APPENDIX H6: POOL FIRE ANALYSIS

H6.1 Introduction

H6.1.1.1 For Jet A1 pool fires, the distance to potential lethality is well approximated by the extent of the flame envelope. For unconfined pool fires this is reasonably approximated by the pool radius. For confined (bunded) pool fires the distance to potential lethality takes into account the extent of predicted flame drag in the wind; this is because the edge of the pool is well defined and a well developed and stable fire is expected to form. Lethality is not expected beyond the flame envelope and these simplifications are used throughout this hazard to life assessment.

H6.1.1.2 These simplifications are consistent with the previous EIA submission for the PAFF [1] and previous environmental impact assessments with similar issues for the Hong Kong Administrative region in which "*the effect distance was considered to be approximately the same as the pool radius*" [37], except that flame drag has been included as a modification for bunded pool fires to avoid any potential optimism close to the site boundary.

H6.2 Basis of Simplification

H6.2.1.1 The simplified modelling of pool fire impact is based on:

- The low radiation fluxes generated outside the flame envelope by Jet A1 fires. In a recent review for UK HSE [76]. Mizner and Eyre [75] note, in relation to a 20m diameter kerosene pool fire experiment that "*During the kerosene fire the soot was so dense that the flame dimensions were extremely difficult to determine.*" Rew and Hulbert [76] also note that "*the average surface emissive power of an 80m diameter kerosene fire is approximately 10kW/m^2*".
- Commonly applied thermal dose relationships such as that derived by Eisenberg [77],
- The size of the potential fires and available evacuation routes (e.g. along the public road between the proposed PAFF and the Steel Mill and away from the fire within the Steel Mill).
- Typically applied escape speeds and resulting exposure durations,
- The period of time available for escape at much lower thermal radiation levels, during the time of development of a large Jet A1 pool fire, or even before ignition occurs. ESR would estimate several minutes are available after ignition of a large bund fire based on available flame spread data (this is discussed extensively in the SFPE Handbook (pages 2-300 to 2-306 of [25])).

H6.2.1.2 Additionally, there is a possibility of escape for people caught within a pool, but away from the ignition source as discussed in H6.3.1.5, although this is not included to avoid potential optimism.

H6.3 Flame Spread and Escape

H6.3.1.1 The rate of flame spread potentially has a large effect on the hazard to life, particularly for a fuel, such as Jet A1, which is spilt at a temperature below its flash point. Flame spread rates over fuel surfaces are discussed extensively in Section 2, Chapter 15 of the SFPE Handbook [25]. Typical flame spread rates for fuels below their flash points are of the order of 0.1 m/s or less (see Figure 2-15.15 of [25]). Flame spread in this region is controlled by liquid heating. For fuels (not Jet A1) spilt at temperatures significantly above their flash points, where flame spread is controlled by the gas phase, typical flame spread rates are of the order of 1-2 m/s. The experiments on which this data is based are relatively small scale, and undertaken in idealised conditions, in comparison to the pool fire sizes considered here. The initial flame spread rate over a Jet A1 pool would be expected to be low (around 0.1m/s) but could increase to around 1-2m/s as radiation from the established flame heated the fuel surface in front of it to its flash point temperature. The transition between these two regimes is uncertain, but it is clear that a large, steady state pool fire will take a significant time to establish.

H6.3.1.2 ESR would therefore expect that a Jet A1 pool fire of greater than 100m diameter (typical of the bund fires considered here) would take several minutes or more to fully establish after ignition.

H6.3.1.3 Until a large, steady state pool fire is established, ESR would expect that the flame will be much shorter, that the radiation levels will be much lower, and the extent of flame drag will be much less. This allows a significant length of time for people to escape as the fire develops. ESR would therefore expect that, unless a person is within or very close to a pool of Jet A1 when it is ignited, they would be expected to be able to escape largely unhindered for a period of several minutes after ignition without receiving a significant thermal dose.

H6.3.1.4 The probability of escape in this time is difficult to estimate accurately, but the flame development rate is less than a typical walking speed and much less than typical escape speeds so the chances of escape would be expected to be high.

H6.3.1.5 There is a possibility of escape for people caught within a pool, but away from the ignition source. A recent study on quantified risk assessment of aircraft fuelling operations for the UK HSE [24] states "*Even if a person is within the area of the ignited spill, they may not suffer fatality. They may escape before the ignition occurs, or they may survive the fire.*" (Section 10.6 of [24]). The study [24] also suggests a 90% probability of a fuelling operator escaping/surviving (Table 10.5 of [24]). The study [24] relates to much smaller releases, which means that the people will have a shorter distance to escape, but must also be close to the ignition point.

H6.3.1.6 There will be a period of time available for escape during the time of development of a large Jet A1 pool fire, or before ignition occurs. Flame spread speeds over liquids below their flash points (e.g. a Jet A1 release from the PAFF) are typically less than 10 cm/s (see SFPE Handbook Figure 2-15.15 and text on pages 2-300 to 2-306 [25]), potentially allowing people to walk away from the ignition source much faster than the flame spread, providing an egress route is available. This could lead to a large reduction in the fatality estimates if applied to the analysis.

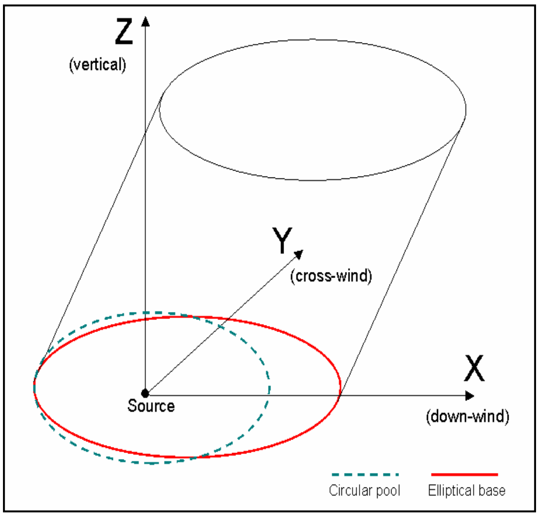
H6.3.1.7 However, none of the risk estimates in this report make any allowance for escape for people within the predicted pool area, to avoid undue optimism, since:

- Jet A1 is very slippery and escape from the deep and flowing pools that could occur from instantaneous failures would be far more difficult than escape from small shallow pools.
- For instantaneous releases, the Jet A1 pools are potentially deep and the liquid flow may knock people over making escape more difficult.
- For large pools, people may be caught between the source of the release and the ignition source so that available escape routes are much more likely to be cut off than for small pools.

H6.4 Pool Fire Modelling

H6.4.1.1 ESR model pool fire hazards using the PFIRE2 code [78], which was developed by ESR and has been used since 1991. The models used in PFIRE2 are similar, but not identical, to the recently developed POOLFIRE6 model [76]. The PFIRE2 model, including recent modifications to include flame sag for tank head fires has been used for thermal radiation and flame drag calculations for the PAFF tanks.

H6.4.1.2 The flame shape used in modelling the thermal radiation flux from a pool fire is typically based on the assumption of a circular pool. PFIRE2 [78] uses a skewed elliptical prism to represent the flame surface, as shown adjacent, allowing for flame tilt and drag in the wind. Other pool fire codes, e.g. POOL [76], POOLFIRE5 [76], POOLFIRE6 [76], Shell's FRED [79] and BP's Cirrus codes [80] adopt a similar geometry, including both flame tilt and drag. It is now common practice to adopt a two zone representation [76] as in PFIRE2 [78] which includes a lower, clear, flame and an upper, smoky, flame. For large diameter Jet A1 pool fires, clear flame height is predicted to be very short or non-existent, consistent with the work of Considine [81].



H6.4.1.3 The flame drag correlation used in PFIRE2 [78] and also recommended in the recent HSE review [76] is that developed by Moorhouse [82] and the flame sag (for tank head fires) is taken as for POOLFIRE6 [76].

H6.5 Thermal Radiation Impact Criteria

H6.5.1.1 An estimate of the probability of fatality can be made on the basis of a thermal dose. One of the most commonly used expressions for this is the Eisenberg probit [77]. Other relationships exist and the Eisenberg probit provides one of the more conservative estimates. A difficult question is always how to evaluate the exposure time. In some cases it is reasonable to integrate the dose received when moving directly away from the fire. However this could not easily occur on the West side of the PAFF, adjacent to the steel mill, where escape would need to be along the road between the PAFF and the steel mill. Similarly, escape routes are not clear within the EcoPark at present, so escape (as a worst case) may also be parallel to the flame edge. However, escapees would be expected to be able to move away from the flames across the roads (assuming that they had not already escaped or been evacuated during the development of a fire). A worst case estimate is that people could be exposed to the flux level estimated at the initial distance from the fire as they escape parallel to the edge of the fire.

H6.5.1.2 For a large contained fire on the PAFF site the typical fire dimension is ~140 m so the travel distance necessary to escape could be up to ~70 m. A typical escape speed is 2.5 m/s (1 m/s is a typical walking speed and 10 m/s is world record sprinting pace), so a typical exposure time would be 30 seconds.

H6.5.1.3 10 kW/m^2 is the surface emissive power of large Jet A1 fires [76], so the thermal flux outside the flame envelope will always be less than this and will reduce as someone moves away from the fire. Jet A1 pool fires are also predicted to take a significant time to develop, as discussed in Section H6.3, and during this time much lower thermal radiation levels would be experienced outside the pool.

H6.5.1.4 The thermal radiation exposure to someone outside the developed flame envelope would therefore be predicted to be less than 10 kW/m^2 for 30 seconds. Thermal radiation exposure is usually expressed as a thermal dose; 10 kW/m^2 for 30 seconds gives a thermal dose of 646 (kW/m^2)$^{4/3}$s. The Eisenberg probit gives a nominal fatality probability of <0.1% for this thermal dose, i.e. fatality is predicted to be very unlikely even for upper exposure levels predicted. The UK HSE define a dangerous dose that would cause severe distress to all persons suffering it and could result in highly susceptible people being killed. The dangerous dose of thermal radiation for average members of society is given as 1000 (kW/m^2)$^{4/3}$s [33]. The exposure predicted here is significantly below this dangerous dose level, so no fatalities would be expected for people located initially outside the flame envelope.

H6.5.1.5 For an unconfined fire on the sea, the pool of Jet A1 will not be uniform in thickness, but will be thicker towards the source of the spill and will become thinner and patchy towards the edge. In the assessment of the effect distance the pool thickness is assumed to be uniform, which is conservative because thinner, patchy layers near the outer edge may not be able to support a stable flame. High winds will also increase emulsification and reduce the stability of the flame near the edge of the pool, so it is not appropriate to consider further flame drag effects in addition to the already conservative analysis of pool spread.

H6.5.1.6 For an unconfined fire on land due to overtopping of the bund and security walls, the liquid pool extent will be transient and the pool extent has been taken as the maximum extent observed in the experiments. The typical timescale before the flow starts to thin and recede (note: time scales as the square root of the length scale in the experiments) is only ~30 seconds and typical liquid flow speeds also exceed flame spread speeds, even for fuel thicknesses of less than 10 mm. Flames near the edge of the flow extent are therefore expected to be transient and a well established pool fire would not be expected to burn up to the edge of spill area considered. The additional effects of flame drag are therefore not taken account of here.

H6.5.1.7 The thermal flux experienced within the flame envelope is much higher and will include direct exposure to the hot combustion gases and smoke. Anyone caught within the flame would be expected to experience severe burns or worse. In this assessment, for conservatism, fatality is assumed for anyone caught within the flame envelope. This leads to two cases:

- For a bund fire, the edge of the pool is constrained and the spill and initial development of the fire may not be clear to someone outside the bund due to the high wall, etc. No escape is assumed for anyone who would be caught within the flame envelope, including the downwind flame drag distance calculated from the edge of the pool.

- For an unconfined pool fire, either on land or on the sea, the development of the pool and the fire spread will be immediately apparent to anyone outside the pool area and they would be expected to escape either before ignition or during the fire development. The impact distance is therefore taken to be the edge of the pool, consistent with not accounting for any escape from within the pool as discussed in Section H6.3. The largest uncertainty here is also in the assessment of the pool spread, and the stability of a flame near the edge of a flowing pool, which is treated conservatively.

H6.5.1.8 It may be noted that the DNV 2000 marine study [38], although using an effect distance equal to the pool radius throughout, identified that the impact distance could potentially spread 2-3m beyond the pool edge for small pools (much shorter distances for large pools). In the previous EIA [1] an additional 3 m was added to the pool radii to give the effects distances. Although this approach has not been adopted here, it may be noted that an additional 3 m added to the unconfined pool fire effects distances in this study would add between 1 and 5% to the predicted PLLs (the largest percentage difference is for the pipeline, which has one of the lowest PLLs). The effect this would have on the predicted risk levels in this study is not significant.

H6.6 Tank Head Fire

H6.6.1.1 A tank head fire on one of the large PAFF tanks has been modelled as a 43.5m diameter pool fire 24.7m above ground level. Thermal radiation levels at ground level are not predicted to lead to fatalities outside the tank area, so no off-site fatalities are predicted.

H6.6.1.2 Simple heat transfer modelling for the roof of an adjacent tank indicates that the roof is unlikely to fail directly even under the maximum thermal flux of 10 kW/m^2 predicted outside the flame envelope. However, the metal may exceed the auto-ignition temperature of Jet A1 with thermal fluxes ~5 kW/m^2 over a significant area of the roof. The storage tanks will be a minimum of 15m from shell to shell [14] but a thermal flux in excess of 5 kW/m^2 may occur at roof level with the wind blowing directly from one tank to another. In these conditions, an adjacent tank roof may potentially also be set on fire if the tank roof and shell are not cooled by the fixed deluge system or fire service intervention. However, some time will be required to heat the Jet A1 sufficiently to form a flammable mixture adjacent to the heated roof and so escalation from a tank head fire is not expected immediately. To heat a 1m height of Jet A1 by 1^{o}C requires a heat input of approximately $2190\ J/kg/K \times 840\ kg/m^3 \times \pi(43.5\ m)^2/4 \times 1\ m = 2.7\ GJ$. Over the corresponding heating area, this requires a heat input of

2.7 GJ/(π × 43.5 m × 1 m) = 20 MJ/m^2. At a mean net thermal flux of 5 kW/m^2 all around the tank this would require about 1 hour. Even on one of the hottest days of the year (with a maximum temperature of 33^{o}C or more), the heat-up of the Jet A1 liquid to above it's flash point will take several hours and at more typical temperatures may take of order 1 day. This allows ample time for evacuation of surrounding areas.

H6.7 Bund Fire

H6.7.1.1 The PAFF bunds have areas of between 10,000 and 20,000 m^2, depending on whether the tank areas themselves are included. For indicative calculations, we approximate the pool area as ~15,000 m^2, giving an equivalent pool diameter of 140 m. For pools including the EVA road, a further 20m is added to the diameter.

H6.7.1.2 Since the thermal flux levels outside the flame envelope are not expected to lead to fatalities, only the extent of the flame drag is of concern for bund fires. Flame drag distances, estimated using the ESR PFIRE2 code [78] are provided below:

Location	Pool diameter (m)	Flame Drag (m) in Wind Speed			
		0 m/s	2 m/s	5 m/s	10 m/s
Pump Platform Bund	36	0.0	3.6	9	14
Tank Bund	140	0.0	0.4	19	35
Tank Bund plus EVA Road	160	0.0	0.0	20	38

H6.7.1.3 The site fence is a minimum distance of 10 m from the security wall and 18.5 m from the bund wall (see Figure 10.2), so only tank bund fires in wind speeds above 5 m/s and fires including the EVA road in wind speeds of 5 m/s and above are predicted to have any significant potential off-site impact. At low wind speeds, the flame envelope will be contained entirely within the site boundary.

H6.7.1.4 The probability of fatality is taken as 100% within the predicted flame area and zero outside the predicted flame area. For simplicity and conservatism in the societal risk calculation, the flame drag area is assumed to cover the maximum identified population density it could affect adjacent to the fire.

H6.8 Smoke Plume Impact

H6.8.1.1 The combustion products of aviation fuel include carbon dioxide, nitrogen oxides and sulphur oxides. Incomplete combustion will generate thick black smoke and potentially hazardous gases including carbon monoxide. In the case of fire involving heavier hydrocarbons such as Jet A1 and for large diameter tank/bund fires, smoke production is high. However smoke from such fires is buoyant and does not tend to seriously impact people on the ground in the open air; this was the case in the recent Buncefield tank farm fire for example [35].

H6.8.1.2 Smoke plume rise was considered in the Tung Chung Cable Car EIA [58] and EcoPark EIA [10]. The maximum recorded tilt angle of a flame from experiments was 60^o for a 10.2m diameter pool in a 10m/s wind speed. This applies at high wind speeds and smaller tilt angles apply for larger pool diameters and lower wind speeds. For this case the ESR PFIRE 2 code [78] produces a very similar flame tilt of 62^o. The PFIRE 2 code includes correlations for both flame drag and flame tilt and has therefore been used to assess the smoke envelope from potential fires at the PAFF. The following fires are considered and results for potential smoke impact distances provided in Figure H6.1.

Scenario	Pool Fire Diameter (m)	Fire Height (roof or wall) (m)	Distance to Boundary Fence (m)
Tank Head Fire	43.5	25	28.5
Pump Platform Bund Fire	36	3	10
Tank Bund Fire	140	3	18.5
Fire Within PAFF Security Wall	160	3	10

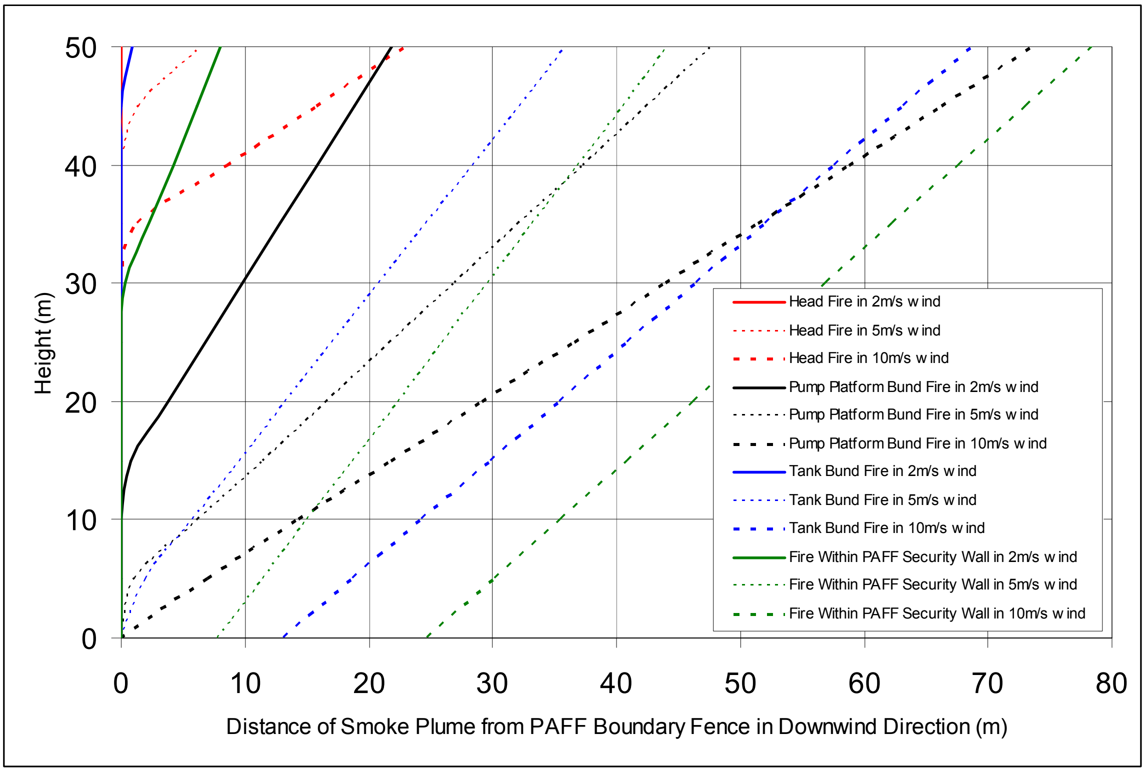


Figure H6.1: Predicted Smoke Envelope For Potential Scenarios at PAFF

H6.8.1.3 A tank head fire is predicted to occur with a frequency of 1.2×10^{-4} /yr per tank (see 10.5.3.3), whilst a bund fire is predicted to occur with a frequency of 1.2×10^{-5} /yr per bund (see 10.5.7.8). Bund fire impacts in a 10 m/s wind therefore have a maximum impact frequency in the worst case direction (2 sectors) of 3.6×10^{-8} /yr based on the wind rose in Section H6.9, whilst a tank head fire would have a maximum impact frequency of 3.6×10^{-7} /yr under these conditions. A 5 m/s wind is more likely, with the worst case direction having a probability of 9.8%. This would give an impact frequency from a bund fire of 1.2×10^{-6} /yr in the worst case direction (This would occur between North and West of the PAFF - see Section H6.9). A pump platform fire would have a worst case impact frequency of 5.5×10^{-7} /yr in a 5 m/s wind, whilst the impact frequency from a fire within the security wall would be much lower due to the lower frequency of the initial event.

H6.8.1.4 Unconfined pool fires, both on land and sea, will also produce smoke and this will also tend to rise clear of anyone outside the pool area. For unconfined pool fires, the hazard to life is dominated by the flame over the pool itself since the smoke hazard would only be transitory as the pool spreads and drains away – direct impingement by the flame above the pool would have an immediate effect and is the basis of the hazard range for unconfined pools in this assessment (see Section H6.1). Confined pool fires, including tank head fires, may last many hours or days, generating a continuous smoke plume and are also much more likely to occur at the PAFF.

H6.8.1.5 For planning purposes adjacent to the PAFF it is therefore suggested that occupied building heights be limited by the predicted smoke envelope due to a bund fire at the PAFF in a 5 m/s wind to maintain the risk levels for up to 10 fatalities within the acceptable envelope of the Technical Memorandum criteria [20]. This gives the following building height restrictions:

Distance of Building from closest PAFF Boundary (m)	Proposed Maximum Height (H) of Building (where workers may be at elevated levels) (m)
0	0
5	6
10	13
20	26
30	39
40	52
50	66

H6.8.1.6 In each case, the identified heights are greater than those identified in the EcoPark EIA [10] and the prevailing wind direction is not over this area. Should high occupancy buildings, or building heights in excess of these proposed limits be desired then it would be appropriate to consider the risk levels in more detail.

H6.9 Wind Speed and Direction

H6.9.1.1 Wind speed data is required for assessment of flame drag and smoke plume tilt. Local wind speed and direction data is provided below. The most common wind speed is around 2m/s. High wind speeds around 10m/s occur around 0.3% of the time and higher wind speeds can occur occasionally, particularly under typhoon conditions.

Wind rose data incorporating high wind speeds (based on [83])				
Wind	Percentage of Time Wind Blows with Given Speed (Total = 100%)			
Angle (deg)	0 m/s	2 m/s	5 m/s	10 m/s
15	0.6	17	5	0.1
45	0.3	6.7	3.8	0.2
75	0.2	1.4	0.3	0
105	0.4	2.8	1	0
135	0.2	8.8	4.9	0
165	0	18.8	4.9	0
195	0.1	8.4	0.3	0
225	0.1	3.7	0.2	0
255	0.1	0.5	0	0
285	0.3	1	0	0
315	0.2	3.1	0.6	0
345	0.2	3.7	0.1	0
Total	2.7	75.9	21.1	0.3