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Simplified risk assessment on fire hazard of LPG filling station

Kyoshik Park†

Chemical Engineering Department, Myongji University, Myongji-ro 116, Yongin-si, Gyeonggi-do 17058, Korea
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Abstract−Layer of protection analysis (LOPA) was conducted on the fire hazard of LPG filling stations. Scenarios were developed for jet fire, pool fire, and boiling liquid expanding vapor explosion (BLEVE). For each scenario, independent protection layers (IPLs) of the LPG station were identified and their frequencies were estimated. Risk matrix to determine the risk category was constructed, combining consequence and frequency of each scenario. Three additional IPLs were considered, such as a firewall between the tank lorry parking area and LPG facility, water deluge system for tank lorry, and excess flow shutdown valve for liquid pipeline to stop unexpected excess flow. Adding such IPLs could markedly reduce the risk to the facility.

Keywords: Layer of Protection Analysis (LOPA), LPG Filling Station, Fire Hazard, IPL, Risk

INTRODUCTION

As a city expands with development, the residential area has more chance to be next to hazardous sites, such as LPG filling stations, which once were remote from residential areas to comply with regulations. It's not simple for a regulatory agency to force the station to move away from residential or commercial area to satisfy safety criteria. Instead, they recommend reasonable measures to reduce the corresponding risk by adding appropriate safeguards. The Korean government introduced Off-Site Risk Assessment (ORA) and Korean Risk Management Plan (K-RMP) in 2015 to assess the risk of hazardous sites and suggest measures to reduce it systematically [1,2]. Layer of protection analysis (LOPA) is a very simple and effective way to find such safeguards applicable to the analysis of LPG station.

Since the early 1960s when liquefied petroleum gas (LPG) was first introduced in Korea, the consumption of LPG has kept increasing, and LPG plays an important role as clean, convenient, and environmentally friendly fuel for not only automobiles, but also industrial and residential applications. Although major numbers of LPG stations are far remote from residential or commercial area, many of the stations are still located near populated areas and should be handled with care, as shown in Table 1 [3]. LPG station incidents in Korea are managed by the Korean government and show that major causes of incidents are human errors such as improper coupling of hoses from tank lorries to underground storage tanks, starting vehicles during dispensing, and collisions of vehicles with dispensers. To reduce the risks caused by such incidents, a facile and systematic approach is needed to provide countermeasures.

Evaluating hazard and assessing risk of hazardous facilities is one of the most important activities to keep the site safe. Several studies have been conducted, such as on how to review the current methodologies for plant layout optimization and to resolve facility siting issues [4], on how to reduce accidental exposure to various regents that are toxic, explosive, or carcinogenic [5], or on how to apply advanced layers of protection analysis (LOPA) method to assess the risk of a chemical process [6]. The layer of protection analysis (LOPA) was introduced in the 1990s for semi-quantitative risk assessment, having advantages of both qualitative and quantitative methods of risk evaluation as has been described in the CCPS textbook [7]. LOPA is known to be a powerful analytical tool for assessing the adequacy of protection layers used to mitigate process risk. The LPG station is a relatively simple structure compared with other hazardous facilities, such as chemical processes, and is good for applying LOPA instead of quantitative method to save time and resources. In this work, LOPA was conducted on fire hazards of LPG station. Although unconfined vapor cloud explosion (UVCE) is another significant consequence, it varies widely with environmental factors such as climate and surface roughness and is excluded in this study.

DESCRIPTION OF THE LPG FILLING STATION

Typical LPG filling station facilities in Korea are described in

Table 1. Location of LPG filling station as of 2014 in Korea

Area	Residential	Commercial	Industrial	Suburban	Rural	Total
Number of stations	149	62	213	1,268	343	2,035

†To whom correspondence should be addressed.
E-mail: hwayi21@empal.com

Table 2. Typical equipment of an LPG filling station

Facility	Equipment	Capacity (unit)
Storage	Butane tank	15 ton (1EA)
Loading / Unloading	Liquid pump	5.5 kW
	Gas compressor	5.5 kW (7.5 HP)
	Dispenser	3EA
	Loading arm	50A, 25A
Safety	Emergency power supply	26 kW
	Gas detector	9EA
	Emergency shutdown valve	50A 1EA

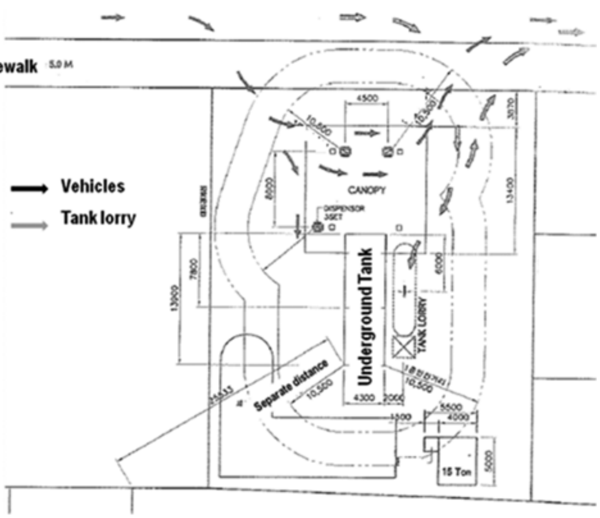

Fig. 1. Layout of LPG station.

Table 2 and Fig. 1, as the described by Melchers and Feutrill [8] and Park et al. [9]. Every facility at an LPG filling station must keep a distance of at least 10.5 m apart from the border of the station for safety in Korea, which is quite similar to that of Australia by Melchers and Feutrill. [8] This distance is defined as safety distance in regulation related to LPG station. LPG composition is assumed for butane, which is used in Korea in the most cases. The compressor connected to the vapor line of 25A (25 mm diameter) compresses vapor butane from underground storage tanks to pressurize tank lorries. Then the butane in the tank lorry is unloaded to an underground tank via liquid line of 50A (50 mm diameter). Vehicle is filled via 50A liquid line from underground tank with outlet pressure of 8.0 kg/cm^2.

LAYER OF PROTECTION ANALYSIS

1. Estimating Consequences and Severity

1-1. Release Rate

Major sources of release at LPG filling station include, but are not restricted to, pipelines, gasket/flanges, and dispense hoses by Melchers and Feutrill [8]. In this work, three equivalent diameters of a hole are assumed according to the type of release source. The smallest one, 12.5 mm, is considered having a diameter equivalent to the leak from slightly loosened flange or corroded gasket (Case 1). The next one, 25 mm, is an equivalent diameter to the release from heavily loosened flange or corroded gasket of 50A pipeline or rupture of 25A pipeline (Case 2). An equivalent diameter of 50 mm is assumed for rupture of 50A pipeline or disconnection of unloading liquid line (Case 3). Melchers and Feutrill suggested the relative probabilities of the above three cases are 0.85, 0.10, and 0.05, respectively [8].

Table 3. Mass flow of LPG (butane) for the Case A, B, and C at liquid phase and vapor phase release

Equivalent diameter of release (mm)	Release rate (kg/s)	
	Liquid phase	Vapor phase
12.5 (Case 1)	2.28	0.21
25 (Case 2)	9.12	0.85
50 (Case 3)	36.57	-*

*The LPG station has no 50 mm diameter line for vapor phase

By assuming liquid phase release from loading hose of dispenser, underground inlet pipeline, or under liquid level of tank lorry, the mass flow rate Q_m resulting from a hole of equivalent area A is given by Eq. (1) [10].

$$Q_m = AC_0\sqrt{2\rho g_c P_g} \tag{1}$$

where C_0 denotes the discharge coefficient and a complicated function of the Reynolds number of the fluid escaping through the release and the diameter of the hole and taken as 0.61 [11]. With outlet pressure of liquid pump, 8 kg/cm^2, the calculated the release rates for each case are given in Table 3.

LPG vapor release takes place through vapor return line, gas compressor, or above liquid level of tank lorry. The vapor release velocity through a hole is sonic since the storage pressure is greater than twice of atmospheric pressure. The mass flow rate Q_m resulting from a hole of equivalent area A is given by Eq. (2) [12].

$$Q_m = C_0 A P_0\sqrt{\frac{\gamma g_c M}{Z R_g T_0}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}} \tag{2}$$

where M=58 kg/kmol, Z=0.984 and $\gamma=C_P/C_V=1.1176$ at 15 °C, and the constant term $\sqrt{\gamma\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}}$ is estimated to be 0.632 for butane.

The mass flow rates of Case 1, 2, and 3 are summarized in Table 3.

1-2. Jet Fire

Jet fire can occur by an immediate ignition of released vapor, and has a huge momentum. The flame is treated as a multiple source radiator and the impingement distance and the heat radiated from the source is expressed simply by the following [13].

$$L_i = 6\sqrt{Q_m} \quad (0 < Q_m(\text{kg/s}) < 50) \tag{3}$$

$$q_x = \frac{F_r(-\Delta H_C)Q_m \tau}{4\pi x^2} \tag{4}$$

$$\tau = 1 - 0.0565 \ln x \tag{5}$$

Although the fraction of heat radiation F_r is a function of heat

Table 4. Heat flux from a jet flame at the specific distance of 21 m

Equivalent diameter of release (mm)	Release rate Q_m (kg/s)	Flame length L_i (m)	Heat flux q_x (kW/m^2)
12.5 (Case 1)	0.21	2.75	1.09
25 (Case 2)	0.85	5.53	2.18

released, 0.13 is taken conservatively. The transmissivity factor τ is expressed as a function of distance simply [10]. The heat flux at the specific distance of 21 m, which is equivalent to twice of safety distance defined by the law and located in residential area, can be calculated by Eqs. (3)-(5) as summarized in Table 4.

1-3. Pool Fire

Release of liquid phase LPG and the formation of liquid pool with release duration can be expressed by equation as [14]

$$A(t)=\frac{Q_m}{v_r}\left(1-e^{\frac{v_r\cdot t}{\rho\cdot z}}\right) \quad (6)$$

In case of ignition, the pool fire may occur and the area can be described as Eq. (7).

$$A_f(t)=\frac{Q_m}{b_r}-\left(\frac{Q_m}{b_r}-A_0\right)e^{-\frac{v_r\cdot t}{\rho\cdot z}} \quad (7)$$

The diameter of the pool fire for each case is given in Fig. 2, showing maximum values. Although wind has effect on the consequence area by tilting the flame, it is not easy to calculate the area case by case. In this work, only a simple case without wind is calculated. In case of small release with 12.5 mm equivalent diameter, with 25 mm equivalent diameter, and with 50 mm equivalent diameter, the maximum radii of flame are estimated to be 2.6 m, 5.3 m, and 10.5 m, respectively.

The heat generated by pool fire and the corresponding heat flux can be approximated as [13]

$$q=b_r(-\Delta H)A \quad (8)$$

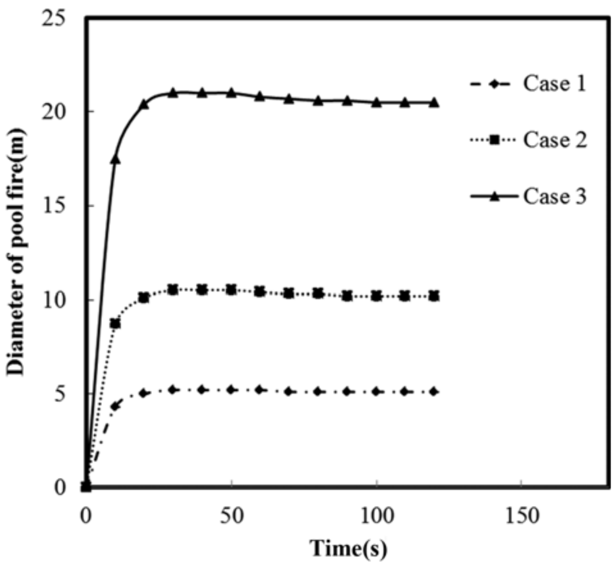

Fig. 2. Size of LPG pool with time.

Table 5. Heat flux from a pool fire at the specific distance of 21 m

Equivalent diameter of release (mm)	Release rate Q_m (kg/s)	Maximum diameter D (m)	Heat flux q_x (kW/m^2)
12.5 (Case 1)	2.28	5.2	15.1
25 (Case 2)	9.12	10.5	41.6
50 (Case 3)	36.57	21.0	140.9

$$q_x=\tau q/4\pi x^2 \quad (9)$$

The heat flux for three cases is predicted for a specific distance of 21 m, which is equivalent to the twice of separation distance by regulation as shown in Table 5.

1-4. Boiling Liquid Expanding Vapor Explosion (BLEVE)

LPG in tank lorry might be heated by nearby jet fire or pool fire to cause a BLEVE [9,17]. The major damage caused by BLEVE of LPG tank because of the radiative heat of a fireball can be analyzed by the following equations [17]:

$$t_{BLEVE}=0.852M_{fireball}^{0.26} \quad (10)$$

$$D_{max}=6.48M_{fireball}^{0.333} \quad (11)$$

$$H_{BLEVE}=0.75D_{max} \quad (12)$$

$$q_x=\frac{F_r M_{fireball}(-\Delta H_C)}{\pi D_{max}^2 t_{BLEVE}} \quad (13)$$

The BLEVE can take place only in a tank lorry since underground tanks cannot be heated enough to initiate BLEVE. During unloading from a tank lorry to underground tank or dispensing to vehicles, liquid phase LPG may be released from a disconnected coupler or a damaged pipeline to form an LPG pool, and a pool fire might develop in the presence of an ignition source. In that case, the nearby tank lorry is under a pool fire risk. When external fire heats the tank lorry, a safety relief valve is activated and vapor releases through the valve forming a jet fire before explosion [9]. The typical capacity of a butane tank lorry is 13 tons, and 3 ton release was assumed during heating the tank lorry before BLEVE and 10 tons take part in BLEVE. The maximum diameter of the fireball is then estimated to be 129 meters having 97 meter height and 9.0 second duration time [9]. By Eqs. (10)-(13), heat flux at 21 m can be predicted as 421 kW/m^2.

1-5. Summary of Consequence and Severity

The heat flux and corresponding damage of jet fire, pool fire, and BLEVE are summarized in Table 6. The jet fire has rather slight level of consequence, as shown in the table. The pool fire has heavier level of consequence than jet fire corresponding to high level of damage, so that even at small-scale release of liquid, the operator cannot perform his or her duty and must be sheltered by equipment. With a medium scale release, the pool fire has enough energy to cause damage to the process equipment. With a large-scale release, the pool fire can become so hazardous that 100% fatality at the distance of 21 m is estimated in about 10 seconds' exposure. For BLEVE, the hazard of a fire ball becomes extremely high so that immediate exposure may cause a fatality.

Table 6. Heat flux from fire hazards at the specific distance of 21 meters

Fire hazard	Equivalent diameter of release (mm)	Release rate Q_m (kg/s)	Heat flux q_x (kW/m^2)	Corresponding damage (LOPA textbook)	Hazard level (LOPA textbook)
Jet fire	12.5 (Vapor line) Case 1	0.21	1.38	No discomfort for long exposure (Minor or no injury)	Low (Low consequence)
	25 (Vapor line) Case 2	0.85	2.77	Time to pain threshold in 30-40 seconds (Single injury, not severe)	Medium (Medium consequence)
Pool fire	12.5 (Liquid line) Case 1	2.28	15.1	Operators are not likely to perform duty (One or more severe injury)	High (High consequence)
	25 (Liquid line) Case 2	9.12	41.6	Sufficient to cause damage to equipment (One or more severe injury)	High (High consequence)
	50 (Liquid line) Case 3	48.57	187.1	100% fatality about 10 seconds exposure (Fatality or permanently disabling injury)	Very high (Very high consequence)
BLEVE	-	-	421	100% fatality less than 3 seconds exposure (Fatality or permanently disabling injury)	Extremely high (Very high consequence)

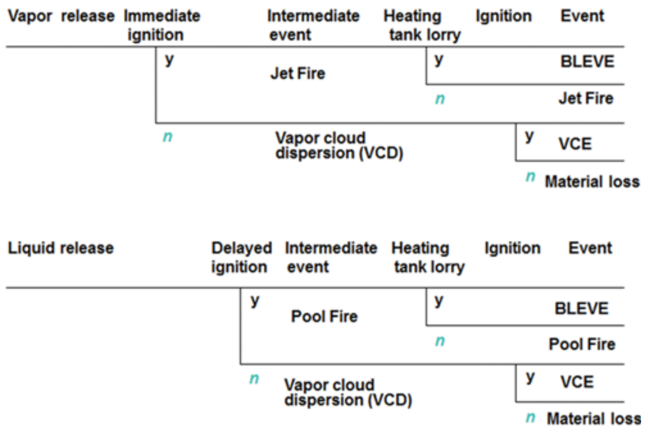

Fig. 3. Event tree analysis on fire hazard of LPG filling station.

2. Developing Scenarios

Event tree analysis (ETA) on the fire hazard of LPG filling station has been conducted as shown in Fig. 3. We can have jet fire if gas releases from the gas pipeline with immediate ignition. More specifically, a jet fire is assumed by an immediate ignition of vapor released from loosened gasket of a vapor line, corroded vapor line, or rupture of vapor line. These are described further in scenarios S1-S3. Pool fire may occur if LPG releases in liquid pipeline to make a pool and is then ignited. More specifically, a pool fire is assumed by an immediate ignition of a liquid pool formed by release from loosened gasket of liquid line, corroded liquid line, rupture of liquid line, ruptured unloading arm by tank lorry start during unloading, or unloading arm by misconnection during unloading. They are described in scenarios S4-S10. BLEVE is assumed in the case that the jet fire or the pool fire heats the vapor part of the tank lorry parked near the fire. Initiation events are LPG release from a loosened gasket, from a pipeline failure, or from a tank lorry or vehicle starting during unloading or dispensing. Ignition is the enabling event of the jet fire and the pool fire while heating nearby tank lorry is the enabling event of the BLEVE.

2-1. Jet Fire

S1: Failure of gasket at vapor line (initiating event)→small scale release with equivalent diameter of 12.5 mm→ignition (enabling event)→jet fire

S2: Failure of vapor line (initiating event)→small scale release with equivalent diameter of 12.5 mm→ignition (enabling event)→ jet fire

S3: Rupture of 25A vapor line (initiating event)→medium scale release with equivalent diameter of 25 mm→ignition (enabling event)→jet fire

2-2. Pool Fire

S4: Failure of gasket at liquid line (initiating event)→small-scale release with equivalent diameter of 12.5 mm→ignition (enabling event)→pool fire

S5: Failure of liquid line (initiating event)→small-scale release with equivalent diameter of 12.5 mm→ignition (enabling event)→pool fire

S6: Failure of gasket at liquid line (initiating event)→medium scale release with equivalent diameter of 25 mm→ignition (enabling event)→pool fire

S7: Failure of liquid line (initiating event)→medium scale release with equivalent diameter of 25 mm→ignition (enabling event)→ pool fire

S8: Rupture of liquid line (initiating event)→large-scale release with equivalent diameter of 50 mm→ignition (enabling event)→ pool fire

S9: Leak in the tank lorry transfer line during unloading→large-scale release with equivalent diameter of 50 mm→ignition (enabling event)→pool fire

S10: Improper coupling of hose during unloading→large-scale release with equivalent diameter of 50 mm→ignition (enabling event)→pool fire

2-3. BLEVE

S11: Dispenser hose rupture by vehicle start with dispenser hose connected→failure in quick detection and action→ignition→fire around dispenser→heating tank lorry by the fire nearby dispenser (enabling event)→hot spot→BLEVE

Table 7. Scenario development for the fire and the explosion hazards

Scenario number	Initiating event	Event (Equivalent diameter of release)	Enabling event	Consequence
S1	Loosening gasket at vapor line	Small scale release (12.5 mm)	Ignition	Jet fire
S2	Failure of vapor line	Small scale release (12.5 mm)		
S3	Rupture of vapor line	Medium scale release (25 mm)		
S4	Loosened gasket	Small scale release (12.5 mm)	Ignition of pool	Pool fire
S5	Failure at liquid line			
S6	Loosened gasket	Medium scale release (25 mm)		
S7	Failure at liquid line			
S8	Rupture of liquid line	Large scale release (50 mm)		
S9	Leak in tank lorry transfer line during unloading			
S10	Improper coupling of hose during unloading			
S11	Dispenser hose rupture	Medium scale release (25 mm)	Heating nearby tank lorry	BLEVE
S12	Dispenser flange leak	Small scale release (12.5 mm)		
S13	Disconnection during unloading	Large scale release (50 mm)		
S14	Tank lorry start during unloading	Large scale release (50 mm)		
S15	Loading arm flange leak	Small scale release (12.5 mm)		
S16	Loading arm rupture	Large scale release (50 mm)		

S12: Dispenser flange leak→failure in quick detection and action →ignition→fire around dispenser→heating tank lorry by the fire nearby dispenser (enabling event)→hot spot→BLEVE

S13: Disconnection during unloading by bad connection of coupler by human error→failure in quick detection and action→ ignition→fire around loading arm→heating tank lorry by the fire nearby loading arm (enabling event)→hot spot→BLEVE

S14: Tank lorry start during unloading→failure in quick detection and action→ignition→fire around loading arm→heating tank lorry by the fire nearby loading arm (enabling event)→hot spot→ BLEVE

S15: Loading arm flange leak→failure in quick detection and action→ignition→fire around loading arm→heating tank lorry by the fire nearby loading arm (enabling event)→hot spot→BLEVE

S16: Loading arm rupture→failure in quick detection and action →ignition→fire around loading arm→heating tank lorry by the fire nearby loading arm (enabling event)→hot spot→BLEVE

The above scenarios are summarized in Table 7.

3. Identifying Independent Protection Layers (IPLs) and Determining the Frequency of Scenarios

3-1. Identifying IPLs

An independent protection layer (IPL) is defined by a device, system, or action that can prevent a scenario from proceeding to its undesired consequence as described in the LOPA textbook. The safeguards are candidate IPLs and can be categorized as process design, basic process control system (BPCS), critical alarm and human intervention, safety instrumented function (SIF), physical protection, post-release protection, plant emergency response, and/or community emergency response. In this work, the IPLs for jet fire are vapor line emergency shutdown valve (ESV), fire extinguisher, and gas detector. The IPLs for pool fire are liquid line ESV, fire extinguisher, and gas detector. The IPLs for BLEVE are liquid line shut down valve, liquid line ESV, fire extinguisher, gas detector, and fuse metal safety valve of tank lorry.

3-2. Determining the Frequency of Scenarios

For each scenario, frequency is estimated by Eq. (14)

$$f_i^C = f_i^I \times \prod_{j=1}^{J} \mathrm{PFD}_{ij} \qquad (14)$$

For a jet fire, the frequency is calculated by the S1-S3 as follows.

$$f_i^{jet} = f_i^I \times \left(\prod_{j=1}^{J} \mathrm{PFD}_{ij} \right) \times P^{ignition} \qquad (15)$$

The frequencies of occurrences of jet fires are calculated by Eq. (15) with the PFDs given in Table 8. With vapor line gasket (PFD= 1.0×10^{-2}), vapor line emergency shutdown valve (PFD=3.5×10^{-2}), fire extinguisher (PFD=0.04), gas detector (PFD=1.8×10^{-1}), and the probability of an immediate ignition of 0.296, the frequency of the small scale jet fire by the gasket failure is estimated by Eq. (15) as $f_1^{jet}=7.5\times10^{-7}$. Likewise, the frequency of the small-scale jet fire by the pipeline failure and can be approximated as $f_2^{jet}=7.5\times10^{-8}$. The frequency of the small-scale jet fire is the summation of f_1^{jet} and f_2^{jet}, which is 8.3×10^{-7}. The medium scale jet fire is also found as $f_3^{jet}=7.5\times10^{-10}$.

The frequencies for a pool fire are also calculated for scenarios S4-S10.

$$f_i^{pool} = f_i^I \times \left(\prod_{j=1}^{J} \mathrm{PFD}_{ij} \right) \times P^{ignition} \qquad (16)$$

Table 8. Frequency of each event

	Event	Likelihood	Reference
A	Bad connection of coupler by human error	1.0×10^{-5}/connection	19
B	ESV failure	3.5×10^{-2}/y	21
C	Failure in early stage extinguish by extinguisher	0.04	19
D	Failure in early stage recognition	0.1	20
E	Failure in screening fire by firewall	1.0×10^{-2}	21
F	Failure in shutdown valve for excess flow	1.0×10^{-2}	20
G	Failure in water deluge system	0.1	21
H	Frequency of unloading	490/y	19
I	Gas detector failure	1.8×10^{-1}/y	21
J	Gasket failure	1×10^{-2}/y	15
K	Heating vapor part of tank lorry	3.0×10^{-2}	19
L	Leak at dispenser flange	1.8×10^{-3}/y	21
M	Leak at loading arm flange	1.2×10^{-3}/y	21
N	Manual valve failure	4.4×10^{-3}/y	20
O	Piping leak	1×10^{-3}/y	15
P	Probability of immediate ignition	0.296	21
Q	Probability of tank lorry heating by fire nearby dispenser	0.03	21
R	Probability of tank lorry heating by fire nearby loading arm	0.7	21
S	Quick coupler failure	1.0×10^{-4}	20
T	Rupture of loading arm	3.5×10^{-4}/y	20
U	Tank lorry fuse cock failure	3.5×10^{-2}/y	15
V	Tank lorry start during unloading	0.33/y	20
W	Tank lorry start during unloading or Vehicle star during dispensing	3/y	19

The frequencies of each scenario can be estimated by Eq. (16) for PFDs of liquid pipeline failure and liquid line emergency shutdown valve (ESV) failure.

$f_4^{pool}=7.5\times10^{-7}$, $f_5^{pool}=7.5\times10^{-8}$, $f_6^{pool}=7.5\times10^{-7}$, $f_7^{pool}=7.5\times10^{-8}$,
$f_8^{pool}=7.5\times10^{-10}$, $f_9^{pool}=9.0\times10^{-7}$, $f_{10}^{pool}=3.7\times10^{-8}$

Thus, the frequency of small scale pool fire is the summation of S4 and S5, 8.3×10^{-7}, medium scale pool fire is the summation of S6 and S7, 3.3×10^{-3}, and large scale pool fire is the summation of S8, S9, and S10, 9.4×10^{-7}.

For a BLEVE, the frequency is calculated by the S11-S16 as follows.

$$f_i^{BLEVE}=f_i\times\left(\prod_{j=1}^{J}PFD_j\right)\times P^{heating} \tag{17}$$

A BLEVE will occur if we have a jet fire or a pool fire and it heats the vapor part of tank lorry for a while. With the IPLs given the above scenarios S1-S10, an additional IPL is installed like the fuse metal safety valve of a tank lorry. The frequency of failure in early stage detection and action comes from either failure in manual valve shutdown or failure in emergency valve shutdown, and can be calculated by the FTA illustrated as in Fig. 4.

$$f^{dfailure}=(DI+N)+(DI+B)=[(1.8\times10^{-1})(0.1)+4.4\times10^{-3}]+[(1.8\times10^{-1})(0.1)+3.5\times10^{-2}]=7.54\times10^{-2}$$

The frequency of S11-S16 can be estimated by Eq. (17), additionally assuming the probability of vapor phase heating is 0.1 [19].

$$f_{11}^{BLEVE}=(SW)(f^{dfailure})(P)(CQ)(K)=(3\times0.0001)(7.54\times10^{-2})(0.296)(0.04\times0.03)(0.1)=8.03\times10^{-10}$$

$$f_{12}^{BLEVE}=(L)(f^{dfailure})(P)(CQ)(K)=(1.8\times10^{-3})(7.54\times10^{-2})(0.296)(0.04\times0.03)(0.1)=4.82\times10^{-9}$$

$$f_{13}^{BLEVE}=(AH)(f^{dfailure})(P)(UCR)(K)=(1.0\times10^{-5}\times490)(7.54\times10^{-2})(0.296)(3.5\times10^{-2})(0.04\times0.7)(0.1)=1.07\times10^{-8}$$

$$f_{14}^{BLEVE}=(V)(f^{dfailure})(P)(UCR)(K)$$

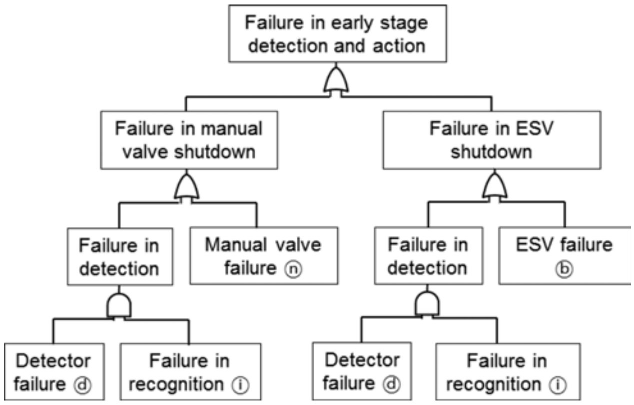

Fig. 4. Fault tree analysis to valuate failure in early stage detection and action.

Table 9. Risk matrix corresponding to jet fire, pool fire, and BLEVE of an LPG station (Conventional)

Consequence / Frequency per year	Low consequence	Medium consequence	High consequence	Very high consequence
10^{-7}	S1 (Small jet fire)		S4, S5 (Small pool fire)	S9 (Large pool fire) S14 (BLEVE)
10^{-8}	S2 (Small jet fire)		S6, S7 (Medium pool fire)	S10 (Large pool fire) S13 (BLEVE)
10^{-9}				S12, S15 (BLEVE)
10^{-10}		S3 (Medium jet fire)		S8 (Large pool fire) S11, S16 (BLEVE)

$$=(0.33)(7.54\times10^{-2})(0.296)(3.5\times10^{-2})(0.04\times0.7)(0.1)$$
$$=7.22\times10^{-7}$$

$$f_{15}^{BLEVE}=(M)(f^{dfailure})(P)(UCR)(K)$$
$$=(1.2\times10^{-3})(7.54\times10^{-2})(0.296)(3.5\times10^{-2})(0.04\times0.7)(0.1)$$
$$=2.62\times10^{-9}$$

$$f_{16}^{BLEVE}=(T)(f^{dfailure})(P)(UCR)(K)$$
$$=(3.5\times10^{-4})(7.54\times10^{-2})(0.296)(3.5\times10^{-2})(0.04\times0.7)(0.1)$$
$$=7.67\times10^{-10}$$

The frequency of BLEVE is the summation of the above six scenarios and gives.

4. Risk Reducing Measures

Risk matrix was listed according to the severity and frequency of outcomes and described in Table 9. Since the hazards associated with jet fires are low or medium with frequencies about 10^{-7}-10^{-8}, the risk is small enough not to require any further safety measures. As shown in the table, the hazard associated with large-scale pool fire and BLEVE is very high. An effective way to reduce the likelihood of large amount of liquid release is to install an excess flow shutdown valve for dispenser to block unexpected sudden flow increasing. With this new IPL with the probability of failure on demand (PFD) of 0.01, [19] the frequencies of the large pool fires reduced to by the following equation:

$$f_{large,\ new}^{pool}=(f_8^{pool}+f_9^{pool}+f_{10}^{pool})\times PFD^{excess\ valve}=9.4\times10^{-9}$$

Three safeguards are suggested to reduce the risk associated with fire hazards additionally. Considering the effectiveness, independence, and auditability, two kinds of post-release protection and one critical alarm have been recommended. As a post-release protection, a firewall between tank lorry parking area and LPG facility is recommended, which will reduce the likelihood of exposure of tank lorry to the fire in dispensing area. AEA report showed that the PFD of a firewall is 0.01. A water deluge system for tank lorry is known to be another effective measure for post-release protection to prevent hot spot at a tank exposed to fire, with the PFD of 0.03 [21]. An additional gas detector installed around loading arm reduced the likelihood of failure in early stage detection by 0.18 [21].

The risk associated with BLEVE can be reduced further if an excess flow shutdown valve for a dispenser is installed or an additional firewall between the tank lorry parking area and storage facility is constructed. Also, an appropriate water deluge system for tank lorry considerably reduces the risk of pool fire or BLEVE. The likelihood of BLEVE for the improved system is estimated by the following equation:

$$f_{new}^{BLEVE}=\begin{bmatrix}(f_{11}^{BLEVE}+f_{12}^{BLEVE})(PFD^{excess\ valve}\times PFD^{firewall})\\ +(f_{13}^{BLEVE}+f_{14}^{BLEVE}+f_{15}^{BLEVE}+f_{16}^{BLEVE})\times PFD^{detector}\end{bmatrix}$$
$$\times PFD^{water\ deluge}=3.98\times10^{-10}$$

CONCLUSIONS

Layer of protection analysis (LOPA) was conducted on the fire hazard of LPG filling station. Three equivalent hole-areas of release were assumed to estimate consequence and corresponding severity. For the liquid phase, the release rate of each case was estimated, while

Table 10. Risk matrix corresponding to jet fire, pool fire, and BLEVE of an LPG station (Improved)

Consequence / Frequency per year	Low consequence	Medium consequence	High consequence	Very high consequence
10^{-7}				
10^{-8}				
10^{-9}			S4, S5 (Small pool fire)	Sum of all large pool fire
10^{-10}	S1 (Small jet fire)		S6, S7 (Medium pool fire)	Sum of all BLEVE
10^{-11}	S2 (Small jet fire)			
10^{-12}		S3 (Medium jet fire)		

only two cases were considered for vapor phase release since an LPG station does not have any 50A vapor line. At the same diameter, liquid phase release rate was much more than vapor phase as shown in Table 3.

The hazards of the jet fire, the pool fire, and the BLEVE were studied and categorized in five levels and compared with the corresponding categories given in the LOPA textbook [7], as summarized in Table 6. For the jet fire, low and medium level of consequence was estimated. For the pool fire, high and very high level hazards were estimated, while extremely high hazards were obtained for the BLEVE.

Scenarios were developed for the jet fire, the pool fire, and the BLEVE. For each scenario, independent protection layer (IPL) was identified and its frequency was estimated.

Risk matrix was prepared with consequence and frequency of each scenario. As shown in Table 9, large-scale pool fire and BLEVE have high risk. Four additional IPLs were considered, such as a firewall between tank lorry parking area and LPG facility, water deluge system for tank lorry, gas detector around loading arm, and excess flow valve for liquid pipeline to stop unexpected sudden flow increasing. By adding IPL of excess flow valve for liquid pipeline, the frequency of large-scale pool fire reduced remarkably. Addition of a firewall between tank lorry parking area and LPG facility, gas detector around loading arm, or water deluge system for tank lorry also reduces the frequency of BLEVE low enough. The results of the improved system are summarized in Table 10.

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NOMENCLATURE

A : equivalent area of release [m^2]
A_0 : area of LPG pool before ignition [m^2]
$A(t)$: area of LPG pool at time t [m^2]
$A_f(t)$: area of LPG pool flame at time t [m^2]
C_0 : discharge coefficient (0.61)
D_{max} : maximum diameter of LPG participating BLEVE [m]
$-\Delta H_C$: heat of combustion [kJ/kg mol]
F_r : fraction of heat radiation (0.1284 for jet fire and pool fire, 0.4 for BLEVE)
H_{BLEVE} : height of BLEVE [m]
L_i : length of jet flame impingement [m]
M : molecular weight of the escaping vapor or gas [kg/kg mol]
$M_{fireball}$: mass of LPG participating BLEVE [kg]
P_0 : process pressure [atm/m^3]
P_g : gauge pressure [atm/m^3]
$P^{heating}$: probability of heating vapor part of tank lorry
$P^{ignition}$: probability of ignition
$PFD^{excess\ valve}$: probability of failure on demand of excess flow valve for dispenser
$PFD^{firewall}$: probability of failure on demand of firewall between LPG facility and tank lorry parking area
$PFD^{water\ curtain}$: probability of failure on demand of water deluge system for tank lorry
Q_m : mass flow rate [kg/s]
R_g : ideal gas constant [0.082057 m^3 atm/kg mol K]
T_0 : temperature of the source [K]
Z : compressibility factor
b_r : combustion rate of LPG [0.099 kg/m^2 s]
f_i^C : frequency of scenario
g_c : gravitational constant [1 (kg m/s^2)/N]
q : heat flux [kW/m^2]
q_x : heat flux at distance x m [kW/m^2]
t_{BLEVE} : time of BLEVE duration [s]
v_r : vaporization rate of LPG [0.03 kg/m^2 s]
x : distance from radiation [m]
z : pool depth [m]
γ : ratio of the heat capacity (=C_p/C_v)
ρ : density of fluid [kg/m^3]
τ : atmospheric transmissivity

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