

## APPENDIX H4: REVIEW OF CATASTROPHIC TANK FAILURE INCIDENTS

### H4.1 Introduction

H4.1.1.1 This appendix provides a review of tank failure incidents based primarily on the incidents identified in Appendix G of McBride [9] and their relevance to the instantaneous failure of one of the PAFF tanks. McBride [9] splits the incidents covered into 4 categories:

- Incidents involving aviation fuel (Table G1).
- Tank failures involving failure of secondary containment (Table G2).
- Catastrophic failure of tanks containing petroleum products (Table G3).
- Large multiple tank fires at tank farms (since 1985).

H4.1.1.2 The incidents in each of these tables are reviewed in turn, followed by the catastrophic tank failure incidents listed in the EIA Report [1] and other recently recorded incidents.

### H4.2 Incidents Involving Aviation Fuel [9]

H4.2.1.1 McBride reviews tank failures involving aviation fuel or kerosene at facilities similar to those of proposed PAFF in Appendix G, Table G1 [9]. ESR have reviewed the relevant incidents, as described by McBride [9], with the following comments.

Incident	Brief Description and ESR Comments
-, -	1.3 million litres of jet fuel was lost due to failure of corroded tank bottom plates.
Ajjacio, Corsica, 1970	Two tanks containing one million litres of kerosene exploded causing US\$300,000 damage.
1971	Fire in aviation fuel tank took 34 hours to bring under control.
Netherlands, 1975	A metal storage tank of 5000m <sup>3</sup> capacity encased in concrete and covered with earth, 1/3rd full of aviation fuel exploded when lightning struck a tree adjacent to the tank. The tank allowed to burn out.
Harare, Zimbabwe, 1978	22 of 28 tanks containing diesel, jet fuel and gasoline were destroyed during a 3 day fire. Ignition source tracer bullets and rockets. The 40 acre terminal was largely destroyed.
-, 1979	A tank farm operator reported an arc of light around a handrail and instrument housing during a short hailstorm. No damage.
Yokohama, Japan, 1981	An explosion in an underground storage tank containing jet fuel. Nearby residents were evacuated and there were 2 injuries.
US, 1985	A 40 m diameter aviation fuel tank ignited when fire fighting foam was applied.
Auckland, New Zealand, 1986	Leak of up to one million litres of kerosene from an oil storage tank into a harbour and into water table.
Tarragona, Spain, 1987	An explosion occurred in a pipe rack carrying crude between a refinery and a terminal. 5 tanks destroyed and others damaged. Sabotage suspected.

Incident	Brief Description and ESR Comments
Baltimore airport, US, 1989	Jet fuel overflowed a storage tank due to a defective bleed valve.
Denver, Colorado, 1990	A fire that burned for 55 hours at the fuel storage area for an airport destroyed or damaged 7 tanks and consumed more than 1.66 million gallons of jet fuel, causing \$30 million damage. No reported injuries.
Avonmouth, UK, 1994	A port worker was killed in a fire at a fuel pipeline at dock. Fire spread to kerosene in tanks at the storage depot and burned for 18 hours.
Dronka, Egypt, 1994	Blazing liquid fuel flowed into the village of Dronka, Egypt. The fuel came from a depot of eight tanks, each holding 5000te of aviation or diesel fuel. The release occurred during a rainstorm and was said to have been caused by lightning. 420 fatalities reported.
Dikson, Russia, 1995	Pipeline ruptured at storage tank under weight of snow at airport. 1800 tonnes of jet fuel poured over snow and ice and then to sea.
-, 1995	Jet fuel tank spill at a refinery. During a period of low ambient temperatures, the sight glass on a storage tank water drainage piping failed and 8200 bbl of Jet A fuel released.
Trainer, US, 1998	A 55-foot tank containing 16,000 bbl jet fuel exploded and burned at a refinery. Approximately 700,000 gallons of fuel burned for more than four hours before being brought under control. No death or serious injury.
Anchorage, Alaska, US, 2000	A fire occurred on a tank during tank cleaning. The tank contained 2000 gallons of jet fuel. No injuries.
UK, 2000	Jet fuel was seen to be shooting from a stationery tank in a continuous stream. The incident occurred due to valves on the tank being opened by vandals. Approx 150,000 litres was released into the environment. Bund drain valve was left open and allowed oil to escape. Company fined.

H4.2.1.2 Fatalities are recorded for two of the incidents above:

- At Avonmouth in 1994 a port worker was killed in a fire at a fuel pipeline at a dock, which spread to kerosene tanks.
- At Dronka in Egypt in 1994, 420 people were killed when burning fuel, released from tanks at a military fuel depot, spread through a village on flood waters. Supporting records to the MHIDAS database for this incident [32] say that this was a military fuel depot storing gasoline as well as jet fuel. It is also, in ESR’s opinion, likely that the jet fuel would have been JP4, which is highly flammable, in contrast to Jet A1 (JP4 was commonly used for ground based military aircraft until recently but it has largely been replaced by the safer JP8 which is similar to Jet A1). A recent review of secondary containment issues notes in relation to this incident [69], “There was no secondary containment in place to contain the release. If well designed bunding and good drainage systems had been in place, the burning fuel may have been contained on the site without spreading the fire.”

H4.2.1.3 In the first case, the fatality was on-site and appears to have been caused by the pipeline incident rather than the tank fire. In the second case the fires appear to have involved

more highly flammable substances than Jet A1 and a set of additional circumstances not present at the PAFF, including a lack of adequate bunding.

H4.2.1.4 These are the only examples of tank incidents with aviation fuel or kerosene given in Table G1 of McBride [9] that resulted in fatalities.

H4.2.1.5 None of the incidents given in Table G1 of McBride [9], and listed above, appear to involve a instantaneous, or rapid, release of the tank contents, although some involve explosions resulting in tank fires.

### H4.3 Incidents Involving Secondary Containment Failure [9]

H4.3.1.1 McBride [9] reviews tank failures involving failure of the secondary containment in Appendix G, Table G2 [9]. ESR have reviewed these incidents, as described by McBride [9], with the following comments.

Incident	Brief Description and ESR Comments
Ponca City 1924	Failure of oil tank due to a dramatic drop in temperature, with bund overtopped due to momentum from release. No fire or fatalities listed.
Meraux 1957	Petrol tank ruptured and fell across bund. Fire occurred, but no fatalities listed. The MHIDAS records [32] note an operator closing a valve and also the presence of cast iron fittings (hence brittle failure is the likely cause) and also a wave spreading over the bund.
US 1970	Release from bund due to bund valve being left open, not overtopping.
Trieste 1972	Terrorist attack started severe pit fires on large floating roof tanks. Boilover caused release from bund. No fatalities listed.
Umm Said 1977	Refrigerated propane (LPG) tank failed catastrophically (no listed failure mode, but brittle fracture possible for carbon steel at low temperature). The bund had inadequate capacity. 7 fatalities listed. ESR note: this incident also destroyed the adjacent process plant. Views differ on the effect that a full capacity bund would have had.
Australia 1986	Failure of C4 heavy ends tank around base due to explosion in tank ullage space in a fire. The bund had inadequate capacity. Fire and 5 fatalities noted. ESR note: C4 is LPG, so contents were highly volatile.
Auckland 1986	Leak from kerosene tank into harbour and water table. No fire or fatalities listed. Reason secondary containment ineffective not listed.
Lyon, 1987	Tanks rocketed due to explosions. Noted that tanks had no rupture seam at roof. Fire and 2 fatalities listed.
Floreffe 1988	Catastrophic rupture of 48 year old diesel tank on initial fill, after it had been relocated and reconstructed. Testing included only partial x-ray of welds and hydrotest to 5 feet (i.e. about 10% of tank height - 100% is now normal practice). According to Lees [44] "The investigation found that the rupture occurred due to low temperature embrittlement initiated at a flaw in the tank shell base metal, about 20 cm up from the bottom". No fire or fatalities are listed. ESR note: this is probably the most famous bund overtopping incident, also referred to as the Ashland or Monongahela tank collapse after the company and the river.

Incident	Brief Description and ESR Comments
Long beach 1992	Bund overtopped due to excessive fire water application. Fire but no fatalities listed.
1993	Spill due to overfilling of gasoline floating roof tank, with major explosion. Fire and 1 fatality listed.
Florida 1993	Overflow of gasoline tank with explosion. Fire and 1 fatality listed.
Hailsham 1995	Leak from hydrochloric acid tank. No fire or fatalities listed. No cause of leak from secondary containment listed
UK 2000	Jet oil released due to valves from tank being opened by vandals. Leak from secondary containment due to bund valve being left open. No fire or fatalities listed.

H4.3.1.2 Of the 14 incidents listed above 3 involved material of similar flammability, or material less flammable than, Jet A1 (Auckland 1986, Floreffe 1988, UK 2000). None of these cases resulted in a fire. A further case (Hailsham 1995) involved hydrochloric acid which is not flammable.

H4.3.1.3 Of the 14 incidents listed above, 4 are clearly identified as involving bund overtopping due to the momentum of the release

- Ponca, 1924,
- Umm Said, 1977,
- Floreffe, 1988.
- Meraux, 1957.

H4.3.1.4 The other causes were:

- Boilover (Trieste 1992), which is not applicable to Jet A1 storage at the PAFF.
- Bund valves being left open (US 1970, UK 2000) which would release Jet A1 into the drainage system rather than towards SWS).
- Rocketing (Australia 1986, Lyon 1987) of a tank which is mitigated by the lower flammability of Jet A1 giving a lower risk of explosion in the PAFF tanks.
- Excessive fire water application (Long Beach 1992).
- Overfilling (-, 1993, Florida, 1993 - note descriptions could potentially be the same incident) with fuel ejected through the top of the tank.
- Not listed (Auckland 1986, Hailsham 1995).

H4.3.1.5 Six of the incidents are considered as applicable to instantaneous failures: Ponca, 1924; Umm Said 1977; Floreffe 1988; Meraux, 1957; Australia 1986, Lyon 1987. These are considered further in Appendix H3.

#### H4.4 Catastrophic Tank Failure Incidents [9]

H4.4.1.1 McBride reviews catastrophic tank failures involving petroleum products in Appendix G, Table G3 [9]. McBride [9] states that these refer to incidents involving 100% loss of the tank contents over a short period of time and exclude those due to overheating, boilover, brittle fracture and causes specific to floating roof tanks. ESR have reviewed these incidents, as described by McBride [9], with the following comments.

Incident	Brief Description and ESR Comments
-,-	Small tank containing lubricating oil had a catastrophic failure of a shell/bottom junction when the tank was over pressurised by compressed air injected for mixing. There was no effective pressure relief and a weak shell-roof seam which had been rendered ineffective due to the addition of reinforcing brackets. The PAFF tanks will not have injectors for mixing and will be fabricated with a weak shell to roof seam.
-,-	Extensive fires in bunds over pressured 6 tanks, rupturing the roofs and resulting in tank top fires and over pressured one tank that ruptured at the shell to base seam releasing contents. A further tank boiled over. Failures occurred after a prolonged period (2 days) under fire attack.
Norfolk, US, 1970	Floating roof tank containing petrol ignited by lightning. Overheating of wall released burning contents. Tank was allowed to burn out over 2 days.
US, 1970	Failure of a shell to floor seam due to lightning igniting vapour in slop oil tank.
Trieste, 1972	Terrorist explosion on 40" discharge lines of large floating roof tanks. Initially resulted in bund fire, followed by boilover.
Addyston, 1976	Methanol tank struck by lightning. Tank rocketed and burning contents overflowed surrounding dykes
US, 1978	Three tanks failed catastrophically in an earthquake.
El Dorado, 1980	Solvent tank ruptured. Cause cited as mechanical failure.
Colon, 1986	Light crude oil storage tank ruptured, spilling contents. Cause not cited.
Brisbane, 1988	Petrol tank ruptured at fuel depot. Tank not licensed for petrol due to separation distances and corrosion.
Richmond 1989	Earthquake ruptured a gasoline storage tank. The spill was contained in the bund and was not ignited.
El Segundo, 1993	Fuel oil tank ruptured and bund held all but a few percent of the spill, which entered a storm drain.
Fawley, 1993	Bunker oil tank developed a 15ft split and spilled oil. Mist blown onto cars and houses by strong wind, but no ignition.

H4.4.1.2 Of the 14 incidents listed above:

- Five involved failure of the shell to floor seam (first item, second item, US 1970, Addyston 1976, Norfolk 1970). Two occurred due to lightning igniting the vapour in the ullage space, one in a methanol tank (Addyston 1976) and one a slops tank (US 1970). Methanol is much more flammable than Jet A1 and in ESR's opinion slop oil (which could contain many different oils) would also be expected to be more flammable than Jet A1. Two incidents (second item, Norfolk 1970) occurred after

fire attack. One (first item) was due to direct overpressure and a weak shell-roof seam that had been rendered ineffective due to the addition of reinforcing brackets.

- 2 occurred due to earthquakes, (US 1978, Richmond California 1989). California is more prone to major earthquakes than Hong Kong (it is unknown where the other US incident was). No fatalities are listed for either incident.
- 1 occurred when a petrol tank which was not licensed for petrol storage ruptured (Brisbane 1988). Several thousand people were evacuated but the spill did not ignite.
- 2 involved boilover in fires (second item<sup>3</sup>, Trieste 1972).
- 4 incidents (El Dorado 1980, Colon 1986, El Segundo 1993, Fawley 1993) do not have specific cited causes.

H4.4.1.3 Whilst the PAFF tanks could fail due to prolonged fire attack (noting Jet A1 is difficult to ignite) the failures would occur after a long period allowing time for evacuation and are therefore not relevant to estimating off-site fatalities.

H4.4.1.4 Two of the incidents involving shell to floor failure could be relevant to the PAFF (Addyston 1976, US 1970), although both involved potentially more flammable contents than the PAFF tanks. The two failures in earthquakes (US 1978, Richmond California 1989) could also be applicable, although the PAFF is located in a much less seismically active area than California, for example and it is not apparent that the failures were instantaneous.

#### **H4.5 Large Multiple Tank Fires [9]**

H4.5.1.1 McBride reviews large multiple tank fire incidents in Table G4 of Appendix G [9]. These incidents are not relevant to assessment of the risk from instantaneous failures of the PAFF tanks, since fire escalation between tanks and any subsequent major failures should allow ample time for effective evacuation. They would therefore not affect the societal risk calculations and are not considered in detail here.

H4.5.1.2 However, multiple tank fire incidents are a potential issue to fire fighters, as noted in and safeguards including water spray and weak shell to roof joints are incorporated in the PAFF design.

#### **H4.6 Catastrophic Tank Failures In Previous EIA Report [1]**

H4.6.1.1 Table 10.6 of the previous EIA Report [1] lists catastrophic failures of petroleum products tanks since 1970.

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<sup>3</sup> Note: second incident counted twice as overpressure and boilover

Date	Location	Fuel	Failure Cause
29th July 1993	El Segundo, CA, USA	Fuel oil	Not known
11th May 1993	Fawley, UK	Bunker oil	Mechanical
Oct 1989	Richmond, CA, USA	Gasoline	Earthquake
6th Feb 1989	New Haven, CT, USA	Heating oil	Mechanical
11th July 1988	Brisbane, Australia	Gasoline	Corrosion
2nd Jan 1988	Floreffe, PA, USA	Diesel oil	Mechanical
28th Dec 1980	El Dorado, KS, USA	Solvents	Mechanical

H4.6.1.2 All these incidents, except New Haven 1989, have been covered in the discussion of the incidents identified by McBride (see Sections H4.3 and H4.4). The MHIDAS abstract for New Haven 1989 [32] says “A storage tank containing 4 million usgall of heating oil ruptured spilling between 100,000 & 200,000 usgall. Some 20,000 usgall rushed into a dike, but was confined. Danger of oil leaking to harbour reduced by frozen ground.” The release did not ignite and no injuries or fatalities were recorded.

H4.6.1.3 The EIA Report [1] identifies quantities lost outside the bund of 2% for El Segundo and 40-71% for Floreffe (Table 10.6 of [1]).

#### H4.7 Other Recorded Incidents

H4.7.1.1 Wilkinson [55] lists 8 brittle failures, including Ponca 1924, Meraux, Floreffe 1988 and Brisbane 1988, covering the period 1919 to 1988, plus a further 10 failures of liquefied flammable gas tanks and 8 failures following explosion or bund fires. The relevant ones have already been reviewed above and so are not reviewed further here.

H4.7.1.2 A recent report for UK HSE on secondary containment failures [69] includes 46 incidents in which secondary containment (including no bunding or inadequate bunding) failed to contain a release. It is notable that, of the incidents considered, “about a third of the incidents involve a lack of secondary containment provision” (Section 5.2.1 of [69]) and “approximately half of the incidents involve inadequately designed secondary containment or site layout” (Section 5.2.2 of [69]). The most relevant incidents have been considered above and so are not reviewed further here.

H4.7.1.3 The United States Environmental Protection Agency (EPA) records environmental impact incidents in the USA and some of these are potentially relevant to catastrophic tank ruptures. Two summaries have been published by EPA on the subject ([61], [51]) that include different incidents to those considered above.

H4.7.1.4 The first report covers explosions of flammable vapours within tanks causing failures of the shell-to-bottom seam after an explosion, described as follows [61]:

- “In a 1992 incident, while workers were welding the outside of a tank empty of liquid, the residual vapour in the storage tank exploded and propelled the tank upwards and into the adjacent river. Three workers were killed and one was injured.”
- “In a 1994 incident, during a grinding operation on a tank holding petroleum-based sludge, the tank was propelled upwards, injuring 17 workers and spilling its contents over a containment berm into a nearby river.”

- *“In a 1995 incident, during a welding operation on the outside of the tank, the combustible vapour inside two large, 30-ft. diameter by 30-ft. high, storage tanks exploded and propelled the tanks upwards - one landing more than 50 feet away. The flammable liquid inside was instantly released and ignited, resulting in a massive fire that caused five deaths and serious injuries.”*

H4.7.1.5 The above incidents relate to storage of petroleum liquids that generate flammable vapours within the tank and “all occurred in older, atmospheric steel storage tanks” [61]. The alert further notes that “A properly designed and maintained storage tank will break along the shell-to-top seam. Then, the fire would more likely be limited to the damaged tank and the contents would not be spilled.” [61]. Recommendations are made in the alert, including design to standards such as API 650 and maintenance to API 653. The potential hazards identified in the alert [61] are all inapplicable to the PAFF or addressed in the design, as follows:

<b>Identified Hazard [61]</b>	<b>ESR Comment for PAFF Tanks</b>
<i>“Atmospheric storage tanks that do not meet API-650 or other applicable codes and contain flammable liquids or liquids that may produce combustible vapour.”</i>	PAFF tanks are designed to API 650 and contain Jet A1, which does not produce a flammable vapour under ambient conditions because it is stored below its flash point. Inapplicable.
<i>“Tanks with corrosion around the base and/or steel tanks whose base is in direct contact with ground and exposed to moisture.”</i>	PAFF tanks will be constructed on a plinth, above the bund floor rather than in direct contact with the ground and water should drain away. Allowed for in design.
<i>“Tanks or associated structures (e.g., pipes) with weakened or defective welds”</i>	PAFF tanks are designed to API 650 and will be maintained to API 653 and incorporate corrosion allowances in both wall and floor plates [16]. Allowed for in design.
<i>“Tanks used to store mixtures containing water and flammables where the water phase is at the tank bottom and may contribute to internal bottom corrosion.”</i>	PAFF tanks will contain Jet A1 product which should not be delivered with significant water contamination. PAFF tanks are designed to API 650 and will be maintained to API 653 and incorporate corrosion allowances in both wall and floor plates [16]. Inapplicable and allowed for in design.
<i>“Tanks containing combustible vapour and not equipped with flame arrestors or vapour control devices to limit emissions.”</i>	PAFF tanks contain Jet A1, which does not produce a flammable vapour under ambient conditions because it is stored below its flash point. Inapplicable.
<i>“Possible ignition sources near tanks containing combustible vapour.”</i>	PAFF tanks contain Jet A1, which does not produce a flammable vapour under ambient conditions because it is stored below its flash point. Hazardous area classification limits ignition sources local to the tanks. Inapplicable and allowed for in design.

H4.7.1.6 These three incidents (Paragraph H4.7.1.4) are considered further in the analysis in Appendix H3, although inapplicable to the situation at the PAFF.

H4.7.1.7 The second report covers catastrophic failures of liquid fertilizer tanks built by either Carolyn Equipment Company of Fairfield, Ohio or Nationwide Tanks Inc. of Hamilton, Ohio, described as follows [51]:

- 3/1997 in Iowa – A 1-million gallon tank containing ammonium phosphate ruptured and released its contents. The walls of the ruptured tank fell onto two other tanks and broke their valves. ... Much of the release was contained by an earth dike, but immediate construction of a secondary temporary dike was necessary to keep the release from flowing into the nearby Missouri River.
  - 7/1999 in Michigan – A 1-million gallon tank full of ammonium polyphosphate ruptured and damaged three other tanks. Fortunately, the tanks were surrounded by earthen dikes lined with polyethylene. This minimized environmental damage.
  - 1/8/2000 in Ohio - A 1 million gallon tank of liquid fertilizer ruptured and damaged four adjacent tanks. The wave of liquid broke a concrete dike wall and hit five tractor-trailer rigs, pushing two of the rigs into the river. A total of 990,000 gallons of material were released. More than 800,000 gallons of the liquid spilled into the Ohio River. ...
  - 3/8/2000 in Ohio – At the same facility, a 1.5 million gallon tank of ammonium phosphate ruptured and damaged three nearby tanks causing them to leak. Two of the tanks held phosphoric acid and the third one held ‘Ice-Melt’, a magnesium chloride mixture. The released liquid overflowed the dike walls into nearby creeks.
- ...

H4.7.1.8 The failures above were attributed to weld failure (“all of the above ground storage tanks that failed appeared to have defective welds [51]) and involved more corrosive liquids than Jet A1 that “are not considered hazardous and are not regulated by the U.S. Environmental Protection Agency” [51]. API 650 and API 653 are cited as appropriate standards for design, construction and welding for hazard reduction and prevention.

H4.7.1.9 The fertilizer tank failures are not considered directly applicable to the PAFF tanks because they were attributed to weld defects in tanks from specific manufacturers, contained liquids significantly different to Jet A1, and were not built to the same standards as the PAFF tanks (API 650 and 653 standards being part of the recommendations for the alert).

H4.7.1.10 Wilkinson [55] lists 8 brittle failures, including Ponca 1924, Meraux, Floreffe 1988 and Brisbane 1988, covering the period 1919 to 1988, plus a further 10 failures of liquefied flammable gas tanks and 8 failures following explosion or bund fires.

H4.7.1.11 Additionally, in 1996, about 5,000 litres of aviation fuel at Kai Tak International Airport was spilt from the top of one tank during product receipt. Most of the spilt product was contained within the bunded area. A small amount of fuel, about 200 litres, over spilt onto the road due to lack of clearance between the tank and the tank farm boundary wall. The duty operator, who was working close to the tank, arrested the spill within 2 minutes, by activating the emergency shut down button, thus closing the main inlet valve of the receiving line. There was no injury. The entire spilt product was subsequently recovered and disposed as a downgraded product. The 200 litres of aviation fuel evaporated within a few hours.

## **H4.8 Buncefield**

H4.8.1.1 *“At around 06.00 on Sunday 11 December 2005, a number of explosions occurred at Buncefield Oil Storage Depot, Hemel Hempstead, Hertfordshire. At least one of the initial explosions was of massive proportions and there was a large fire, which engulfed over 20 large fuel storage tanks over a high proportion of the site. There were 43 people injured in the incident, none seriously. There were no fatalities. Significant damage occurred to both commercial and residential properties in the vicinity and a large area around the site was evacuated on emergency service advice. About 2000 people were evacuated. Sections of the M1 motorway were closed.” [45]*

H4.8.1.2 The investigation is ongoing, but an initial report has been produced by the investigation team [35] following on from three interim reports identifying the information identified to date. Relevant details are noted here based on these investigation reports.

H4.8.1.3 The site stored gasoline, diesel and aviation fuel (Jet A1). Products were delivered to site via multi-product pipelines. The release of fuel started when one tank (Tank 912) overflowed due to overfilling from one of the import pipelines at up to 890 m<sup>3</sup> /hr. The protection system to shut off the tank at its maximum level did not operate and gasoline flowed down the outside of the tank, forming a rich fuel/air mixture in the bund. The vapour cloud thickened to a depth of about 2m and flowed out of the bund across adjacent roads and car parks.

H4.8.1.4 The vapour cloud ignited, causing an explosion and leading to a large fire that engulfed over 20 large storage tanks containing petrol, diesel and Jet A1. The main explosion appears to have been centred on one of the car parks. There was no sudden, instantaneous release of fuel from any of the tanks and the resulting fires were all extinguished by the fire services after 4 days.

H4.8.1.5 The vapour cloud is understood to have formed due to part of the overflowing gasoline flow detaching from the tank wall and fragmenting into droplets as the flow cascaded downwards.

H4.8.1.6 The investigation report states (Para. 26 of [35]) *“These conditions would promote the evaporation of the lighter components of petrol, eg butanes, pentanes and hexanes. The free-fall of droplets leads to entrainment of air and mixing between the air and fuel vapour, and the formation of a rich fuel/air mixture. Cooling of the surrounding air, already saturated with water vapour by the evaporation, would cause some of the water content to precipitate as an ice mist, which is consistent with the cloud of mist visible on CCTV”.*

H4.8.1.7 The wind speed was very low and the atmosphere was stable (para 62 of [45]), which would promote dispersion of flammable vapour over a longer distance.

H4.8.1.8 The investigation report identifies 7 incidents that have similarities with the Buncefield incident (Annex 5 of [35]), all of which are associated with spills of gasoline.

H4.8.1.9 The fuel released was petrol (gasoline). According to the investigation report (Annex 7 para 6 of [35]), *“the product released on site was at the top end of the winter grade limit*

*for vapour pressure. A reasonable estimate of the butane content of the released material is 10% by weight.”* The stated vapour pressure was around 100 kPa.

H4.8.1.10 The prime candidate for the ignition source appears to be an explosion within an emergency generator cabin, consistent with the site of the main explosion, although an explosion in a pump house is also a possibility (para 28 of [35]).

H4.8.1.11 The current best estimates of the peak overpressures that are 700-1000 mbar (para 29 of [35]), which is significantly in excess of the overpressures normally predicted for ignition of vapour clouds in open areas and the investigation report states (para 31 of [35]) that “*further research is needed to try to discover the actual mechanism for generating the unexpectedly high overpressures seen at Buncefield*”.

H4.8.1.12 Two factors noted in the investigation report are known to ESR to lead to potentially higher explosion overpressures. The first is ignition of an external cloud by a high energy ignition source (an explosion within a building) and second is the presence of an aerosol mist within the flammable cloud. Both are known to increase flame speeds and hence overpressures. The weather at the time of the incident was calm, cold (~0°C), stable and humid (~99% RH) leading to formation of a water/ice mist due to evaporative cooling of the vapour cloud (para 28 of [45] and para. 26 of [35]).