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Risk Evaluation for Fire and Explosion Accidents in the Storage Tank Farm of the Refinery

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Dow's fire & explosion index (F&EI) evaluation method and accident tree analysis (ATA) are used to conduct qualitative analysis and quantitative analysis over the risk of fire and explosion accidents in the storage tank farm of a large refinery. Firstly, Dow's F&EI evaluation method is used to conduct the safety evaluation for six storage tanks in the refinery. F&EI evaluation results show that the LPG (liquefied petroleum gas) spherical tank has the highest fire and explosion risk, which may reduce the hazard level of the tank to some extent after compensation through safety measures. Furthermore, ATA is used to analyze the fire and explosion accidents of LPG spherical tank, obtain minimal cut set (MCS) that affect the top event, calculate and sort the structural important degree of basic event, confirm the primary factors which affect the accident of the LPG spherical tank, and put forward appropriate prevention measures, thus improving the safety and operation reliability of LPG spherical tank.

1. Introduction

A large refinery is featured by many types of products, large storage volume, and flammable and explosive materials in the tank, resulting in greater chance of fire and explosion accidents. And once an accident occurs, it is easy to result in chain reactions, thus causing significant losses and major social influence (Liu, 2011). Hence, in order to avoid such accidents, it is of great significance to conduct the qualitative and quantitative safety evaluation studies on the fire and explosion accident risks of the tank farm in the refinery (Dong et al., 2012). In this study, the refinery has a crude oil production capacity of 1000×104 tons/year. Covering an area of 2.4km^2, the plant is mainly divided by function into process installation area, storage and transportation area, public utility and auxiliary facility area and pre-plant management area. The plant mainly consists of crude oil tank farm, intermediate raw material tank farm, product tank farm and pressure tank farm, etc. Volumes of crude oil tank, gasoline tank, diesel tank, propylene spherical tank, liquefied petroleum gas (LPG) spherical tank, and benzene are 100,000m^3, 30,000m^3, 30,000m^3, 2,000m^3, 3,000m^3 and 3,000m^3, respectively. Through identification of major hazard installations for dangerous chemicals (GB18218-2009), it can be seen that the storage and transportation system constitutes a major hazard installation. The hazard level of the tank farm is Level I (Sinopec Group, 2008).

2. Dow's fire & explosion index evaluation method (7th edition)

2.1 Selection of material factor (MF)

Material factor (MF) is an inherent characteristic that indicate the energy released by the material in the fire or explosion arising from ignition or other chemical reactions. The material factor (MF) of each unit component is obtained from the following table.

2.2 Calculation general process hazards factor (F_1)

General process hazards are main factors for determining the damage of an accident, including six items such as Exothermic reaction(A), Endothermic reaction(B), Material processing and transportation (C), Enclosed or indoor process unit(D), Passageway(E), and Discharge and leakage control(F). Appropriate factors are selected based on the specific situation and input in the calculation table. And these hazards factors are added to result in general process hazards factor of the unit (F_1) in Table 1. Basic factor is 1.

Table 1: Calculation general process hazards factor (F_1)

Evaluation of storage tank		Crude oil tank	Gasoline tank	Diese l tank	Propylene spherical tank	LPG spherical tank	Benzene tank
Material factor (MF)		16	16	10	21	21	16
Item	Hazards factor range						
A	0.30-1.25						
B	0.20-0.40						
C	0.25-1.05	0.40	0.40	0.40	0.40	0.40	0.40
D	0.25-0.90						
E	0.20-0.35						
F	0.25-0.50	0.25	0.25	0.25	0.25	0.25	0.25
F_1		1.65	1.65	1.65	1.65	1.65	1.65

2.3 Calculation special process hazards factor (F_2)

Special process hazards are main factors that affect the occurrence possibility of an accident, including twelve items such as toxic materials (0.2×NH) (A), Negative pressure (< 500mmHg)(B), Operation within or near explosion limit (C), Dust explosion(D), Pressure(E), Low temperature(F), Flammable and unstable substances(G), Corrosion and abrasion(H), Leakage— joint and filler(I), Equipment using open flame(J), Hot-oil heat exchange system (K) and Rotating equipment(L). Basic factor is 1.

Table 2: Calculation special process hazards factor (F_2)

Evaluation of storage tank		Crude oil tank	Gasoline tank	Diesel tank	Propylene spherical tank	LPG spherical tank	Benzene tank
Material factor (MF)		16	16	10	21	21	16
Item	Hazards factor range						
A	0.20-0.80	0.2	0.2	0.2	0.2	0.2	0.4
B	0.50						
C		0.50	0.50	0.50	0.50	0.50	0.50
D	0.25-2.00						
E		0.20	0.20	0.20	0.50	0.50	0.20
F.	0.20-0.30						
G		1.7	1.1	1.2	1.7	1.8	1.0
H	0.10-0.75	0.30	0.20	0.10	0.10	0.10	0.2
I	0.10-1.50	0.30	0.30	0.30	0.30	0.30	0.30
J							
K	0.15-1.15						
L	0.5						
F_2		4.2	3.5	3.5	4.3	4.4	3.6

2.4 Calculation of process unit hazards factor (F_3)

Process unit hazards factor (F_3) is the product of general process hazards factor (F_1) and special process hazards factor (F_2): $F_3=F_1\times F_2$; F_3 ranges between 1~8 normally. Generally, it does not exceed 8.0. If F_3 is greater than 8.0, it shall be calculated at the maximum of 8.0.

2.5 Calculation of fire & explosion index (F&EI)

Fire & explosion index (F&EI) is used to estimate and evaluate the possible damage arising from the accident occurred in the process unit. It is the product of material factor (MF) and process unit hazards factor (F_3), F&EI = MF×F_3. F&EI calculation results are listed in Table 3.

Table 3: Calculation table of fire & explosion index

Evaluation of storage tank	Crude oil tank	Gasoline tank	Diesel tank	Propylene spherical tank	LPG spherical tank	Benzene tank
$F_3 = (F_1 \times F_2)$	6.9	5.8	5.8	7.1	7.3	5.9
$F\&EI = F_3 \times MF$	110	93	58	149	153	94
Degree of hazard	Medium	Mild	Mildest	Significant	Significant	Mild

2.6 Determination of compensation factor (C_0)

Table 4a: Summary of process control safety precautions factor (C_1)

Item	Compensation factor range	Crude oil tank	Gasoline tank	Diesel tank	Propylene spherical tank	LPG spherical tank	Benzene tank
a	0.98	0.98	0.98	0.98	0.98	0.98	0.98
b	0.97-0.99				0.98	0.98	
c.	0.84-0.98				-	-	
d.	0.96-0.99	0.98	0.98	0.98	0.98	0.98	0.98
e.	0.93-0.99	0.98	0.98	0.98	0.97	0.97	0.97
f	0.94-0.96				-	-	0.95
g	0.91-0.99	0.94	0.94	0.94	0.94	0.94	0.94
h	0.91-0.98				-	-	
i	0.91-0.98	0.94	0.94	0.94	0.94	0.94	0.94
C_1		0.83	0.83	0.83	0.8	0.8	0.78

Table 4b: Summary of material isolation safety precautions factor (C_2)

Item	Compensation factor range	Crude oil tank	Gasoline tank	Diesel tank	Propylene spherical tank	LPG spherical tank	Benzene tank
j	0.96-0.98	0.98	0.98	0.98	0.98	0.98	0.98
k	0.96-0.98	0.98	0.98	0.98	0.98	0.98	0.98
l	0.91-0.97	0.98	0.98	0.98	0.98	0.98	-
m	0.98	0.98	0.98	0.98	0.98	0.98	0.98
C_2		0.92	0.92	0.92	0.92	0.92	0.94

Table 4c: Summary of fire prevention facility safety precautions factor (C_3)

Item	Compensation factor range	Crude oil tank	Gasoline tank	Diesel tank	Propylene spherical tank	LPG spherical tank	Benzene tank
n	0.94-0.98	0.98	0.98	0.98	0.98	0.98	0.98
o	0.95-0.98	0.98	0.98	0.98	0.98	0.98	0.98
p	0.94-0.97	0.94	0.94	0.94	0.94	0.94	0.94
q	0.91				0.91	0.91	
r	0.74-0.97						-
s	0.97-0.98						
t	0.92-0.97	0.97	0.97	0.97	0.97	0.97	0.97
u	0.93-0.98						
v	0.94	0.94	0.94	0.94	0.94	0.94	0.94
C_3		0.82	0.82	0.82	0.75	0.75	0.82
$C_0=C_1 \times C_2 \times C_3$		0.63	0.63	0.63	0.55	0.55	0.60

Selecting proper Safety compensating measures can effectively prevent accident from happening, lowering the maximal possible property loss to an acceptable level. Security measures may be divided into three classes: process control (C_1), material isolation (C_2) and fire prevention facility (C_3). $C_0=C_1 \times C_2 \times C_3$. Process control ($C_1$) include Emergency power supply(a), Cooling device(b), Explosion inhibition device (c), Emergency cut-off device(d), Computer control(e), Inert gas protection (f), Operation procedure (g), Inspection of chemically active substances(h) and Analysis on other process hazards(i); fire prevention facility (C_3).
Material isolation safety precautions factor (C_2) include Remote valve(j), Discharge/draining device(k), Emission system(l) and Interlock device(m).

Fire prevention facility safety precautions factor (C3) include Leakage testing device(n), Structural steel(o), Firefighting water supply and drainage system(p), Special fire-extinguishing system(q), Sprinkler fire-extinguishing system(r), Water curtain(s), Foam fire-extinguishing device(t), Handheld fire-fighting device(u) and Cable protection(v).

2.7 Determination of influence radius and exposure area

Influence radius is determined by the following steps: obtaining exposure radius R by look up the diagram based on the value 0.84×F&EI, and calculating the exposure area S: $S=\pi R^2$, where R is exposure radius in m.

2.8 Calculation of MPPD

MPPD refers to maximal possible property damage and may be classified into basic MMPD and actual MPPD, as shown in Table 5. Basic MPPD = Property value within the affected area×DF; Actual MPPD = Basic MPPD×Compensation factor C_0.

Table 5: Summary of Dow's F&EI results for the tanks (RMB 10,000)

Equipment evaluated / Hazard indicator	Crude oil tank	Gasoline tank	Diesel tank	Propylene spherical tank	LPG spherical tank	Benzene tank
R (m)	28	24	15	38	39	24
S (m^2)	2462	1809	707	4534	4776	1809
Property value	M1	M2	M3	M4	M5	M6
Hazard factor	0.74	0.67	0.24	0.81	0.82	0.66
Basic MPPD	0.64M1	0.52M2	0.50M3	0.78M4	0.82M5	0.58M6
C_0	0.63	0.63	0.63	0.55	0.55	0.60
Actual MPPD	0.47M1	0.42M2	0.15M3	0.45M4	0.45M5	0.40M6

Dow's F&EI results show that LPG spherical tank has the highest fire and explosion hazard and diesel tank has the lowest one; in case of fire or explosion, LPG spherical tank may have an influence radius of up to 74m, within which 82% of the property may be damaged. Through compensation with security measures, i.e. if some measures are taken, the hazard level of each tank for fire or explosion may be reduced to some extent, and the security of each tank may be guaranteed effectively during normal production and operation. However, in order to ensure the equipment safe and reliable, the security protection system, as a comprehensive system, must combine excellent staff quality and correct operation procedure guidance based on security measures compensation items (Wang, 1999). Therefore, ATA method is further used for analysis on fire and explosion accidents of LPG spherical tank.

3. ATA method for fire and explosion of LPG spherical tank

Taking LPG spherical tank with a capacity of 3×104m3 in the large refinery as the example, this study further analyzes the fire and explosion accident tree of LPG spherical tank (Gu, 2001).

3.1 Investigation into accident causes

Investigation is conducted with respect to all direct causes and various factors relating to the accident (equipment failure, human error and poor environment factor).

3.2 Plotting of accident tree

With "fire and explosion of LPG spherical tank" as top event, analysis is made with respect to basic causes for triggering top event until all basic events are identified, and then the accident tree is established with logic gate, as shown in Figure 1.

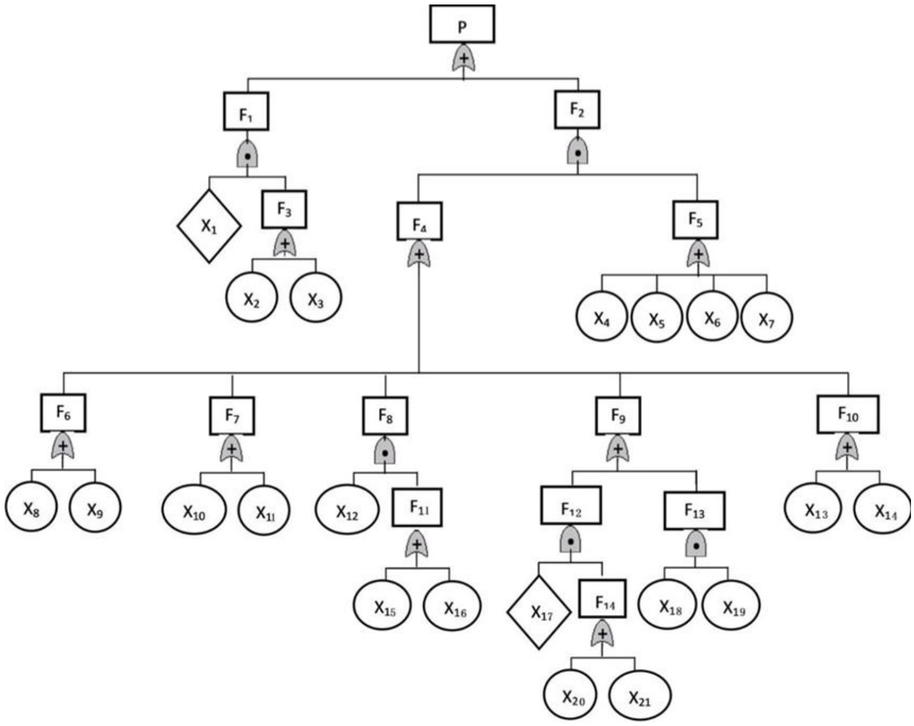

Figure 1: Accident tree for fire and explosion of LPG spherical tank. P :Fire and explosion of LPG spherical tank, F_1: Tank explosion due to overpressure, F_2: Fire blast caused by ignition source, F_3: Safety valve failed, F_4:Fire source, F_5:LPG leakage, F_6: Open flame, F_7: Electric spark, F_8: Thunder-strike spark, F_9: Electrostatic spark, F_{10}: Impact spark, F_{11}: Lightning arrestor failed, F_{12}: Electrostatic in tank, F_{13}: Electrostatic on human body, F_{14}: Grounding damage, X_1: Tank pressure exceeding the safety limit, X_2: Safety valve spring damaged, X_3: Improper selection of safety valve,X_4: Valve sealing failed, X_5: Flange sealing failed, X_6: Tank body damaged, X_7: LPG leakage due to misoperation, X_8: Smoking in the tank farm, X_9: Violation of prohibition of open flame in the tank farm, X_{10}: Use of non-explosion-proof appliance, X_{11}: Damage of explosion-proof appliance, X_{12}: Thunder-strike, X_{13}:Use of any tool made of iron, X_{14}: Wearing shoes with iron nail, X_{15}: Grounding resistance exceeding the criteria, X_{16}: Grounding wire damaged, X_{17}: Electrostatic accumulation in the tank, X_{18}: Failure to work with static protective clothing, X_{19}: Contact with conductors during the operation, X_{20}: Grounding resistance not conforming, X_{21}: Grounding terminal damaged.

3.3 Determination of minimal cut set

Minimal cut set is the set of basic events that may lead to top events to the lowest degree (i.e. top event may not occur if any of basic events contained in the cut set does not occur). All minimal cut sets of the accident tree are obtained with the “top-down” replacement method (Jing and Jia, 2004). The accident tree is then converted into equivalent Boolean equation:

$P = X_1X_2 + X_1X_3 + X_4X_8 + X_4X_9 + X_4X_{10} + X_4X_{11} + X_4X_{13} + X_4X_{14} + X_5X_8 + X_5X_9 + X_5X_{10} + X_5X_{11} + X_5X_{13} + X_5X_{14} + X_6X_8 + X_6X_9 + X_6X_{10} + X_6X_{11} + X_6X_{13} + X_6X_{14} + X_7X_8 + X_7X_9 + X_7X_{10} + X_7X_{11} + X_7X_{13} + X_7X_{14} + X_4X_{12}X_{15} + X_4X_{12}X_{16} + X_4X_{17}X_{20} + X_4X_{17}X_{21} + X_4X_{18}X_{19} + X_5X_{12}X_{15} + X_5X_{12}X_{16} + X_5X_{17}X_{20} + X_5X_{17}X_{21} + X_5X_{18}X1_9 + X_6X_{12}X_{15} + X_6X_{12}X_{16} + X_6X_{17}X_{20} + X_6X_{17}X_{21} + X_6X_{18}X_{19} + X_7X_{12}X_{15} + X_7X_{12}X_{16} + X_7X_{17}X_{20} + X_7X_{17}X_{21} + X_7X_{18}X_{19}$

3.4 Analysis on structure important degree

Below is the approximate discriminant of structural importance factor of X_i:

$$I_{\phi(i)} = \sum_{x_i \in p_j} \frac{1}{2^{n_j - 1}} \tag{1}$$

Where, X_i is basic event; P_j is minimal cut (path) set; n_j is the number of basic events included in the minimal cut set P_j where the basic event X_i is located; is the structural importance factor of X_i. The structural importance factor of basic event in this case is calculated as follows:

$$I_{\emptyset(X1)} = \frac{1}{2^{2-1}} + \frac{1}{2^{2-1}} = 1$$

$$I_{\emptyset(X2)} = I_{\emptyset(X3)} = \frac{1}{2^{2-1}} = 0.5$$

$$I_{\emptyset(X4)} = I_{\emptyset(X5)} = I_{\emptyset(X6)} = I_{\emptyset(X7)} = \frac{6}{2^{2-1}} + \frac{5}{2^{3-1}} = 4.25$$

$$I_{\emptyset(X8)} = I_{\emptyset(X9)} = I_{\emptyset(X10)} = I_{\emptyset(X11)} = I_{\emptyset(X13)} = I_{\emptyset(X14)} = \frac{4}{2^{2-1}} = 2$$

$$I_{\emptyset(X12)} = I_{\emptyset(X17)} = \frac{8}{2^{3-1}} = 2$$

$$I_{\emptyset(X15)} = I_{\emptyset(X16)} = I_{\emptyset(X18)} = I_{\emptyset(X19)} = I_{\emptyset(X20)} = I_{\emptyset(X21)} = \frac{4}{2^{2-1}} = 1$$

$I_{\phi(X4)}$,……,$I_{\phi(X7)}$ Valve sealing failed, Flange sealing failed,Tank body damaged,LPG leakage due to misoperation) have greater structural important degree and have greater influence on the top event. Structural importance factor of each basic event is sorted as follows:
$I_{\emptyset(X4)} = I_{\emptyset(X5)} = I_{\emptyset(X6)} = I_{\emptyset(X7)} > I_{\emptyset(X8)} = LL = I_{\emptyset(X14)} = I_{\emptyset(X12)} = I_{\emptyset(X17)} > I_{\emptyset(X1)} = I_{\emptyset(X15)} = LL = I_{\emptyset(X21)} > I_{\emptyset(X2)} = I_{\emptyset(X3)}$

3.5 Main affecting factors and prevention measures

There are 35 possible reasons for fire and explosion accidents of LPG spherical tank. In order to prevent the fire or explosion accident through ATA analysis, it is necessary to start with each basic event that causes the accident with consideration given to the following measures (Guo, 2009; Zu, 2004):
1) regularly check the valve and its connecting flange to prevent the leakage; 2) regularly check the tank body to avoid tank body crack and cracking due to such causes as corrosion; 3) strengthen security check and prohibit smoking in the tank farm; 4) prohibit using non-explosion-proof appliance in the tank farm, and strengthen the check of the explosion-proof appliance; 5) Not allow tapping on the ground, pipelines and equipment with ironware; 6) frequently check the lightning-proof and electrostatic-proof equipment and grounding resistance to ensure they meet the safety specification; 7) strictly control process parameters to prevent liquid overpressure in the tank; 8) clothing and work shoes must be worn before work.

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