb**

Aircraft: **Boeing 727-100** Tank type: **Center tank**

Location: **Bogota, Colombia** Fuel type: **Jet A**

The airplane was climbing through 10,000 feet when an explosion occurred. Investigator reports discovered evidence of a bomb explosion. Close examination of the aircraft structure revealed evidence on the RH side of the passenger cabin between the emergency overwing exits. The evidence indicated the force generated by the blast compromised the structural integrity in this area causing a fuel tank rupture, fire, and inflight structural breakup of the right wing. The local ambient temperature reported at the airport was 52°F.

Cause Unknown

15. Date: **11 May 1990** Flight phase: **Parked / Push Back**

Aircraft: **Boeing 737-300** Tank type: **Center tank**

Location: **Manila, Philippines** Fuel type: **Jet A**

While being pushed back from the gate, the center tank exploded and burned. At the time of the explosion, the engines were not running and the aircraft electrical power and air-conditioning were supplied by the Auxiliary Power Unit (APU). Preliminary evidence indicates that ignition of the fuel-air mixture in the center fuel tanks was the cause of the explosion and subsequent fire. The investigation focused on the center fuel tank, which was determined to be the source of the explosion, and the possibility of an explosive or incendiary device, an external source of ignition or mechanical and/or electrical failure as a source of ignition. The investigation found no evidence of a bomb, an incendiary device, or sabotage. The investigation has yet to reveal the exact ignition source.

At the time of the accident, all the fuel boost pumps were in the "on" position. The center fuel tank had not been filled since 9th March 1990. During the pushback of the airplane the center fuel tank low pressure light illuminated, indicating that the center fuel tank had been emptied of all usable fuel. Laboratory examination of the fuel samples from the airplane and fuel storage tanks indicates that the fuel vapor in the center tank would have had a flash point of between 112 - 117°F. The ambient temperature at the time of the accident was 95°F. The fuel was estimated to be approximately 115°F based on samples of fuel drawn from other similar airplanes following the incident. It was estimated that approximately 90 pounds of fuel was in the center tank.

Of the 114 passengers and six crew members, eight were fatally injured and 30 sustained injuries.

Mitigating Action Taken

Boeing published an all operators bulletin reminding flight crews to not operate the center boost pumps when no usable fuel was available in center tank.

16. Date: **17 July 1996** Flight phase: **Climb**

Aircraft: **Boeing 747-100** Tank type: **Center tank**

Location: **New York** Fuel type: **Jet A**

The airplane was climbing near 13,800 feet (msl) when an inflight explosion occurred in the center wing fuel tank approximately 13 minutes after takeoff, resulting in loss of structural integrity inflight. The center wing tank was estimated to contain approximately 100 gallons of fuel. Prior to dispatch of the airplane, the air-conditioning air cycle machines, located under the center wing tank, had been operating for up to 2 hours. The center wing tank estimated fuel temperatures was 113-115°F. At the altitude and temperatures of the event, the fuel tank air/vapor mixtures were considered to be flammable. The fuel type was Jet A. There were 230 fatal injuries including the flight crew.

Mitigating Action Taken

A series of service bulletins have been issued against the B-747 series, covering fuel pump electrical installation inspections, addition of a scavenge pump flame arrestor, and inspections and replacements of FQIS wiring and probes.

For the B-737 series (which has a similar fuel system), bulletins covering fuel tank system component and wiring inspections, and flame arrestors in the vent system are being incorporated.