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Fire Safety Concerns on Residential Areas Located Adjacent to Oil Tanks

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Abstract

Hong Kong is a dense urban city with very limited usable area. Flammable liquid storage tanks and LPG storage have to be placed near to the residential areas, highways and flight paths. It is estimated that oil tank fire can go up to 700 MW when there is any accident in fuel storage areas. The heat flux emitted to the near residential estate would be as high as 17 kWm^{-2}. Such big fire would not only affect health and safety of the citizen, but also disrupt the operation of the whole city for a very long time. Therefore, hazard assessment of oil tank fire should not only include several small fire scenarios. Proper fire safety measures and provisions for big fires should be developed. These issues will be discussed in this paper with simple empirical expression derived from fire dynamics. Advanced technologies, such as fire robots, are recommended to facilitate fighting against big fires.

Symbols List

A fire pool area in m^2

a calculation parameter for view factor

b calculation parameter for view factor

D diameter of fire ball in m

d diameter of pool fire in m

E emissive power of the fire in kW m^{-2}

F total view factor

F_H view factor of horizontal part

F_V view factor of vertical part

H flame height in m

Δh heat of combustion in MJ kg^{-1}

l calculation parameter for view factor

m burning rate of fuel in kg s^{-1} m^{-2}

m_f mass of fuel leaked in kg

Q heat released in fire in kW or otherwise specified

q heat flux in kW m^{-2}

R distance from the centre of fire pool or flame in m

s calculation parameter for view factor

t time of fire lasted in s

χ radiative fraction of heat conveyed from a fire

ε emissive power of the fire ball in kW m^{-2}

τ air transmitivity

1. Introduction

Although Hong Kong is densely populated today, Tsing Yi Island was a piece of waste land 30 years ago. Therefore, many oil tanks were allocated in the area. However, it is now an urban area with many public housing estates and private residential buildings and lies underneath the entrance flight path to the Chek Lap Kok airport with many public estates and private apartments. The storage of large volume of flammable materials in fuel tanks and LPG storages near residential areas has led to grave concerns of the public. Residents living on this island worry about the fire safety problem [1-7]. The oil tank companies claimed [8] in 1988 that safety provisions are adequate, even saying that people staying in buildings next to the oil tanks are better protected. Key fire safety provisions specified in the local Fire Service Installation (FSI) [9] are very limited. Apart from a risk management scheme which was released to the general public in the 1980s [10,11], there are no reported fire hazard assessments of the oil tanks that are supported by full-scale experimental studies.

In the past, big oil tank fires had occurred in other countries, such as that in Japan after the severe earthquake [12] and the Buncefield Incident [13]. On 2 August 2003, a very big fire occurred [e.g. 14,15] in an illegal warehouse which stored highly flammable liquids in Macau. The fire lasted for over 10 hours, generating large amount of pollutants discharged to the upper atmosphere. Furthermore, several big fires had occurred in the shopping area on Fa Yuen Street [16] and in the Lion Rock Tunnel [17]. It is difficult to conclude that the residential buildings located next to oil tanks in Tsing Yi are well protected against the big fires. The hidden problem behind the oil tank fire in residential areas was raised again [18].

Wind action is a transient phenomenon depending on the ambient conditions. Fire will spread rapidly with the presence of strong wind [e.g. 19]. In addition, buildings adjacent to taller buildings or hillside might give a very complicated air flow pattern [e.g. 20,21]. Smoke and even flame would spread in a very complex manner. The simulated fire environment of burning a gas station adjacent [22] to a high-rise building was very hazardous.

2. Fire Protection Systems Adopted

There are five petrol chemical storage sites on Tsing Yi Island, which were constructed at different times. Some were constructed many years ago. Public and private residential occupancies are located within 1 km radius of those storage plants, as shown in Figure 1. Fire safety provisions in the oil tanks were therefore not designed up to the current standards and codes published afterwards [23]. Some new tanks were constructed with fire protection that complies with the codes in 1992 [23].

It should be noted that only the construction requirements of the premises were covered by this code [23]. Active fire safety provisions should follow the FSI Codes [9]. Although the FSI codes had been upgraded and updated several times in the last two decades, very few changes in the requirements for the FSI were specified in this type of occupancy. No specified fire safety strategy is specified to handle any possible big disasters. This might be due to the high cost involved and other external factors and their consequence in storing suppressing agents. For example, a fire that broke out in a fuel storage with a capacity of about 200,000 tonne in London [13] would use up 250 m^3 foam concentration and 55,000 m^3 water [13]. Performance of FSI in handling possible fire hazards in those existing oil tanks should be evaluated properly under big fires. Effect of strong heat flux and high smoke volume on residents nearby should be watched. Special fire fighting [13] technologies for handling such big fires and the environmental impact of discharging a large amount of foam should be considered.

As listed, in the safety assessment report for storage area [24,25] and other publications [26] by oil companies, some cases were portrayed as very low risk to the public. There are reported incidents such as The Buncefield Incident, which was caused by overfilling the oil tanks [27]. Therefore, the safety measures developed and implemented by the oil companies should be further reviewed. There are queries on the “proper adoption” of “design data” in risk assessments and sensitivity analysis [26]. Proper public announcement scheme and the emergency plans after big disasters are not clearly illustrated. As reported by the investigators of the Buncefield Incident, the safety and environment of the communities should be taken into account [28]. Risk assessment and updated code requirement should be watched out and amended accordingly.

3. Possible Fire Sizes Reviewed

Fire engineering data of such local oil tanks were published in the literature [25,29]. It is possible that they are using parameters determined overseas. In NFPA handbook, the largest value of possible fire in oil storage area, i.e. the design fire size for an oil truck of 100 MW [30], might be used. The possible fire scenario was taken as a "pool" fire on oil spillage.

There was a proposal to erect an A1 jet fuel storage plant with a capacity of 400,000 m^3 [31] in Hong Kong . The size is even bigger than the large-scale oil export terminal in Russia [32]. Therefore, based on the pool fire area in the risk assessment of that large-scale oil export terminal [32], the possible fire sizes for the fuel stored locally are shown in Table 1.

Values calculated are based on the data found in the literature about burning rate m (in $kgs^{-1}m^{-2}$), heat released in fire Q (in kW) [33] in terms of the pool fire area A (in m^2), and heat of combustion Δh (in $MJkg^{-1}$) with the following formula :

$$Q = m \times A \times \Delta h \qquad (1)$$

The fire sizes range from 695 MW to 475 GW, which are much bigger than the values used in common fire cases. As reported in the news [29], consultant said that there is extremely low chance of such a fire outbreak. A big fire was claimed to happen only at most twice per billion years, taking reference from the overseas experiences. However, it is dangerous to apply overseas standards [e.g. 30] directly in Hong Kong. That is because the living style, education, social awareness, citizen responsibility and types of housing are extremely different from those in USA. Even fire dampers for fire resistance separation were not checked properly until one year after occupying the building, leading to complaints! Therefore, it is very difficult to justify the assumption that the chance of having a big fire is so low. Several fire cases related to oil storage were found in the media [34-40]. Two questions commonly asked on possible fire cases are:

- Are there adequate fire control facilities?
- Has the society prepared to pay for the possible consequences after big disasters?

These two points would be discussed in next section.

4. Impacts of Big Fires

In order to assess the effectiveness of the previous assessments, the historical development of Tsing Yi Island is described here. In the old days, Tsing Yi Island was not densely populated and traffic load was lower. But in the last few decades, large-scale infrastructure projects, such as the relocation of airport, expansion of transportation network, and the construction of new highways, were carried out on Tsing Yi Island. The highways were built on the hill side next to the storage plants. Airplanes would fly over the island in designated flight paths [41]. Therefore, the impacts of big fires may be imposed on the occupancies in the surrounding buildings, the vehicles moving on the highways and even the aeroplanes in the sky [42].

If a big fire breaks out in oil tanks, it will be an environmental disaster. [13] It would not just affect the territory that the fire breaks out, but also other countries across the sea [43]. Combustion products, including CO, CO_2, NO_x, soots and other toxic aerosols, are pollutants. Human, animals and crops will be harmed by breathing in poisonous gas; water sources will be contaminated if the pollutants are dissolved in water sources. Therefore, acid rains ruin the plants.

Radiation heat from original fire source can cause the collapse of storage tank [44]. The fire can be expanded exponentially due to the chain reactions of storage tank rapture, until all tanks are on fire. Besides, strong heat flux and heavy smoke will have thermal impacts and induce health problems on firemen. The heat flux q (in kWm^{-2}) at distance R (in m) from the centre of the fire pool is calculated based on literature data [45] on heat release rate Q (in kW) through a radiative fraction χ (taken to be 0.2 for minimum values and 0.45 for maximum values):

$$q = \frac{\chi Q}{4\pi R^2} \quad (2)$$

or by empirical formula developed by Shokri and Beyler [46] based on R and diameter of pool fire d (in m):

$$q = 15.4\left(\frac{R}{d}\right)^{-1.59} \quad (3)$$

Using equations (2) and (3), the estimated values of q at distances 0.5 km and 1 km are shown in Tables 2 and 3 respectively.

A more detailed calculation is carried out based on another method developed by Shokri and Beyler. The equation takes the flame, height and view factor into consideration [46]. Heat flux q can be calculated by using estimated flame height H (in m), emissive power of the fire E (in kWm^{-2}), and max view factor on the ground F. The formulas are shown in reference [46] and summarized as below.

$$q = E \cdot F \quad (4)$$

where

$$E = 58(10^{-0.00823d}) \quad (5)$$

and

$$F = \sqrt{F_H^2 + F_V^2} \tag{6}$$

The vertical and horizontal view factors F_H and F_V on the ground are:

$$F_H = \frac{b - \frac{1}{s}}{\pi\sqrt{b^2 - 1}} tan^{-1} \sqrt{\frac{(b+1)(s-1)}{(b-1)(s+1)}} - \frac{a - \frac{1}{s}}{\pi\sqrt{a^2 - 1}} tan^{-1} \sqrt{\frac{(a+1)(s-1)}{(a-1)(s+1)}} \tag{7}$$

$$F_V = \frac{1}{\pi s} tan^{-1} \frac{1}{\sqrt{s^2 - 1}} - \frac{1}{\pi s} tan^{-1} \sqrt{\frac{(s-1)}{(s+1)}} + \frac{ah}{\pi s\sqrt{a^2 - 1}} tan^{-1} \sqrt{\frac{(a+1)(s-1)}{(a-1)(s+1)}} \tag{8}$$

where a, b, s and l are shown in the literature [46].

$$H = 0.23Q^{0.4} - 1.02d \tag{9}$$

The calculated results for q at different H are shown in Table 4. The heights of the highways are below 100 m [47], but values of H range from 55 to 308 m in tall buildings in Hong Kong [9]. Therefore, there are great chances for the flame to spread to the vehicles, drivers and passengers. The heat fluxes would be higher than the values listed in Tables 2 to 4. Residents are likely to be affected.

The available time for evacuation should be estimated to avoid any casualties. The threshold is

40 s with 10 kWm^{-2} exposure [48]. It should be noted that threshold values for high thermal exposures are evaluated by a log-log scale. Based on the maximum values of q at 0.5 km, 1 km and 2 km away from the fire in Table 2, the maximum exposure times are about 2.33 s, 14.6 s and 91 s respectively. Under such high heat fluxes, the occupants will be in danger in a short time. Emergency evacuation will also be affected with the total evacuation times extended.

High heat flux will also obstruct the deployment of the fire brigade and affect the proper functioning of the fire engines. These problems would lower the effectiveness of firefighting. When it is difficult for the firemen and water jets to approach the fire source, water jets would drag down the dark smoke, lowering visibility in the area.

However, all assessment reports of oil plants or storage tanks only address the issues related to design premises; the impact on the oil complex due to external factors (excluded arson) are not discussed. There is no reinforcement to prevent travel accidents, for example a bus falling off the bridge, a case that happened at Ting Kau in 2003 [49]. If a similar case occurs in the highway next to the petrol chemical complex, it will be a nightmare in Hong Kong. Note that the exits of tunnels are pointing west, giving higher chance of traffic accidents in the afternoon as cars are driving towards sunset.

5. LPG Storage

Besides accidental leakage of flammable liquids of the oil tank, there are also explosion risks in LPG storage area. Those explosions would generate big fires ball and heat flux in the area. An example of estimating thermal radiation impact of explosion of LPG in storage area was illustrated [44].

Local situation should be assessed based on the storage capacity, and a site survey should be carried out to evaluate the values in the areas. Unfortunately, a close observation is not welcome and high power telescope must be utilized for long-range observation. Only ball shape LPG storage tanks were found while there are no clear labels of the storage vessels as shown in Figure 1. It is difficult to differentiate LPG storage from other oil tanks, especially for those underground tanks and other new LPG storage tank [8]. Therefore, the estimations were only based on the announced design capacities of LPG [13,50] of 3000 Mg and 5850 Mg.

The heat flux q generated by the explosion of the above storage tanks can be calculated by air transmitivity τ (taken to be 0.63) and emissive power of the fire ball ε (in kWm^{-2}):

$$q = \varepsilon F \tau \tag{10}$$

ε is given in terms of the mass of leaked LPG m_f (kg) as:

$$\varepsilon = \frac{0.343 \Delta h m_f}{R^2 t} \tag{10a}$$

F is the view factor calculated by the diameter of the fire ball D (in m) and time of fire ball lasted t_L (in s):

$$F = \frac{D^2}{4R^2} \tag{10b}$$

The calculated diameter of the fire ball can be over 100 m. As mentioned in last section, the thermal impact on the surroundings is also significant under the explosion of LPG tanks. The maximum calculated results at 0.5 km, 1 km and 2 km are 2.37 kWm^{-2}, 0.593 kWm^{-2} and 0.148 kWm^{-2} respectively.

6. Fire Safety Systems Proposed

In the existing FSI codes, two classifications of premises are related to this topic – bulk fuel storage and petro-chemical complexes [9]. The fire safety requirements in those two classes are listed in the codes. Those oil storage sites were erected decades ago. Although there is a long list of specified requirements, it is not demonstrated that providing such requirements work for these premises. Further, requirements were only based on those listed in the codes before the 1987 edition [51]. In these years, the only amendments made were the elimination of audio/visual advisory systems and the incorporation of visual alarm into fire alarm system. Therefore, an in-depth review is necessary.

Two points should be noticed:

- Point 1: Actual performance of systems in real situations

Note that Testing and Commissioning of the new systems and regular inspections were carried out when the premises are not operating. The corresponding noise and visual obstructions influencing the actual performance of fire alarm system should be taken into consideration.

- Point 2: Coverage of systems

In such high risk premises, fire detection systems should be provided. Fire detection systems can respond faster so that the occupants can be evacuated within a short time. Other requirements are also based on lots of engineering judgments. Fire safety would rely on whether the engineering designs are holistic and rigorous enough.

The existing fire system was claimed to would work well [8,24]. However, a court case on an environmental assessment report aware the public to review the quality of many engineering projects [52]. More comprehensive and illustrative engineering approaches should be addressed accordingly.

Therefore, a thorough understanding of the actual system performance is a must. Some improvement work is required such as water shell to cover the related area in order to lower the radiative heat imposed on other area. Pure water could be used as shell for heat absorption, but foam solution should be used to protect adjacent tanks. The effectiveness of existing foam systems depends on the design of coverage and prompt activation. Surrounding tanks may receive much more heat than designed when the activation of the foam system is slower than expected. Of course, the heat received may not be high enough to heat up the flammable fuels to self-ignition points, but it can increase the chance of explosion [32]. This approach can limit the oxygen supply to the tanks. Also, the foam blanket can serve as another pressure wave absorber in case of explosion. Hence, the spilled flammable fuels would not be ignited due to the foam blanket. This design required higher foam concentration. Foam systems should be reviewed and it should be ensured that there is sufficient foam concentration supply in case of big fire. This is a precautionary measure to avoid the same problem once occurred in London [53].

Fire robots could also be useful in handling big fires in terms of effectiveness. Firemen will not be subject to toxic gas, and their health and safety are better protected. These robots can be mobile or fixed at certain key points for surveillance. They be equipped with fire fighting tools and provide more information to assist in emergency operation.

All these proposed safety systems are criticized as ‘excessive’ by some parties. Huge amount of resources will be lost after big fires. Foam solution discharged in small fires would damage the environment. However, the consequences would not turn as disastrous if this approach were used in the London case [13]. The direct loss could be reduced significantly than estimated [13]. Further, indirect cost for medical and health care of injured personnel should be taken into account. The problems could last for decades [54].

7. Conclusion

Possible fire sizes were determined by the corresponding heat flux imposed on the occupants at various distances away from the storage tanks by different methods. There are serious consequences under big fires. The current practice [8,9,11] in fire safety analysis should be improved by considering more hazardous scenarios and their consequences [18].

Based on the results of detailed and rigorous analysis, the fire safety management should be improved immediately. Additional fire safety installations might limit the impacts on the adjacent areas in case of hazardous fire. This explains why the nearby residents are yelling out for more protection [1-7,25,29,31]. It is easy to say the big oil tanks are safe even though they are located next to residential area. However, a question should be asked:

Where are the theoretical estimation and experimental evidence to support the claim that the protection system will work in a big fire?

Ignoring the possibilities of having big disasters is very hazardous. Residents living nearby would be significantly affected [34-42]. Emergency management plan should be worked out in face of possible disaster. Firemen and other first respondents would face big challenges. Appropriate training and adequate fire suppression equipment should be provided.

8. Additional Comments

The paper was published as a journal paper [55]. With the practice of publisher, preprint is allowed to upload at a website. There are further studies on this topic [56-71].

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JAFS_OilTankF120123B

Record:
A464UL22-1a (opened 25 July 2023, open from JAFS_OilTankF120123B)
A464UL22-1b (opened 29 August 2023)

Table 1: Estimations on possible fire sizes in a petrol chemical complex

A (m^2)	Q (MW)			
	LPG	Gasoline	Kerosene	Heavy fuel oil
500	2277	1202	842	695
680	3097	1634	1146	945
880	4008	2115	1483	1223
1060	4827	2548	1786	1473
1660	7560	3990	2797	2307
3400	15484	8172	5728	4724
3600	16394	8653	6065	5002
4200	19127	10095	7076	5836
4800	21859	11537	8087	6670
5800	26413	13940	9772	8059
9000	40986	21632	15163	12506
10600	48272	25477	17859	14729
11500	52371	27640	19375	15979
14100	64211	33889	23756	19592
17200	78329	41340	28979	23899
17400	79240	41821	29316	24177
18000	81972	43263	30326	25011
20000	91080	48070	33696	27790
26700	121592	64173	44984	37100
34800	158479	83642	58631	48355
104200	474527	250445	175556	144786

All values calculated are based on the burning rate and heat release data by Babrauskas and Grayson (1992).

Table 2: Range of incident heat flux on the ground

Q (MW)	Distance	q (kWm^{-2})					
		0.5 km		1 km		2 km	
Min	Max	Min	Max	Min	Max	Min	Max
695	2277	0.044	0.326	0.011	0.082	0.003	0.020
945	3097	0.060	0.444	0.015	0.111	0.004	0.028
1223	4008	0.078	0.574	0.019	0.144	0.005	0.036
1473	4827	0.094	0.692	0.023	0.173	0.006	0.043
2307	7560	0.147	1.083	0.037	0.271	0.009	0.068
4724	15484	0.301	2.219	0.075	0.555	0.019	0.139
5002	16394	0.319	2.350	0.080	0.587	0.020	0.147
5836	19127	0.372	2.741	0.093	0.685	0.023	0.171
6670	21859	0.425	3.133	0.106	0.783	0.027	0.196
8059	26413	0.513	3.785	0.128	0.946	0.032	0.237
12506	40986	0.797	5.874	0.199	1.468	0.050	0.367
14729	48272	0.938	6.918	0.235	1.730	0.059	0.432
15979	52371	1.018	7.505	0.254	1.876	0.064	0.469
19592	64211	1.248	9.202	0.312	2.301	0.078	0.575
23899	78329	1.522	11.225	0.381	2.806	0.095	0.702
24177	79240	1.540	11.356	0.385	2.839	0.096	0.710
25011	81972	1.593	11.748	0.398	2.937	0.100	0.734
27790	91080	1.770	13.053	0.443	3.263	0.111	0.816
37100	121592	2.363	17.426	0.591	4.356	0.148	1.089
48355	158479	3.080	22.712	0.770	5.678	0.192	1.419
144786	474527	9.222	68.005	2.306	17.001	0.576	4.250

Table 3: Incident heat flux on the ground

A (m^2)	d (m)	q (kWm^{-2})		
		0.5 km	1 km	2 km
500	25	0.133	0.044	0.015
680	29	0.170	0.057	0.019
880	33	0.209	0.069	0.023
1060	37	0.243	0.081	0.027
1660	46	0.347	0.115	0.038
3400	66	0.613	0.204	0.068
3600	68	0.641	0.213	0.071
4200	73	0.725	0.241	0.080
4800	78	0.806	0.268	0.089
5800	86	0.937	0.311	0.103
9000	107	1.328	0.441	0.147
10600	116	1.513	0.503	0.167
11500	121	1.614	0.536	0.178
14100	134	1.898	0.631	0.209
17200	148	2.223	0.738	0.245
17400	149	2.244	0.745	0.248
18000	151	2.305	0.766	0.254
20000	160	2.506	0.833	0.277
26700	184	3.154	1.048	0.348
34800	211	3.893	1.293	0.430
104200	364	9.310	3.092	1.027

Table 4: Range of incident heat flux on the ground

H (m)		q (kWm^{-2})					
		0.5 km		1 km		2 km	
Min	Max	Min	Max	Min	Max	Min	Max
24	55	8.256	8.259	8.628	8.628	8.811	8.811
26	61	7.510	7.514	7.912	7.912	8.110	8.110
28	67	6.851	6.857	7.277	7.277	7.486	7.486
30	71	6.361	6.368	6.801	6.802	7.017	7.018
34	83	5.150	5.160	5.617	5.618	5.845	5.845
40	106	3.252	3.271	3.720	3.722	3.947	3.947
41	108	3.110	3.129	3.576	3.578	3.801	3.801
42	113	2.737	2.759	3.193	3.195	3.413	3.413
44	119	2.429	2.452	2.874	2.876	3.088	3.088
45	126	2.018	2.044	2.443	2.446	2.648	2.648
49	146	1.207	1.241	1.569	1.572	1.741	1.741
51	154	0.962	0.998	1.294	1.297	1.452	1.453
52	158	0.852	0.889	1.169	1.172	1.319	1.320
53	169	0.611	0.650	0.888	0.891	1.019	1.020
55	180	0.423	0.464	0.659	0.663	0.771	0.772
55	180	0.413	0.455	0.647	0.651	0.758	0.759
55	182	0.386	0.428	0.613	0.617	0.721	0.721
56	188	0.309	0.351	0.515	0.518	0.612	0.613
57	206	0.152	0.196	0.302	0.305	0.373	0.374
58	223	0.067	0.109	0.171	0.174	0.222	0.222
51	308	--	--	0.005	0.006	0.010	0.010

(a) Western part

(b) Southern part

Figure 1: Storage tanks in Tsing Yi Island