APPENDIX H3: INSTANTANEOUS TANK FAILURE FREQUENCY

H3.1 Catastrophic Failures

H3.1.1.1 Many types of tank failures can be termed “catastrophic”, including failures releasing liquid slowly into a bund as well as a instantaneous failure. It is apparent from the physical tests undertaken for the PAFF tanks (see Section 10.6.7) that even very major failures involving a 1m high failure at the base of the tank do not result in major flows outside the PAFF boundary. It is therefore important to differentiate this case from other “catastrophic” failures.

H3.1.1.2 In theory, the estimation of an event frequency from historical data is straightforward and involves dividing the number of incidents over a given period by the number of item years of experience. However, in practice, both numbers can attract a degree of uncertainty and the applicability of the incidents and experience to the case of interest need to be considered.

H3.2 History Of Instantaneous Failures

H3.2.1.1 Historical catastrophic failure incidents are reviewed in Appendix H4. The following incidents are identified as relevant to a instantaneous release from a storage tank (but not necessarily relevant to the PAFF tanks):

Incident	Brief Description and Comment	Applicability to PAFF
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.	Very old tank designed to different standards with low temperature failure (brittle fracture), therefore not applicable to PAFF tanks.
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.	Very old tank designed to different standards and subject to brittle failure. Therefore not applicable to PAFF tanks.
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. Note: this incident also destroyed the adjacent process plant. Views differ on the effect that a full capacity bund would have had.	Liquefied gas tank of significantly different design to PAFF tanks and failure probably attributable to brittle fracture. Bund capacity also inadequate. Therefore not applicable to PAFF tanks.

<table>
<tr><th>Incident</th><th>Brief Description and Comment</th><th>Applicability to PAFF</th></tr>
<tr><td>Floreffe 1988</td><td>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. 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.</td><td>Very old, reconstructed, tank to different standards and not fully hydrotested with low temperature failure (brittle fracture), therefore not applicable to PAFF tanks.</td></tr>
<tr><td>US, 1970</td><td>Failure of a shell to floor seam due to lightning igniting vapour in slop oil tank.</td><td>PAFF tanks do not have vapour in the flammable range because the Jet A1 is stored below its flash point. Weak shell-to-roof seam also acts as mitigation. Therefore not applicable to PAFF tanks.</td></tr>
<tr><td>Addyston, 1976</td><td>Methanol tank struck by lightning. Tank rocketed and burning contents overflowed surrounding dykes</td><td>PAFF tanks do not have vapour in the flammable range because the Jet A1 is stored below its flash point. Weak shell-to-roof seam also acts as mitigation. Therefore not applicable to PAFF tanks.</td></tr>
<tr><td>US, 1978</td><td>Three tanks failed catastrophically in an earthquake.</td><td rowspan="2">Seismic failure remains a possibility for the PAFF tanks, although Hong Kong has a much lower seismic hazard than USA, particularly California (Richmond). Events therefore are not completely impossible, but would be much less likely for PAFF tanks. Seismic failure of a tank may also not cause an instantaneous releases and the magnitude of the seismic event would also be expected to cause major failures elsewhere (e.g. SWS building and EcoPark).</td></tr>
<tr><td>Richmond 1989</td><td>Earthquake ruptured a gasoline storage tank. The spill was contained in the bund and was not ignited.</td></tr>
<tr><td>1992 EPA</td><td>Incidents listed in EPA alert [61]</td><td>PAFF tanks do not have</td></tr>
</table>

Incident	Brief Description and Comment	Applicability to PAFF
1994 EPA 1995 EPA	resulting in tanks failing at floor to shell joint due to internal explosions (see Section H4.7).	vapour in the flammable range because the Jet A1 is stored below its flash point. Weak shell-to-roof seam also acts as mitigation. Therefore not applicable to PAFF tanks.

H3.2.1.2 The above list is incomplete in terms of brittle failures. Wilkinson [55] lists 8 such brittle failures, including Ponca 1924, Meraux 1957 , Floreffe 1988 and Brisbane 1988, covering the period 1919 to 1988. However, McBride (Paragraph 59 of [9]), agrees with the previous EIA [1] that low temperature embrittlement is not relevant to storage of aviation fuel in Hong Kong. However. Wilkinson [55] lists a further 10 failures of liquefied flammable gas tanks and 5 failures following explosion or bund fires that are not applicable to the instantaneous failure of a PAFF tank.

H3.2.1.3 It is clear that catastrophic failures of tanks have occurred, resulting in either complete removal of the tank wall when the tank rockets due to an explosion in the vapour space, or an "unzipping" due to rapid brittle fracture initiated at a defect. Failures have also occurred in earthquakes, although it is not clear how rapid the failures were.

H3.2.1.4 These failures have all occurred in older tanks and design standards have since improved, largely in response to these types of failures. In particular tanks designed to API 650, such as the PAFF tanks: are manufactured from materials designed to avoid brittle fracture; include welding procedures, radiographic inspection and qualification of welders to avoid out of tolerance defects; and include a frangible shell to roof seam to relieve overpressure by failing the top of the tank rather than the bottom [16].

H3.2.1.5 Further factors, including the ambient temperature in Hong Kong and the storage of Jet A1 below its flash point make brittle fracture and overpressure failures highly unlikely, even without improvements in design standards.

H3.2.1.6 Of the 4 incidents clearly identified above as involving bund overtopping due to the momentum of the release:

- Two occurred many years ago (Ponca 1924 and Meraux 1957) one involving a rapid temperature change and the other mentions cast iron fittings present. Tank design and testing has advanced since these incidents.
- One was a refrigerated LPG tank possibly subject to brittle fracture and which also had an inadequate bund capacity (Umm Said 1977).
- One involved a failure (cause identified as low temperature embrittlement) on first filling in subfreezing temperatures of a 48 year old, relocated and reconstructed tank that had only partial hydro-testing (Floreffe 1988).

H3.2.1.7 All of these incidents include significant causative factors that are not present for the PAFF tanks.

H3.3 Previous Catastrophic Failure Frequency Estimates

H3.3.1.1 A number of estimates have been made with regard to the frequency of catastrophic failure of atmospheric storage tanks. The following catastrophic failure frequencies were listed in the previous EIA Report (Table 10.9 of [1]):

Source	Type of Failure	Failure Frequency (per tank-year)
Batstone & Tomi	Catastrophic rupture	3×10^{-5}
COVO Study	Serious leakage (50 mm hole)	1×10^{-4}
	Catastrophic rupture	6×10^{-6}
Taylor	Large Leak	8.8×10^{-4}
	Catastrophic rupture	1×10^{-5}
E&P Forum	Major Release	6.9×10^{-6}
Davies (Prokop)	Catastrophic Rupture	2×10^{-7}
Christiansen & Eilbert	Catastrophic Rupture (All tanks)	4×10^{-6}
	Catastrophic Rupture (tanks > 10,000 barrels)	9.2×10^{-6}

H3.3.1.2 The Dutch guidelines on QRA include a frequency of 5×10^{-6} /tank-year for an instantaneous release to atmosphere from a single containment tank (Table 3.5 of [34]). McBride [9] also notes that this frequency estimate is based on “expert judgement”. A UK figure for cold catastrophic failure contained in the SRAG for highly flammable liquids is 3×10^{-6} /tank-year (Criterion 3.4.5, Table 4 of [33]). The source of this data is not quoted in the SRAG [33].

H3.3.1.3 Further estimates for catastrophic failure frequencies are available elsewhere. Wilkinson [55] quotes 12 different figures for tank failure frequencies covering the range 10^{-9} to 5.8×10^{-5} /tank-year and 7 upper limit values between 10^{-5} and 1.75×10^{-2} /tank-year covering atmospheric, refrigerated and pressurised storage. Some of the frequency estimates cited are based on upper confidence limits from tank populations in which no failures had occurred (i.e. estimations of upper limits which may significantly over-predict the risk levels).

H3.3.1.4 For general purpose liquid storage, Davies/Wilkinson ([46], [55]), provide estimates of instantaneous tank failure frequencies of $< 2 \times 10^{-5}$ /tank-year (based on no failures in 150,000 tank years) and 2×10^{-7} /tank-year (based on 2 failures in 20 years of operation of an estimated 600,000 tanks in the USA between 1968 and 1988). Higher estimates apply to refrigerated storage (e.g. mean values of 5.8×10^{-5}, 1.7×10^{-5} and 2.3×10^{-5} per tank year based on 2, 2 and 1 failures in the populations, respectively [55]).

H3.3.1.5 Davies [46] states that “Although the number of actual failures is small, the historical records and the theoretical estimations indicate a generic failure rate for bulk storages of the order of 10^{-7} - 10^{-6} per year.”

H3.4 Tank Population

H3.4.1.1 Given an estimate of the numbers of applicable incidents over a period, all that is required to estimate the event frequency is the population of tanks.

H3.4.1.2 Prokop [54], in considering whether other tank collapses were likely after the Ashland (Floreffe) collapse in 1988 states "EPA said that considering the number of above-ground tanks (an estimated 600,000), it had few problems with them. Such total tank collapses are rare, the last occurring in New Jersey in 1969." This estimate is used by Wilkinson/Davies ([55], [46]) as a basis for the estimated catastrophic failure frequency of 2×10^{-7} /tank-year ("2 tank collapses in USA in period 1968-88. Tank population estimated at 600,000 over this 20 year period" [55], i.e. 2/(600,000×20) = 1.7×10^{-7} /tank-year, rounded up to 2×10^{-7} /tank-year).

H3.4.1.3 Wilkinson [55] also cites some other estimated tank populations that are of interest for comparison, although not directly relevant: 150,000 vessel years of general purpose liquid tanks in the UK over 50 years (i.e. 3000 tanks) based on data from a single manufacturer; 300,000 pressure vessel years in period 1962-76 (i.e. 20,000 pressure vessels); 2445 refrigerated storage tanks; 10,000 ammonia vessels world-wide (refrigerated or pressurised), 2150 refrigerated storages world-wide.

H3.4.1.4 Atmospheric storage tanks are much more commonly used than refrigerated storage or ammonia storage, so it would be expected that the atmospheric storage tank population would be a large factor higher than the 2150-10,000 tanks identified for these cases.

H3.4.1.5 The Steel Tank Institute [62], provide estimated figures of 2 million underground fuel storage tanks in the USA, declining to 750,000 with an estimated average capacity of order 1,000bbl. A reliable estimate is easier to obtain than for above ground storage tanks due to the US regulatory regime. However, it is noted that there is an increasing trend towards construction of above ground rather than underground storage and so these figures are compatible with the 600,000 estimate in Prokop [54].

H3.4.1.6 Statistical information is readily available (e.g. www.eia.doe.gov) on stocks, production, etc, that can be used for comparison purposes. For example, the U.S. total oil reserve is 1-2 MMMbbl[2] (1,568 MMbbl in 2003 including 638 MMbbl strategic reserve [63]). This quantity could, in theory, be stored in 5,000 to 10,000 tanks of the size of the PAFF tanks (PAFF tank capacity 35,000 m^3 and $1m^3$ = 6.289bbl gives a tank capacity of 220Mbbl), however this would be a serious under-estimate of the tank population since most tanks are much smaller than the PAFF tanks, and there are many more tanks in the upstream oil system and downstream distribution system. The 600,000 tank estimate in Prokop [54] would give an average tank capacity estimate of about 5,000bbl allowing for 50% ullage. This capacity is clearly low for bulk crude oil storage, but would be high for typical sizes identified by the Steel Tank Institute [62] and reasonable for a typical "small" storage tank of 10Mbbl used at oil installations (e.g. 17-18m diameter and 7-8m high). This also does not allow for storage tanks in the distribution system. Overall, these figures are also therefore compatible with the 600,000 tank estimate in Prokop [54].

H3.4.1.7 Whilst accurate estimates of applicable tank populations are not easy to come by, the EPA estimate from Prokop [54] of 600,000 tanks in the USA is considered here to be the most applicable basis and is consistent with other available information.

H3.4.1.8 The U.S. produces ~10% of world oil and consumes ~¼ of world production, so a world-wide estimate for the population of large (1000bbl plus) petroleum storage tanks

[2] Mbbl denotes 1,000bbl; MMbbl denotes 1,000,000bbl; MMMbbl denotes 1,000,000,000bbl

of between 4 to 10 times higher than the 600,000 estimate in Prokop [54] would be reasonable. A figure of 4 times is used for the lower estimate and 10 times for an upper estimate. The cautious best estimate is taken to be the same as the lower estimate since there is a degree of uncertainty in the estimates.

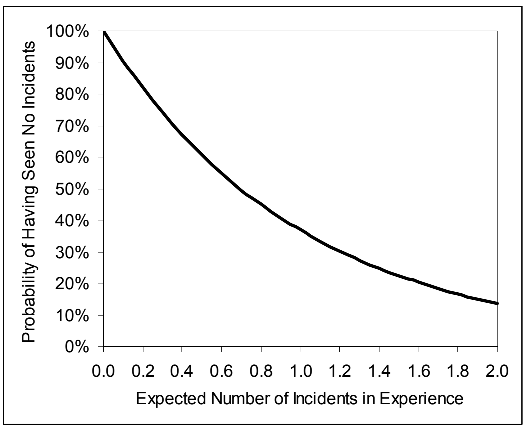
Estimate	Tanks	Basis
Lower Estimate*	2,400,000	Prokop [54] times 4 based on US having ¼ of world oil consumption
Cautious Best Estimate	2,400,000	
Upper Estimate*	6,000,000	Prokop [54] times 10 based on US having 10% of world oil production
* Note lower and upper estimates are reversed in the calculation of failure frequency		

H3.5 Instantaneous Release Frequency For PAFF Tanks

H3.5.1.1 In Section H3.2 11 instantaneous failure incidents were identified, but none are considered applicable to the PAFF. In all cases, the PAFF tanks are expected to be much less likely to fail than the tanks associated with the incidents, for very good reasons:

- The PAFF tanks are new and will be designed, tested and operated to modern standards, including API 650 and API 653 [16].
- The tanks will contain Jet A1. Jet A1 does not form a flammable vapour at ambient temperatures (flash point 38°C) and is therefore less susceptible to ignition of vapour in the tank head space (including from lightning) than lower flash point materials such as gasoline (and some other jet fuels).
- Low temperature embrittlement is not relevant to Hong Kong and the storage of aviation fuel (see Paragraph 59 of McBride [9]).
- Corrosion and settlement will be monitored. Corrosion allowances are included in the design, the tank base is elevated relative to the bund floor and the tanks will be inspected as specified in API 653 [16].
- The site will be provided with "security measures such as a double security fencing, CCTV's within the security fence, and security guards on 24 hours duty" [14].

H3.5.1.2 None of the incidents identified are relevant to a instantaneous failure of the PAFF tanks. The associated number of incidents that should be ascribed to this event then depends on the level of confidence with which it is considered that the event could not occur for the PAFF tanks. Where an incident clearly could occur (but hasn't) it is normal to base the expected number of incidents on a 50% chance of it having (or not having) occurred, leading to an estimate of 0.7 incidents based on a Poisson



distribution (a Poisson distribution is appropriate to pseudo-random events such as instantaneous tank failure). The probability of not having seen an incident as a function of the expected number of incidents based on a Poisson distribution is shown adjacent. Since the causes considered are not generally applicable to the storage of Jet A1 at the PAFF then the incident is not expected to occur and assuming a 50% chance of a relevant incident having occurred may give an overly pessimistic estimate. However, it is difficult to assess how pessimistic, so some caution is still required. For the cautious best estimate we allow only a further factor of 2 on the expected number of incidents (0.35), equivalent to a 30% chance that an incident should have occurred in the experience history that was relevant to the PAFF tanks.

H3.5.1.3 For a lower estimate, we take a nominal estimate of 0.1 incidents in the experience period, corresponding to a 10% probability of having seen an incident relevant to the PAFF tanks. For the upper estimate, we assume that the 11 incidents listed in Section H3.2 are potentially applicable and that all the additional factors and safeguards identified for the PAFF above have a ~20% chance of failure (a high figure for human error), giving approximately 2 incidents in the experience period; this is considered very pessimistic.

H3.5.1.4 The failures in Section H3.2 and Appendix H4 cover a period from 1924 to 2000 (i.e. 77 years), however incident reporting is likely to be more reliable since around 1970 (30 years), which is taken as the cautious best estimate. A number of incidents are recorded in the 1970s, so it would be unreasonable to take a period of less than 30 years, so this is also taken as a lower limit.

H3.5.1.5 Upper and lower estimates of the instantaneous release frequency for a PAFF tank are summarised below:

Data Applicable to PAFF tank	**Lower Estimate***	**Cautious Best Estimate**	**Upper Estimate***
Tank Population (A) *	6,000,000	2,400,000	2,400,000
Applicable experience years (B) *	77	30	30
Applicable number of incidents (C)	0.1	0.35	2
Instantaneous release frequency per PAFF tank year (C/A/B)	2×10^{-10}	5×10^{-9}	3×10^{-8}
* Note lower and upper estimates for tank population and experience years are reversed in the calculation of failure frequency			

H3.5.1.6 It is appropriate that the estimates for the instantaneous release frequency are all less than estimated by Davies/Wilkinson/Prokop ([46], [55], [54]) since the Davies/Wilkinson/Prokop ([46], [55], [54]) estimate makes no allowance for improvements in tank design or for the specific characteristics of the PAFF tanks which make them much less likely to experience brittle failure or failure of the floor to shell joint due to an internal explosion than an average atmospheric pressure storage tank.

H3.5.1.7 Other, higher estimates (see Section H3.3) identified for catastrophic failure frequencies were not made specifically for the instantaneous release scenario on this type of tank and are not considered appropriate to use directly in this analysis.

H3.5.1.8 Based on the data in Section H3.2 approximately half of the failures (5 out of 11) involved failures of the shell to bottom seam and the other half involved an unzipping scenario. We therefore divide the instantaneous release scenarios for the PAFF tanks equally between these two cases.

H3.6 Aircraft Impact Frequency

H3.6.1.1 Although no incidents in which an aircraft impact lead to a instantaneous failure of a large tank, or any failure considered as catastrophic, are noted in the data reviewed in Appendix H4, the predicted aircraft impact frequency for the PAFF is examined below.

H3.6.1.2 The main potential hazard comes from the volume of aircraft activity from Hong Kong International Airport and there are no significant identified landing sites for aircraft or helicopters local to the PAFF.

H3.6.1.3 The chances of an aircraft crashing from flight at a given location in the vicinity of an airport depends on the lateral orientation and displacement of the location from the runway centreline. Phillips [64], [58] suggests the following expression for the distribution of aircraft crashes from flight in the vicinity of airports:

$$f(R,\theta) = 0.23\exp\left(-\frac{R}{5}\right)\exp\left(-\frac{|\theta|}{5}\right)$$

where R is the radial distance (km) from the runway end, and θ (degrees) is the angle between the vector R and the runway centreline. R and θ are measured from the threshold at the departure end of the runway for aircraft taking off, and from the threshold at the arrival end of the runway for landing aircraft [65].

H3.6.1.4 The aircraft crash frequency on the PAFF can then be estimated using:

F = Crash Rate × N × f(R , θ) × Proportion of flights in specified direction × Proportion of flights using specified runway × Target Area.

where N is the number of aircraft movements per year at the airport.

The number of movements is expected to grow from an historical level of 98,423 /yr in 1998 to 380,000 /yr by 2016. If a third runway is operational by ~2040, the number of movements is expected to increase to 700,000 /yr [66]. For operational and safety reasons, aircraft usually land and take off into the wind. The prevailing wind directions at the airport mean that about 55% of aircraft movements are from the West.

H3.6.1.5 The North and South runways at Hong Kong International Airport are generally operated in segregated mode, with the South Runway being dedicated for departures and the North Runway dedicated for arrivals (apart from cargo flights and Government Flying Services aircraft which generally land at the South Runway). However, in the longer term, aircraft are likely to be landing and departing from both runways simultaneously, so for the purposes of this study we have assumed that arrivals and departures are both divided equally between the North and South Runways [58].

H3.6.1.6 The aircraft crash risk was found to be dominated by landings rather than takeoffs. The following table gives the estimated frequency of aircraft crash onto the proposed PAFF during landings, based on an approach crash frequency of 1.2×10^{-8} per movement per year [58].

H3.6.1.7 The target area of the PAFF has been taken conservatively as [67] 234.65m × 278m = 6.52×10^{-2} km^2. This is to be compared with the total bund area of 3.69×10^{-2} km^2 around the two sets of six tanks, and makes ample allowance for the half wingspan of typical aircraft using the airport.

Loc.	Direction	R (km)	Θ (deg)	f(R, θ)	Impact Frequency, /yr		
				Aircraft Movements	98,000 /yr (1998)	380,000 /yr (2016)	700,000 /yr (2040)
North Runway	From East	5.37	110	2.19×10^{-11}	3.80×10^{-16}	1.47×10^{-15}	2.70×10^{-15}
	From West	6.77	50	2.70×10^{-6}	5.71×10^{-11}	2.21×10^{-10}	4.06×10^{-10}
South Runway	From East	6.94	108	2.39×10^{-11}	4.14×10^{-16}	1.60×10^{-15}	2.95×10^{-15}
	From West	8.22	54	9.06×10^{-7}	1.92×10^{-11}	7.42×10^{-11}	1.37×10^{-10}
				Total	7.63×10^{-11}	2.95×10^{-10}	5.43×10^{-10}

H3.6.1.8 The risk is dominated by landings from the west at the North Runway. The total estimated frequency of aircraft crash onto the PAFF remains below 1×10^{-9} /yr even based on the predicted 2040 traffic levels.

H3.6.1.9 The estimates above are based on the distribution suggested by Phillips [64] and used in [58]. It should be noted that the frequencies predicted by more recent models [68], commonly used in aircraft impact risk analysis, are some two to three orders of magnitude lower and the above estimates may be considered very cautious. The proposed location of the PAFF is at the limit of applicability of the models, which are generally intended for locations within ~5 km of the runways. The crash frequency at this location well away from flight paths and the runway centrelines would generally be treated as negligible in most risk analyses.

H3.6.1.10 For the initial development (8 tanks) the aircraft impact frequency is taken as 2/3 of the 2016 case identified above (8 out of 12 tanks present); 2×10^{-10} /yr. For the final development (12 tanks) the aircraft impact frequency is taken from the 2040 case identified above; 5.43×10^{-10} /yr.

H3.6.1.11 An aircraft impact is considered to occur on the PAFF resulting in a instantaneous rupture of each of the PAFF tanks (see 10.6.2.26) with a frequency 2.5×10^{-11} /yr (initial development of 8 tanks with 2016 impact frequency) and 4.5×10^{-11} /yr (final development of 12 tanks with 2040 frequency). These figures are taken for the cautious best estimate and upper estimates. This is considered an upper limit. For the lower estimate an aircraft crash frequency a factor of 100 lower is taken in line with more recent estimating methods.

H3.7 Probability of Tank Fill Level

H3.7.1.1 The PAFF tanks will operate as a terminal receiving and exporting Jet A1 and will generally be cycled from empty to full and back again since it is required, for product quality reasons, not to mix cargo receipts in the same tank. A failure may occur at any time and the effects of a release will depend on the fill height of the tank when the failure occurs (see Section H7.1). Whilst the tank welds will be most stressed when the tank is full, this will be significantly less than the stress under hydrotest, so it is considered appropriate to distribute the failure probability evenly over fill levels.

H3.7.1.2 The PAFF will typically import and export up to 25,000 m^3 per day at similar flow rates (~1,250 m^3/hr) for the initial development, so on average one tank will be being emptied and one filled 20 hours of each day. The proportion of the time a tank is in the fill/empty cycle will therefore be (20+20)/24/8 ~ 20% for 8 tanks. This is taken as an indicative value since flow rates will increase for the final development. Tanks must be available empty to receive cargo (and may also be empty for maintenance) as well as full ready to export, so the remainder of the time is split equally between full and empty (40% each). An empty tank is still assumed to contain some Jet A1 for caution.

H3.7.1.3 4 separate fill ranges are considered based on differences in consequences (see Section H7.1), with the following probabilities, based on a uniform filling/emptying rate.

Fill Range	Modelled Fill Level	Probability
90%-100%	100%	42%
60-90%	80%	6%
35-60%	35-60%	5%
<35%	<35%	47%

H3.7.1.4 The resulting frequencies of an instantaneous release involving seam failure or unzipping with different fill levels are identified in the event trees in Appendix H9.