APPENDIX H5: IGNITION PROBABILITY

H5.1 Introduction

H5.1.1.1 It is more common in undertaking risk assessments of major hazard facilities to be concerned with ignition of extremely flammable gases and liquids (e.g. natural gas and LPGs) and highly flammable liquids (e.g. gasoline). Flammable liquids, such as Jet A1, present a significantly lower risk of ignition than either of these categories and are less commonly assessed in detail.

H5.1.1.2 Most of the research work on ignition probabilities considers materials that generate significant flammable gas clouds and are much easier to ignite than Jet A1. For example, recent work for the UK HSE ([70], [71], [72]) has concentrated on the ignition of gas clouds, particularly LPG, both on and off site.

H5.1.1.3 Very little data is available for ignition probabilities directly applicable to Jet A1, but it is unreasonable, in ESR's opinion, to simply use ignition probabilities derived for situations involving materials that are much easier to ignite. Available ignition probability data (much of which has only limited statistical support or is based on expert judgement) and the basic situations required to ignite Jet A1 around the PAFF have therefore been reviewed, prior to deriving a range of ignition probabilities for use in the hazard to life assessment.

H5.2 Generic Ignition Probability Data

H5.2.1.1 For offshore blowouts, Lees (Table 16.48 of [44]) provides ignition probabilities of 0.3 and 0.08 for gas and oil blowouts, respectively, based on the work of Dahl et al. These refer to massive releases, based on 123 gas blowouts and 12 oil blowouts. In ESR's opinion, the flash point of the oil released from a blowout is likely to be less than that of Jet A1 and the oil is likely to be highly flammable. There is also likely to be a higher density of ignition sources near the release than at the PAFF. The oil blowout figure (0.08) therefore provides a reasonable limit towards the upper end of the potential ignition probability for Jet A1.

H5.2.1.2 Davies [46] identifies an ignition probability of 0.6 for catastrophic releases from storage but states, in relation to this figure "*These values probably overestimate the actual probabilities since instances of fires are more likely to be reported to the database than examples of liquid releases.*" The 51 incidents quoted are for a range of materials including ammonia, LNG, propane, methanol, petrol, ethylene, crude oil and slops in addition to diesel, kerosene, etc. [73]. Most of the incidents involved liquids that would be classed as either highly flammable or liquefied gases, unlike Jet A1. Davies [46] also uses an ignition probability of 0.3 for a catastrophic release of heptane (a typical component of petrol), which would also be classed as highly flammable rather than flammable as for Jet A1. ESR therefore consider both of these figures potentially very pessimistic for a catastrophic release of Jet A1.

H5.2.1.3 Cox, Lees and Ang [74] present a review of onshore and offshore ignition data and suggest a simple ignition model based on mass release rate to assist in risk based calculations to support area classification. No detail is given on the flammability assumptions for the oil, but the figures may commonly be used for liquids above their flash points.

Release Rate Category	Release Rate kg/s	Gas Leak	Oil Leak
Minor	<1 (0.5 nominal)	0.01	0.01
Major	1-50	0.07	0.03
Massive	>50 (100 nominal)	0.3	0.08

H5.2.1.4 Cox, Lees and Ang (Table 15.1 of [74]) also present statistics on sources of ignition that show around 40% of all ignitions (where a cause was known) are due to flames and hot surfaces. The release rate associated with a massive oil release here is characteristic of a very large failure, but far lower than for a instantaneous failure of one of the PAFF tanks.

H5.2.1.5 Estimates by Browning [74], also quoted in Lees [44] suggest that the probability of ignition relative to a massive LPG release would be 0.1 for a flammable liquid with flash point below 110°F (43°C) or with temperature above flash point and 0.01 for a flammable liquid with flash point 110°F-200°F (43°C-93°C), based on expert judgement. Jet A1 has a flash point >38°C, but is normally stored below its flash point and hence a relative probability of 0.1-0.01 is most applicable to Jet A1. A geometric average value of the relative ignition probability of ~0.03 may therefore be appropriate (e.g. for an ignition probability of 0.1 for LPG we would expect an ignition probability for Jet A1 of 0.003 on this basis).

H5.2.1.6 The most applicable incident based data for Jet A1 ignition is from a recent study on quantified risk assessment of aircraft fuelling operations [24]. The estimate relates specifically to the "*risk from aircraft fuelling operations involving Jet A1*" (section 1.2 of [24]) and suggests a basic ignition probability of the order of 0.0001 (Section 10.5 of [24]) from historical experience of aircraft refuelling incidents. The authors [24] also say "*This figure is subject to considerable uncertainty and could be an order of magnitude too high. However, based on the limited historical evidence it is considered to be a reasonably conservative best estimate which is suitable for the purposes of this particular risk assessment.*" However, this typically relates to small (0.001 - 1 m^3, largest 17 m^3) spills spreading over areas of 1 m^2 to 1000 m^2 and it is recognised that there are factors that may increase this probability. In particular, an area scaling factor is proposed based on the ratio of the spill area to an average spill area of 83 m^2 [24] and a factor to allow for the fuel being released as a mist is also suggested. Spill areas considered for instantaneous releases from the PAFF run to over 10,000 m^2 and would therefore result in a typical ignition probability of ~0.1 based on this scaling. However, this is a very large extrapolation and should not be relied on. It is also apparent that this figure is a factor of 100 less than the Cox, Lees and Ang [74] figure for small releases (gas or liquid - Paragraph H5.2.1.3), consistent with Browning's estimate of the ignition probability difference between LPGs and flammable liquids with high flash points.

H5.2.1.7 Recent work undertaken for HSE in the UK for the ignition of flammable gas clouds ([70], [71], [72]) considers the number and effectiveness of ignition sources in an area. Ignition sources in an area are characterised by the basic ignition probability if the source is active and in contact with flammable gas (p), the ignition source density (μ - per hectare) and measures of the intermittency of the source (the time the source is active, t_a (minutes) and the time period between each activation, t_i (minutes)). The overall ignition probability for an area over which a flammable cloud spreads can then be calculated by summing up the appropriate terms.

H5.2.1.8 Generic ignition source densities are also presented (Table D.2 of [71]) for the model currently in use by the UK HSE:

Ignition Source Densities μ (per hectare) in UK HSE Model (Table D.2 of [71])			
Period	Industrial	Urban	Rural
Day	0.25	0.20	9.9×10^{-3}
Night	0.17	0.13	6.5×10^{-3}

H5.2.1.9 The report [71] also contains aggregated ignition characteristics for some typical industrial activities and plant. Pertinent figures are summarised below, omitting the intermittency factors which are not relevant here.

Ignition source area parameters (Tables B.12 and C.4 of [71])				
Ignition Source	Land use	Time	Ignition source density μ (per hectare)	Source Ignition probability (p)
Road vehicles	Urban	Day	0.51	0.1
		Night	0.13	0.1
	Rural	Day	0.027	0.1
		Night	0.0068	0.1
Base Metals Industry (furnaces & high temp processes)		Day	0.028	1
		Night	0.009	1

H5.2.1.10 Parameters for ignition sources on-site are considered in [72], however, for a instantaneous failure of one of the PAFF tanks, the off-site ignition sources are expected to dominate.

H5.2.1.11 For the special case of continuously active ignition sources the model [71] simplifies to give a probability of ignition $P_{ign} = 1 - exp(-\mu Ap)$, where A is the area covered by the flammable cloud in hectares.

H5.2.1.12 For example, using this method [71] for a flammable gas cloud covering the road area outside the PAFF and lorry parking area within SWS up to the SWS building (approximately 10,000 m^2), the estimated ignition probability would be 0.05, taking the urban daytime case and 0.013 at night. On the above basis, a flammable gas cloud covering the whole of SWS (10 hectares [21]) would have an ignition probability of 0.24 (day) and 0.09 (night - ignoring SWS being a 24 hour operation).

H5.2.1.13 Jet A1, under ambient conditions does not generate a flammable vapour above its surface, so the use of the above method [71] for Jet A1 should formally give an ignition probability of zero, since that is the area the flammable vapour would be expected to cover. Some factor, for example those expressed by Browning (see Paragraph H5.2.1.3) should therefore be included to allow for the differences between a pool of Jet A1 and a flammable gas cloud.

H5.2.1.14 The above methods are all generic and it is important to consider the specific potential ignition sources that are present, before making final estimates of the ignition probabilities for use in the QRA.

H5.3 Requirements For Ignition of Jet A1

H5.3.1.1 Jet A1, at ambient temperature in Hong Kong is below its flash point and does not produce sufficient vapour to ignite even if a strong ignition source is present above its surface. Definitions of flash point, fire point and auto-ignition temperature, relevant to this study, are provided below.

H5.3.1.2 "*The flash point of a liquid fuel is the temperature (presumed to be uniform) at which the vapor and air mixture lying just above its vaporizing surface is capable of supporting a momentarily flashing propagation of a flame when prompted by a quick sweep of a small gas flame pilot near the surface.*" (SFPE Handbook page 2-190 [25]). The minimum flash point of Jet A1 is specified as 38^{o}C, but can be higher. Some figures for kerosene (Jet A1 is a kerosene type fuel) range from 52.8-60.0^{o}C depending on test method (SFPE Handbook page 2-191, Table 2-8.1 [25]). The actual flash point for a specific batch of Jet A1 will vary, but should always be greater than 38^{o}C. Flash point may also be defined, as "the temperature at which the vapour pressure of the flammable substance is sufficient enough to give a concentration of vapour in the air that corresponds to the lower flammability limit". These two definitions are consistent.

H5.3.1.3 "*The fire point of a liquid fuel is very similar in definition to the flash point, except that the flame does not merely flash and cease, but must also be self sustained, so as to continue burning the liquid.*" (SFPE Handbook page 2-190 [25]). Also, "*The fire point consistently exceeds the flash point by about 20 to 40^{o}C.*" (SFPE Handbook page 2-190 [25]). To ignite a pool of Jet A1, we therefore expect that the temperature of the pool must be raised locally to between 58^{o}C and 100^{o}C, to support a spreading flame. At liquid pool temperatures below these, momentary ignition of splashed Jet A1 liquid or combustible vapour is expected to lead to a brief flash of flame, rather than a sustained and spreading fire.

H5.3.1.4 Vapours within the flammable range, may be ignited by ignition sources such as sparks from electrical equipment, static discharges, etc. However, a liquid pool of Jet A1 would not generally be ignitable from this type of ignition source because it is below its flash point.

H5.3.1.5 "*The autoignition temperature, T_a, of a vapor (or gas) and air mixture is the minimum temperature at which the mixture is self-igniting.*" (SFPE Handbook page 2-190 [25]). The minimum auto-ignition temperature of Jet A1 is 220^{o}C. Under less ideal circumstances, the auto-ignition temperature may be substantially higher. HSL measured auto-ignition temperatures of 690^{o}C and 540^{o}C for tests using sprays of Jet A1 onto heated surfaces [24], but Jet A1 has also been ignited when sprayed onto hot engines where the probable maximum temperature was 420^{o}C [24]. The auto-ignition temperature varies significantly with the concentration of vapour and hence these variations with the details of the test, or any practical hazard situation, are to be expected. In many circumstances, surface temperatures much higher than 220^{o}C may therefore be required to ignite Jet A1.

H5.3.1.6 It is by no means certain that flame will spread over the surface of a fuel at a temperature below its flash point, even if ignited. For example, the SFPE handbook (page 2-302 of [25]) cites investigations which "*indicate that flames do not spread away from the ignition source in liquid pools $\leq$1.5 mm deep*" (the liquid considered was decane, which is a hydrocarbon at the light end of Jet A1 components) and reproduces a figure for flame spread rate over decane showing a region of no flame spread for thin pools (Figure 2-15.7 [25]).

H5.3.2 Heating and Ignition of Jet A1 Outside the PAFF in SWS

H5.3.2.1 A number of hot processes are present within the adjacent SWS site that could heat a pool of Jet A1 running beneath them and increase the vaporisation rate. If the vaporisation rate is sufficient, then this could give rise to a flammable mixture some distance above the surface of the Jet A1. This situation is examined in the following paragraphs.

H5.3.2.2 The "hot" processes at SWS are identified by Thomas Maylor (Paragraph 29 of [21]) as:

"(a) the re-heat furnace, which operates at a temperature of 1100°C;
(b) the rolling mill, which operates at a temperature of 1000°C;
(c) flash welding, which operates at a temperature of 1200°C;
(d) the cooling bed where bars are cooled from 610°C and warehouse bays, where the rebars are stored at temperatures ranging between 230 and 100°C; and
(e) the crane conductors, which produce sparks."

H5.3.2.3 There is little question that if Jet A1 liquid physically enters the re-heat furnace then it will vaporise and ignite. It is also considered that Jet A1 encountering the flash welding process will ignite and that it would also ignite if it entered the proposed future arc furnace. However, ignition is less obvious for some of the other areas since a bulk flow of Jet A1 may not come in direct contact with the hot surfaces, but rather is expected to flow under them. Below, we examine the situation for the rolling mill.

H5.3.2.4 The rolling mill reduces steel billets of up to 150mm square (Paragraph 21 of Maylor [21]) to rebars ranging from 10mm to 50mm diameter (Paragraph 21 of Maylor [21]), at a temperature of approximately 1000°C (see Paragraph H5.3.2.2). The hot metal route appears to be at least 0.5m above the floor level (based on ESR visit to SWS and photographs in the Affirmation of Thomas Maylor [21]). Any flows of Jet A1 over the step within SWS to approach the rolling mill are expected to be shallower than those closer to the PAFF. We therefore examine the worst case effect of heating of Jet A1 beneath the hot metal route.

H5.3.2.5 The underside of a steel bar at 1000°C is taken to radiate as a black body according to Stefan's law σT^4 (Stefan's constant is taken as 5.7×10^{-8} $\mathrm{Wm^{-2}K^{-4}}$). This is a pessimistic assumption since the emissivity of the surface will be less than 1, however, it is not expected to be significantly lower than 1. This gives a thermal flux of 150 $\mathrm{kW/m^2}$, and 22.5 kW/m for the emission along the length of a 150mm wide bar.

H5.3.2.6 This flux will illuminate the surface of the Jet A1, approximately 0.5m below. If we (conservatively) assume that the liquid is static beneath the bar, then this flux will be available to vaporise Jet A1 once it has heated it up. Taking an indicative latent heat of vaporisation of 291 kJ/kg (SFPE Handbook [25] Page A-35, Table C1, for kerosene), 22.5 kW/m could vaporise ~0.08 kg/s.

H5.3.2.7 To estimate the concentration in the air flow, we take a typical height of the cloud of 0.5m (i.e. the distance to the hot surface that could ignite the vapour) and a typical air flow. Maylor states (Paragraph 30 of [21]) that "A draft of over 1m/s is created at floor level in windless conditions". An average concentration in this flow can then be estimated as: $(q_j/W_j)/(2v_a\rho_a h/W_a)$ where q_j is the mass vaporisation rate of Jet A1, v_a is the air flow speed, ρ_a is the density of air (1.2 kg/m^3), W_j and W_a are the molecular weights of Jet A1 and air, respectively (156 and 29 g.mol^{-1}) and h is the characteristic height (i.e. the height of the hot metal route). The factor of 2 arises because the convective flow is driven by the hot metal and hence the flow will be from both sides towards the hot metal route. Taking the indicative values above, gives a concentration of (0.08/156)/(2×1×1.2×0.5/29) = 1.2%. This is above the lower flammability limit of Jet A1 (0.7%).

H5.3.2.8 The above demonstrates that, it may be possible for the hot metal route to ignite a pool of Jet A1 below it. However, any of the following would reduce the vapour concentration at the hot metal surface to a level below its lower flammability limit, where ignition would not occur:

- Reduction in the metal size by a factor of ~2 in the rolling process.
- A continued flow of Jet A1, preventing the Jet A1 from heating up sufficiently to vaporise at the full rate for a stagnant pool. For example, a flow 1cm deep passing at 0.3 m/s would experience a temperature rise of only 4°C (22.5kW/m / (0.3ms^{-1} × 0.01m × 800 kg/m^3 × 2.19 kJ/kg/K)), leaving the liquid well below the fire point and leading to little vaporisation.
- Obscuration of the direct line of sight between the hot metal and the pool by the rolling line by a factor of ~50%. Within the rolling process (i.e. once the steel has passed through the furnace and flash welding regions) then the levels of equipment between the hot metal and the floor (see photographs in TGM-4 of Maylor [21]) appear to give at least this level of obscuration, and much higher in some regions.
- A higher air flow by a factor of ~2, compared with that assumed (1 m/s).
- Reduction in the metal temperature to around 800°C.
- Drainage of the Jet A1 into the grated drainage areas shown along the hot metal route (see photographs in TGM-4 of Maylor [21]).

H5.3.2.9 It is therefore ESR's view that it is by no means certain that a pool of Jet A1 flowing beneath the hot metal route in the rolling mill would ignite.

H5.3.2.10 For the cooling beds, the surface heat fluxes are at least a factor of 4 lower ((610+273)4/(1000+273)4) and for the warehouse at least a factor of 20 lower ((230+273)4/(1000+273)4). The hot bars are also smaller diameter, cooling down and more sparse. A flammable vapour significantly above the pool surface is therefore not expected in these regions. Direct contact between a bulk Jet A1 flow and the rebar in the warehouse may lead to some enhanced heating of the liquid, but is unlikely to ignite the Jet A1 directly because the temperatures are too low. Direct contact between Jet A1 and the hot metal within at least part of the cooling beds would be expected to lead to ignition. However, this is less likely due to the step within the SWS building.

H5.3.2.11 The crane conductors in the SWS warehouse are too high to provide a direct ignition source to a liquid Jet A1 pool on the ground because a flammable mixture is very unlikely to occur at these heights.

H5.3.3 Ignition Sources outside the PAFF in the EcoPark

H5.3.3.1 On the opposite side of the PAFF to SWS, lies the EcoPark development. The final details of all the processes and their locations that will be present here are not yet available, but general information is available from the EcoPark EIA [10] (this was not available at the time of the earlier EIA for the PAFF [1]). This has been reviewed to identify the nature of the potential sources of ignition in the EcoPark that could ignite a large spill of Jet A1 outside the PAFF. The main hot processes and plants summarised in the table below:

Potential Temperature	Building/Plant	Location Relative to PAFF	Hot Processes
370°C-480°C	Administration building	Adjacent to PAFF	Kitchen, Smoking Engines, exhausts etc
	Marine frontage management office	140m from PAFF	Kitchen, Smoking Engines, exhausts etc
	Marine frontage - vessel berthing loading/unloading	50m from PAFF	Engines, exhausts etc
	Road vehicle access routes	Main routes typically 100m	Engines, exhausts etc
	Road vehicle – loading unloading	Potentially vehicles next to PAFF plot limit	Engines, exhausts etc
	Solid waste collection point	50m from PAFF	Engines, exhausts etc
375 -1200°C	Fluorescent lamp processing	Adjacent to PAFF	Elemental mercury and phosphor powder thermal reduction unit
Around 1500°C	Glass recovery		Molten glass furnace
Around 500°C	Glass recovery		Glass products annealing etc
Around 100°C	Inedible rendering (organic food waste)		Continuous cooking
~1,540°C. ([10] 3.6.13)	Ferrous metal recovery		Electric arc furnace
Around 1200°C or cooler	Ferrous metal forming		Reheating and rolling
327° to 1,083°C, averaging at	Aluminium recovery		Melting and refining
	Lead recovery		Rotary/ reverbatory sweating and melting

Potential Temperature	Building/Plant	Location Relative to PAFF	Hot Processes
622°C. ([10] 3.6.13)	Zinc recovery		Sweating, melting furnaces, reduction
	Copper recovery		Sweating / furnaces
Melting point 125-175°C	Plastics	Adjacent to PAFF	Melting – fuel powered furnace

H5.3.3.2 Many of the identified ignition sources are typical of an industrial area, particularly the vehicle activity. However there are a number of specifically identified processes that may be present that operate at elevated temperatures similar to those in SWS. These include a ferrous metal arc furnace and ferrous metal forming which would be similar to the processes within SWS and would involve temperatures in excess of 1000°C. The non-ferrous metal recovery would generally operate at lower temperatures. It is not clear precisely where in the EcoPark these facilities would be located, however they are assumed to be within the Phase 1 area. Unlike SWS, it is also unclear at present what barriers to flow may be present between the PAFF and the EcoPark, although there is a clearly identified elevated planting area between Phase I and Phase II of the EcoPark (Figure 2.3a of [10]). The scale of some of the processes is also not clear and will depend on future developments.

H5.3.3.3 Caution is therefore required in identifying the potential ignition probability for the EcoPark area. A single ignition source, such as the arc furnace, within Phase 1 would result in an ignition source density of 1/8.3316 ha = 0.12 /ha, which is significantly above that assigned for generic base metal industries (0.028 /ha (H5.2.1.9)) probably due to the generally smaller scale of the facilities in EcoPark. However, it is below that identified separately for industrial areas (0.25 (H5.2.1.8)). Other ignition sources, depending on location and elevation appear more in line with general industrial area ignition sources and could reasonably be accounted for by using an ignition probability expression for industrial areas, allowing a factor for the high flash point of Jet A1.

H5.3.4 Ignition Probability Estimates Within The QRA

H5.3.4.1 The locations around the PAFF and within SWS have been divided into different regions for the purposes of ignition probability modelling as shown in Figure H5.1.

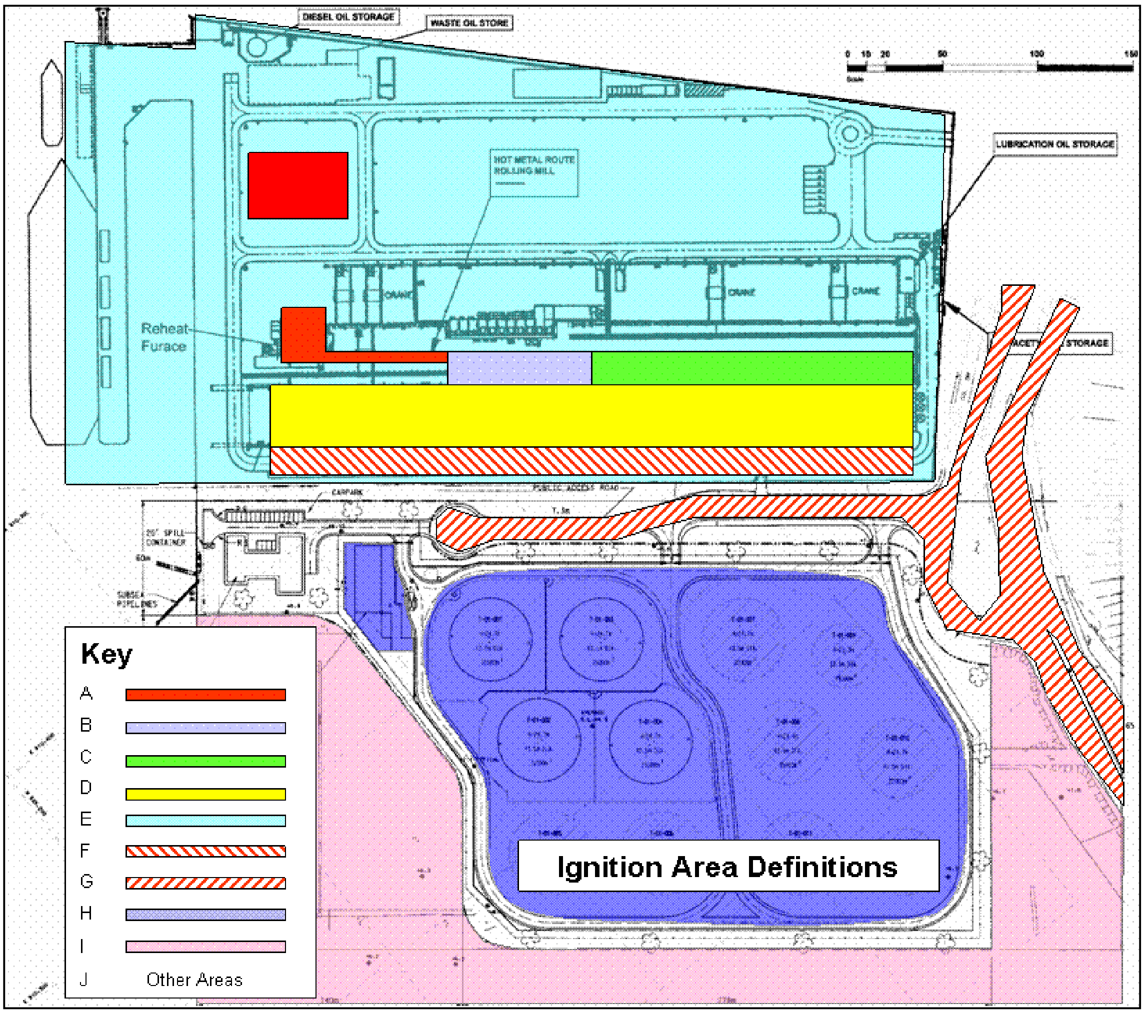

Figure H5.1: Definition of Ignition Probability Zones

H5.3.4.2 For cautious best estimate values of ignition probability we take the most appropriate flammable gas ignition probability estimates and apply a factor of 10 reduction to allow for the high flash point of Jet A1, as identified by Browning (see Paragraph H5.2.1.5). For the lower estimate, we apply the factor of 100 as identified by Browning (see Paragraph H5.2.1.5) and consistent with differences in other estimates of ignition probability for Jet A1 and flammable gases (see Paragraph H5.2.1.6). For the upper estimates we apply a factor of 0.3, since it would still be unreasonable to treat the ignition probability as equivalent to that for a flammable gas.

H5.3.4.3 Where conditions of higher vaporisation and auto-ignition are likely, modifications are made based on the analysis in Section H5.3.2.

H5.3.4.4 The following ignition probability estimates are made for each zone based on either a simple probability figure or an area dependent ignition probability calculated from an ignition source density μ and an area ignition probability p:

- Jet A1 flowing into the flash welding region or the reheat furnace (Zone A), to a depth of more than 1mm is assumed to ignite and propagate a flame back to the main flow. An ignition probability of 1 is used.

- Jet A1 flowing beneath the hot metal route at 1000°C (Zone B) in significant quantities may well ignite, but this is by no means certain. ESR's judgement is that an ignition probability of 0.5 for a flow in this area would be an appropriate cautious best estimate, with an upper estimate of 1 and a reasonable lower estimate of 0.1.

- Jet A1 flowing beneath the process regions identified as above 600°C (Zone C) is unlikely to be ignited directly, but will have a significantly enhanced vaporisation rate that could lead to a higher ignition probability. As a cautious best estimate, an area ignition probability for flammable gas in base metal industries is taken in this region, unmodified (p=1). As a lower estimate a factor of 10 reduction is applied to the source ignition probability (p=0.1) to account for the lower flammability of Jet A1 and as an upper estimate the overall ignition probability of 0.08 is used, taken for a massive oil release from Cox, Lees and Ang (see Paragraph H5.2.1.3).

- Jet A1 flowing through the warehouse area (Zone D) is unlikely to be ignited directly, and will have only a small increase in temperature and vaporisation rate, but could be ignited by other local ignition sources, e.g. welding. As a cautious best estimate for Jet A1, an area ignition probability for flammable gas in base metal industries is taken in this region, with the source ignition probability modified by a factor of 10 due to the flash point (p=0.1). For the upper estimate, a factor of 0.3 is applied (p=0.3), allowing for the potential heating, and for the lower estimate a factor of 100 reduction is taken (p=0.01).

- Jet A1 flowing in other areas within the SWS building (Zone E) is treated in the same way as Zone D, due to the various hot surfaces present.

- The vehicle bays and road within SWS (Zone F) are treated as an urban road vehicle area, and the daytime values are used throughout. This will be pessimistic because the movement of vehicles will be much less than on an urban road, however this estimate is used for simplicity and conservatism. For the cautious best estimate a factor of 10 reduction is applied to the source ignition probability (p=0.01) to account for the lower flammability of Jet A1. For the upper estimate, a factor of 0.3 is applied (p=0.03) and for the lower estimate, a factor of 0.01 is applied (p=0.001).

- The public road between the PAFF and SWS (Zone G) and other public roads are treated as an urban road vehicle area, and the daytime values are used throughout. For the cautious best estimate a factor of 10 reduction is applied to the source ignition probability (p=0.01) to account for the lower flammability of Jet A1. For the upper estimate, a factor of 0.3 is applied (p=0.03) and for the lower estimate, a factor of 0.01 is applied (p=0.001).

- Ignition within the PAFF bunded area (Zone H) is expected to be associated with limited vehicle access and hot work, etc, under permit to work procedures, since there is no significant source of heating present to vaporise the Jet A1 in normal operation, and ignition sources are specifically controlled by hazardous area classification. Ignition by the initial cause of the incident may also be possible, although this is considered unlikely for the case of Jet A1. Ignition probabilities for classified areas are not simple to evaluate, since ignition sources should be well controlled. In some cases an ignition probability of 0 has been assumed (see [72]) although this is clearly potentially optimistic. More detailed attempts to evaluate an ignition probability for classified areas have also been made recently [72] but these are subject to large uncertainty. For the purposes of this assessment, we simply assume that the classified area is equivalent to a rural area and take the daytime ignition source density of 9.9×10^{-3} /ha (see Paragraph H5.2.1.8). This is expected to be conservative, but not to greatly affect the results of the assessment. For the cautious best estimate, a factor of 10 reduction is applied to the ignition probability to allow for the low flammability of Jet A1. For the upper estimate, a factor of 0.3 is applied and for the lower estimate, a factor of 0.01 is applied. The PAFF bund area is ~4 ha, so the overall ignition probabilities for the bund are 0.004 for the cautious best estimate, 0.01 for the upper estimate and 0.0004 for the lower estimate.

- For ignition within the EcoPark (Zone I) an initial estimate could be made based on an industrial area, as for other areas, below. However, the presence of at least 1 high temperature furnace which could form a good ignition source for Jet A1 is also taken into account. This would suggest an ignition probability at the upper end (0.3) for the cautious best estimate (it is not clear that the Jet A1 would flow into such a furnace, but a higher value is justified than the usual 0.1) and an ignition source density of 1/8.3316 ha = 0.12 /ha. For a spill covering the whole area of Phase I of the EcoPark, the two assumptions give similar ignition probabilities (0.19 and 0.25). The two ignition sources expressions are combined to provide the final cautious best estimate since a degree of uncertainty remains. This gives an ignition source density of 0.25 (maximum of the two) and an ignition probability for the sources of $((0.25\times0.1+0.12\times.3)/0.25 = 0.24$. For the upper estimate, an ignition probability of 1 is applied (p=1) and for the lower estimate, a factor of 0.01 is applied (p=0.01) to cover the possible range of activities present.

- All other areas are treated as industrial areas and a daytime value of 0.25 is applied for the ignition source density. For the cautious best estimate for Jet A1 a factor of 10 reduction is applied to the ignition probability (p=0.1). For the upper estimate, a factor of 0.3 is applied (p=0.3) and for the lower estimate, a factor of 0.01 is applied (p=0.01).

- Jet A1 released onto the sea, or released from a submarine pipeline will be well below its flash point due to contact with the water. A sub sea release from the submarine pipeline will also entrain water in the rising Jet A1 plume leading to some of the oil being emulsified at the surface and the plume may break up into smaller surface pools. A Jet A1 pool on the sea will generally be more difficult to ignite than a Jet A1 pool on land. The most volatile fractions will also vaporise most quickly as the Jet A1 spill "weathers", and the action of wind and waves may emulsify the spill, making the resulting surface spill more difficult to ignite. For the cautious best estimate (allowing for a large degree of uncertainty) we take the oil leak ignition probabilities from Cox, Lees and Ang (see Paragraph H5.2.1.3) with a factor of 10 reduction applied to the ignition probability to allow for the lower flammability of Jet A1. The same figure is used for the upper estimate, whilst a factor of 100 reduction is applied for the lower estimate.

- For aircraft impact on a PAFF tank, resulting in instantaneous failure of the tank, an ignition probability of 1 is taken, due to the impact energy, aircraft engines, etc.

H5.3.4.5 Note that the ignition probability for general areas within SWS is identified as lower than for other surrounding areas for the PAFF. This is because the main potential ignition sources are identified separately within SWS, whereas the ignition probability for the surrounding area (e.g. SIA) includes all the potential ignition sources.

Location			Ignition Probability Estimate		
			Lower Estimate	Cautious Best Estimate	Upper Estimate
A	Reheat furnace and flash welding (plus future arc furnace)		1	1	1
B	Rolling Mill above $1000^{o}C$		0.1	0.5	1
C	Cooling Beds ($600^{o}C$)		$\mu=0.028$ $p=0.1$	$\mu=0.028$ $p=1$	0.08
D	Warehouse bays		$\mu=0.028$ $p=0.01$	$\mu=0.028$ $p=0.1$	$\mu=0.028$ $p=0.3$
E	General areas within SWS		$\mu=0.028$ $p=0.01$	$\mu=0.028$ $p=0.1$	$\mu=0.028$ $p=0.3$
F	Vehicle bays and road within SWS		$\mu=0.51$ $p=0.001$	$\mu=0.51$ $p=0.01$	$\mu=0.51$ $p=0.03$
G	Public road between PAFF and SWS and other public roads		$\mu=0.51$ $p=0.001$	$\mu=0.51$ $p=0.01$	$\mu=0.51$ $p=0.03$
H	Within PAFF Bunds		0.0004	0.004	0.01
I	EcoPark		$\mu=0.25$ $p=0.01$	$\mu=0.25$ $p=0.24$	$\mu=0.25$ $p=1$
J	All other surrounding land areas		$\mu=0.25$ $p=0.01$	$\mu=0.25$ $p=0.1$	$\mu=0.25$ $p=0.3$
-	Ignition of spills on sea	<1 kg/s	0.0001	0.001	0.001
		1-50 kg/s	0.0003	0.003	0.003
		>50kg/s	0.0008	0.008	0.008
-	Aircraft impact on PAFF tank		1	1	1

$P_{ign} = 1 - \exp(-\mu A p)$, where:

P_{ign} is the ignition probability for the spill in the area
μ is the ignition source density per hectare
A is the area covered by the liquid spill in hectares
p is the ignition probability for each individual ignition source