Quantitative Risk Assessment of Medium-Sized Floating Regasification Units Using System Hierarchical Modelling

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ABSTRACT

Currently there are no sufficiently detailed and specific regulations and guidelines applicable to Floating Regasification Units. In view of the fact that these units are likely to become more popular in the near future, their safety needs to be examined urgently.

During the design of the world's first medium-sized floating regasification unit a qualitative risk assessment was carried out. Although the results are useful, they cannot be used for developing rules and regulations directly. For such purposes some detailed quantitative studies are essential. This paper addresses this gap and introduces a hierarchical system modelling method to overcome the problem of the lack of direct statistical accident data of novel systems.

The method was implemented in IQRA (integrated quantitative risk assessment), a piece of software developed in-house for quantitative risk assessment. The safety of the floating regasification unit mentioned above was assessed using this software and the results were compared against the results obtained from conventional qualitative and the quantitative risk assessment.

It was found that the qualitative risk assessment had a tendency to overestimate the frequency of the accidents but to underestimate their consequence, while the quantitative risk assessment based on the result of the qualitative assessment inherently underestimated both the frequency and the consequence of hazards. The hierarchical modelling was found to be an excellent method of dealing with complex systems with short operational history.

Keywords: quantitative risk assessment, LNG regasification unit, FRU, system hierarchy

List of symbols

A_C	Area concerned (m^2)
A_L	Cross-sectional area of leak (m^2)
C_L	Discharge coefficient used for liquid (= 0.61)
C_G	Discharge coefficient (=0.85)
g_c	Gas constant (1kg m/N·sec^2)
MW	Molecular Weight (kg/kmol)
NF_{EX}	Number of fatalities by explosion (persons)
NF_{FF}	Number of fatalities by flash fire (persons)
NF_{PF}	Number of fatalities by pool fire (persons)
NF_{JF}	Number of fatalities by jet fire (persons)
P_A	Atmospheric pressure (Pa)
P_{BW}	Overpressure of blast wave (Pa)
P_s	Absolute pressure inside pipe (Pa)
PB_{PF}	Probit corresponding to probability of fatalities
PO_D	Population distribution (persons)
PR_F	Probability of fatalities
PR_{F_PF}	Probability of fatalities by pool fire
PR_{F_EX}	Probability of fatalities by explosion
Q_{LR}	Leak rate for liquid (kg/s)
Q_V	Leak rate for vapour (kg/s)
q_{TR}	Thermal radiation (W/m^2)
R	Gas constant, 8,314 (J/mol·K)
r_C	Radius of concerned area (m)
t	Exposed time (= 60 seconds)
T_s	Storage temperature (K)
ρ_{LNG}	LNG density (kg/m^3)
λ	Failure rate per year

1. Introduction

With the continuous increase of the world LNG trade reaching 241.1 MT (million tonnes) in 2014, LNG terminals are struggling with the problem of providing stable natural gas supply for power plants and industrial systems. As a consequence, demand for LNG regasification facilities has grown rapidly: the global regasification capacity at terminals was recorded at 724 MTPA (million tonnes per annum) in 2014, which was about 500 MTPA higher than the level in 2000 (IGU, 2015).

To meet the ever rising demand, floating regasification units (FRUs) started to be deployed at offshore sites in 2005 and, as of 2014, a total of 16 FRUs are operating with a total capacity of 54 MTPA across 11 countries (IGU, 2015; Victoria, 2016). FRUs are particularly useful for smaller markets where more flexible and cost-effective ways to satisfy the demand are necessary.

However, LNG is regarded as a dangerous fluid possibly leading to several types of critical accidents, particularly fire and explosion. As a result, a joint project team consisting of Korean Register of Shipping and other stakeholders has investigated the risk of new compact LNG regasification systems to be fitted on a medium-sized FRU by means of a hazard and operability (HAZOP) study during the design of the FRU (Lee, 2016). The study found that the risk level of fire/explosion initiated by leaks from the process equipment is unacceptably high, and safety recommendations were made for installing appropriate number of gas detectors working together with automatic leakage isolation mechanisms near three major systems: the LNG tank, the boil off gas (BOG) processing units and LNG regasification units (Korean Register, 2015).

Although all the participants of the study agreed on the results obtained, it was recognised that HAZOP studies do have inherent limitations. Firstly, it will be difficult to quantify the risk with high credibility, and, secondly, it relies on experts' opinion too much, possibly leading to personal biases and consequent misjudgement (Rausand and Høyland, 2004). As a result, this HAZOP study concluded with a recommendation that a careful examination be carried out to determine the appropriate number of gas detection systems required for each system.

This paper addresses the shortcomings of HAZOP studies and conventional selective quantitative risk assessment by investigating the safety of the FRU using an enhanced framework for quantitative risk assessment using an in-house software based on hierarchical system modelling.

2. Approaches Adopted

2.1. Background

In general, risk assessment can be carried out qualitatively and/or quantitatively (Rausand and Høyland, 2004). HAZOP is a typical qualitative approach and the framework used for a HAZOP study on the regasification unit (Korean Register, 2015) is illustrated in Fig. 1. The main aim of the study was to identify potential hazards associated with the LNG regasification unit fitted on an FRU, and to provide recommendations for enhancing the safety of the FRU in question if and where deemed necessary. It used a combination of HAZOP parameters (flow temperature, pressure and level) and guide words ('no', 'less', 'more' and 'reverse') to identify assorted hazards. The degree of frequency and consequence for the identified hazards was then assessed based on the experience and judgement of the expert panel.

Fig. 1. Qualitative risk assessment framework (Applied HAZOP method) (Lee, 2016; Rausand and Høyland, 2004).

There are many more examples of qualitative studies on LNG systems. For example, Tugnoli et al. (2010) performed the safety assessment of LNG regasification systems onshore, concluding that advanced tools are required for investigating the safety levels of LNG plants more systematically. Nicola et al. (2015) identified potential hazards associated with LNG regasification plants in a qualitative way. They highlighted the lack of experience as the key limitation of the qualitative method. Giardina and Morale (2015) have carried out a qualitative risk assessment by combining an FMECA and HAZOP methods to investigate the safety of LNG regasification plant. Like other qualitative studies, the risk of the proposed plant had been determined based on the knowledge of experts.

Similar to HAZOP, hazard identification study (HAZID), failure mode and effects analysis (FMEA) and What-if analysis are widely acknowledged as cheap and simple qualitative risk assessment methods where a qualitative risk matrix is often used to measure the levels of likelihood and severity. In all these methods the risk is determined by combining the severity of its impact with the likelihood of its occurrence (Rausand and Høyland, 2004). They rely heavily on expert judgment and experience, and this may prove problematic when assessing the risk of systems for which there is lack of knowledge and experiences (Vinnem, 2007; Nicola et al., 2015). Nevertheless, there is no denying that there are some advantages in using qualitative risk assessment methods.

For more stringent safety investigations, however, a quantitative method through which frequency and consequence of unwanted events can be quantified based on reliable statistics and analytical/computer-aided calculations will be necessary (Rausand and Høyland, 2004). On the other hand, for complex systems having a number of equipment working at different operating conditions, the industry often uses ‘selective’ quantitative risk assessment which examines only the risks associated with particular scenarios, operating conditions or sub-systems which are pre-identified as critical or hazardous through qualitative studies. Spouge (1999) and Vinnem (2007) have outlined general guidance of quantitative risk assessment applicable to offshore oil and gas units. Likewise, there are some example studies (Dan et al., 2014; ISO, 2015) using this framework as illustrated in Fig. 2. In this framework, qualitative risk assessment is preceded in order to identify critical parts of systems before ‘selective’ quantitative risk assessment where the focus is placed on investigating the risk of the critically-identified parts.

D’alessandro et al. (2016) has developed a decision-making tool to select an LNG regasification plant site. In this study, the feasibility of the plant site was determined through a selective quantitative risk assessment where potential hazards were identified in a qualitative way. Martins et al. (2016) also carried out a quantitative risk analysis of LNG regasification unit based on the selected hazardous scenarios.

The selective quantitative risk assessment have been also extensively applied to complex LNG technologies in the variety of marine/offshore industries. For example, Jeong et al. (2017a) investigated the explosion risk of a high pressure fuel gas supply system fitted to

LNG fuelled-ships while Chae (2016) compared the risk impacts for different types of on-board LNG liquefaction systems. In addition, Park et al. (2017) have evaluated the safety of structure of LNG liquefaction process systems for FLNG against the potential explosion and Kim et al. (2016) carried out fire simulations to determine the optimal position of water deluge systems for an offshore unit through the selective quantitative risk assessment.

The selective methods, however, inherently rule out the hazards which are either unidentified or deemed minor, possibly underestimating the overall risk level.

Fig. 2. Selective quantitative risk assessment framework (ISO, 2015).

2.2. Proposed method

Due to the short operational history of FRUs the statistical accident data is in very short supply. A method to derive the probability of failure of novel systems from the known historical data is, therefore, needed. Such a method was developed and applied to the current study. In essence, it breaks down the plant to be studied into components for which the historical data exist. The data for the overall system can then be built up by combining the component data. Not only does this method allow the use of existing data on individual components of the system, but it also enables the safety of the whole system be studied instead of concentrating on critical hazards only. A more detailed explanation of this modelling is as follows:

A complex system is divided into several sub-systems according to a set of parameters (e.g. location and operating hours) as illustrated in Fig. 3. Each sub-system is then split into sub-groups in accordance with a further set of parameters (e.g. operating pressure, temperature, system size and fuel phase). This process can be repeated until the lowest unit groups are components for which enough operational experience has been gained and accident data are therefore obtainable, such as pipes, valves, pumps and so on.

Fig. 3. Proposed quantitative risk assessment framework.

In this study, it was found that three-level hierarchy was sufficient to model the LNG regasification unit of the FRU. The risk of each group was individually assessed, and the risk of each sub-system was evaluated by summing up the risk of all its groups. The overall risk was then obtained summing the risk of all the sub-systems (Fig. 4).

Fig. 4. Proposed process of evaluating the overall risk using the hierarchical modelling.

The frequency of failure of an individual component (or sub-system) is combined with the impact of consequences (flash fire, jet fire, pool fire and explosion), completely independent of other components. There are two types of 'cross coupling' between two or more components: one is the probability of the accidents occurring simultaneously; and the other is an accident in one component bringing about an accident in another component. We can ignore the first of these because the probability of this will be extremely low, although there is a small possibility that the simultaneous accident produces a more severe consequence than the sum of the two accidents. The second cross coupling refers to the possibility of one failure escalating into a larger incident involving more than the originator component. However, we have already taken into account this type of escalation in estimating the amount of fuel leaked and accumulated in constructing the accident scenarios. Therefore, it is not unreasonable to treat the components as separate isolated systems. We can, therefore, directly combine the risks of the individual sub-systems to obtain the overall risk of the entire system.

The major consequences of fuel leak can be economical cost, environmental damage and human lives. Whilst recognising the importance of the first two types, we have decided to concentrate on the last, thus reckoning the risk in terms of probability of human lives lost in the form of F-N curves. It means the overall risk of the entire system is sensitive to the density and distribution of population exposed to the potential hazards. Thus it should be noted that the overall risk of the entire system is not a fixed value but can be changed by the density and distribution of population. The hierarchical modelling when applied to this type of risk assessment can be illustrated as in Fig. 5.

Fig. 5 An example of quantitative risk assessment using hierarchical system modelling.

If the estimated risk for the entire system is unacceptably high, safety measures must be applied (such as gas detectors with automatic isolation function). The overall risk is reassessed with the new measures added, and the process continues until the overall risk becomes tolerable.

It is thought that this approach will overcome the shortcomings and limitations of the existing qualitative and selective quantitative analyses. This idea was incorporated into the in-house integrated quantitative risk assessment software called IQRA (Jeong et al. 2017b), and the key data, parameters and models used in this study are discussed below.

2.2.1. Frequency analysis

In the event of a flammable liquid/gas being discharged through a leak, it may be ignited immediately, after some delay or not at all. Immediate ignition leads to a fire: a gas leak develops a jet fire while a liquid leak turns into a pool fire. If, on the other hand, ignition is delayed until the gas disperses, forming a flammable vapour cloud, an explosion (in confined or congested spaces) or a flash fire (in open spaces) may occur (Dan et al., 2014; ISO, 2015). In order to identify all possible routes to these final outcomes an event tree analysis (ETA) was conducted as presented in Fig. 6.

Fig. 6. An event tree (Dan et al., 2014).

The IQRA software quantifies the probability of the occurrence of the final outcomes by adopting the recognized generic data and models which are widely accepted for investigating hydrocarbon releases including LNG. In detail, the frequency of an initial leak from process equipment is analysed with respect to several representative leak hole sizes: 3 mm, 10 mm and 50 mm and 100 mm and full rupture size based on the DNV Leak Frequency Datasheets (DNV, 2012). The software also estimates the probability of ignition which is commonly determined by fuel phase and release rate; and a DNV model for immediate ignition as presented in Table 1 and OGP models for delayed ignition described in Table 2 were used in this study.

Table 1 Probability of immediate ignition (DNV, 2013).

Release rate (kg/s)		Immediate ignition probability
Gas	Liquid	
Less than 1	Less than 1.2	0.0001
1-10	1.2-25	0.001
Over 10	Over 25	0.01

Table 2 Probability of delayed ignition (OGP, 2010).

Release rate(kg/s)	Ignition condition		
	Gas (open deck)	Gas (congested)	Liquid
0.1	0.001	0.001	0.001
0.2	0.0011	0.0023	0.0014
0.5	0.0011	0.0066	0.0022
1	0.0012	0.015	0.003
2	0.0022	0.0174	0.0042
5	0.005	0.0213	0.0066
10	0.0091	0.0247	0.0092
20	0.0168	0.0287	0.0129
50	0.025	0.035	0.02
100	0.025	0.04	0.028
200	0.025	0.04	0.028
500	0.025	0.04	0.028
1000	0.025	0.04	0.028

2.2.2. Consequence analysis

The consequence analysis is carried out in several steps: calculation of liquid release rate; modelling of LNG pool spread and evaporation; and evaluating the impact of fires and explosion for each representative leak hole size.

For liquid leak model, the initial leak rate of LNG is calculated based on the classical work of Bernoulli's equation in consideration of leak hole size as well as operating pressures. With the application of the discharge coefficient, the leak rate through a leak outlet is given by Eq. (1) (DNV, 2013; Crowl and Louvar, 1990; Woodward and Pitbaldo, 2010).

$$Q_{LR}=C_L A_L \sqrt{2\rho_{LNG}(P_S-P_A)} \qquad (1)$$

On the other hand, the gas leak rate is estimated with respect to the two specific flow regimes: sonic flow for higher internal pressures and subsonic flow for lower pressures. For the gas leak model, Eq. (2) defines the pressure at which the flow regimes change from sonic to subsonic (Yoon et al., 2008).

$$(\frac{P}{P_s})_{CR}=(\frac{2}{\gamma+1})^{\frac{\gamma}{\gamma-1}} \qquad (2)$$

Eq. (3) is applicable to a gas leak rate at sonic flow condition:

$$Q_V=C_G A_L P_S\sqrt{\frac{\gamma MW}{RT_S}\left(\frac{2}{\gamma+1}\right)^{\frac{(\gamma+1)}{(\gamma-1)}}} \quad \text{for } \frac{P_a}{P_s}\le\left(\frac{P}{P_s}\right)_{CR} \qquad (3)$$

The leak rate of a gas at subsonic flow through a leak hole is given by:

$$Q_V=C_G A_L P_S\sqrt{\frac{\gamma g_C MW}{RT_S}\frac{\gamma}{\gamma-1}\left[\left(\frac{P_a}{P_s}\right)^{\frac{2}{\gamma}}-\left(\frac{P_a}{P_s}\right)^{\frac{(\gamma+1)}{\gamma}}\right]} \quad \text{for } \frac{P_a}{P_s}>\left(\frac{P}{P_s}\right)_{CR} \qquad (4)$$

To estimate the LNG spread and evaporation, the software adopts the film boiling model of Klimenko (Klimenko, 1981) based on Newton's law of cooling. To estimate the shape of pool fire, the flame model derived by Thomas (1965) is applied. The radiation effect of pool fires with tilted flame by wind effect on personnel is estimated by means of the view factors for vertical and horizontal receiving surfaces given by Hoftijzer (1979) and Ramiro and Aisa (1998). In addition, the present study adopted Cook model (Cook et al., 1990) to estimate the impact of jet fire.

In order to estimate the impact of flash fire, Gaussian gas dispersion models (Woodward and Pitbaldo, 2010; Perkins, 1974) were used in predicting dispersion effect and gas concentration. The software uses TNO multi-energy model 7 models (Woodward and Pitbaldo, 2010; Frank, 1980) for investigating the explosion impact.

To quantify the adverse impact of pool fire (for radiation) and explosion (for overpressure), the probability of fatality (P_f) was estimated by probit models described in Eqs (5) to (7) (Jafari et al., 2012; Zarei et al., 2013; Mohammadfan and Zarei, 2015). Radiation exposure time (t_e) was assumed to be 60 seconds, equivalent to the safety guidelines from the Centre for Chemical Process Safety (CCPS, 2000).

$$\mathrm{PR_F}=0.5\left[1+\frac{\mathrm{PB_{PF}}-5}{\left|\mathrm{PB_{PF}}-5\right|}\mathrm{erf}\left(\frac{\mathrm{PB_{PF}}-5}{\sqrt{2}}\right)\right] \tag{5}$$

For pool fire, $\mathrm{PB_{PF}}=-14.9+2.56\times\ln(\mathrm{q_{TR}}^{4/3}\times \mathrm{t})$ (6)

For explosion, $\mathrm{PB_{PF}}=-77+6.91\times\ln(\mathrm{P_{BW}})$ (7)

2.2.3. Risk assessment

Risk is usually expressed in terms of lives lost and injuries caused by accidents. And, therefore, the degree of risk depends on human population distribution at the site. Using the calculation results from Eqs (5) to (7), the number of fatalities caused by pool fire and explosion are calculated by Eqs (8) to (9) (Zarei et al., 2013; Mohammadfan and Zarei, 2015).

$$NF_{PF}=\int_0^{A_C} PO_D\times PR_{F\_PF}dA=2\pi\int_0^{r_C} PO_D\times PR_{F\_PF}dr \tag{8}$$

$$NF_{EX}=\int_0^{A_C} PO_D\times PR_{F\_EX}dA=2\pi\int_0^{r_C} PO_D\times PR_{F\_EX}dr \tag{9}$$

Flash fires are directional due to wind (evenly distributed in, say, East, South, North and West). Therefore, a quarter of the population (25 %) within the critical zone can be regarded as fatalities as shown in Eq. (10).

$$NF_{FF}=\int_0^{A_C} PO_D\times\frac{1}{4}dA=2\pi\int_0^{r_C} PO_D\times\frac{1}{4}dr \tag{10}$$

Similarly, the direction of a jet fire depends on the positioning of the leak hole (say, up, down, left and right). The jet fires pointing up or down are less likely to come into contact with human bodies, and therefore only the left and right directions are regarded critical (probability of 0.5). For every critical jet fire, one quarter of the population (25 %) within the critical zone can be considered as fatalities as shown in Eq. (11).

$$N_{JF}=\frac{1}{2}\int_0^{A_C} PO_D\times\frac{1}{4}dA=2\pi\int_0^{r_C} PO_D\times\frac{1}{8}dr \tag{11}$$

Finally, the assessed risk is shown as *F-N* curves (frequency vs number of fatalities).

3. Case study

3.1. Description of the case ship

The JSK FRU operating in Port of Benoa, Indonesia (Fig. 7) was selected for a case study. It supplies onshore power plants with natural gas after processing it using the on-board LNG regasification units and its principal dimensions are 46.0 m long, 12.0 m broad and 5.0 m deep.

Fig. 7. Case ship – JSK FRU (*by courtesy of JSK Shipping Co., Ltd*).

It has an LNG loading system and an LNG storage tank fitted on open space while the regasification units are placed in a partially-confined room, designated as the ‘regasification unit space’. Two sides (starboard and aft) of the space are blocked by the wall structures while the other sides (forward and port) are open.

The FRU was designed in such a way that LNG supplied by LNG carriers is stored in an LNG storage tank (IMO C type 400m^3 tank). The storage tank help stabilize the pressure and the flow of the liquid fuel before the regasification process. The feed pumps transfer the stored LNG to the vaporizers where the liquid fuel is transformed into a gaseous form through heat exchange. During the regasification process, the excessive BOG (boil-off gas), naturally occurring inside the storage tank, flows by pressure difference to the BOG process system where the gas is heated by a preheater, before being compressed by compressors. Both the vaporized LNG (natural gas) and the compressed BOG are combined and transported to the power plant nearby. The regasification process is illustrated in Fig. 8.

Fig. 8. Regasification process.

3.2. System hierarchy

Fig. 9 shows a simplified piping system diagram of the FRU topside process broken down into hierarchical groups. The whole system was separated into two sub-systems. The systems placed in open spaces were allocated to Sub-System 1 while the others located in partially-confined spaces were put into Sub-System 2. These were then divided into several sub-groups; the components were placed in the same group if operating conditions (in particular, system pressure, temperature, size and fluid phase) were identical. Fig. 10 summarises the characteristics of each sub-system and sub-group, showing the list of components belonging to each sub-group. This process of system hierarchical modelling now allows the risk of each sub-group to be quantified independently, allowing the risk of the overall system to be estimated.

Fig. 9. Simplified diagram of LNG regasification unit.

Fig. 10. System hierarchy.

3.3. Risk assessment

3.3.1. Frequency analysis

In estimating the system failure leading to LNG leak, the frequency of five leak hole sizes were used for each sub-group, making the total number of cases 20 for Sub-System 1 with its four sub-groups and 30 for Sub-System 2 with its six sub-groups. Fig. 11 shows the frequencies estimated as discussed in Section 2.2 earlier. The results show that the probability of initial leak depends on the equipment involved and their size. For example, the Sub-Group 2 in Sub-System 1 has relatively higher probability of LNG (or gas) leak than other groups. On the other hand, in general, incidences with small hole leakage is more likely to occur than those with larger hole leakage. For example, it can be observed that the frequency of 5mm leak hole is 8.0E-3 /year in Sub-Group 2 while that of 250 mm leak hole is as low as 5.0E-4. The same trend is also observed in other sub-groups. Compared with Sub-System 1, the frequency of system failure for the sub-groups in the Sub-System 2 is relatively higher, especially for the Sub-Group 3 which has many more components than others.

Fig. 11. Estimated leak frequency.

In order to estimate the frequency of the final outcomes, each case of initial leak was subjected to ETA as discussed in Section 2.2. The ETA programmed in the software has seven phases: frequency of initial leak, immediate ignition, leak duration, ventilation system, delayed ignition and final outcomes.

The scenario of limited fuel leak represents a situation where a safety system is immediately activated to isolate the leaky part of the system in the event of a fuel leak occurring. However, since the FRU as it stands does not have gas detection systems or any other relevant safety measures, the first iteration did not consider any safety measures, and therefore the leak duration led to the late isolation scenario. In addition, to ensure that the worst case scenario was followed sufficient leak duration was allowed: thus, the leak recognition and isolation were assumed to be delayed by up to 10 minutes (Dan et al., 2014).

The case ship was designed in such a way as to make natural ventilation always effective for both open deck and the regasification unit space, thus obviating the necessity of a mechanical ventilation system. Therefore, the probability of ventilation system failure was disregarded. On the other hand, the congestion ratio was assumed to be 25 % for Sub-System 1 (as one out of four directions was blocked) and 50 % for Sub-System 2 (as two out of four directions were blocked). For estimating the probability of delayed ignition for gas release, Sub-System 1 adopted the ignition model for open spaces, while Sub-System 2 used the ignition model for congested spaces as described in Section 2.2. An example of

ET (3mm leak hole of Sub-Group 1 for Sub-System 1) is shown in Fig. 12. The other cases for both Sub-Systems 1and 2 also used the same process of ETA.

Fig. 12. ET for 3mm leak hole for Sub-Group 1 of Sub-System 1.

3.3.2. Consequence analysis

The leak rates estimated using Eqs (1) to (4) are presented in Fig. 13. The results show that the main factors determining the rates are leak hole size, leak pressure and fuel phase. For example, the leak rate of Sub-Group 1 in Sub-System 1 having liquid phase with high pressure (3.0 bar) is notably higher than other groups having gas phase or low pressure in the same system. For Sub-System 2, Sub-Group 2 has the highest leak rate due to high pressure (9.35 bar) of LNG flow.

Using analytical and empirical models described in Section 2.2, the impact of each accident (jet fire, flash fire, flash fire and explosion) was evaluated. The impact of each consequence is expressed as the probability of fatalities in accordance with distance. With pool fire, for example, 100% fatalities were assumed where the effect of radiation is 35.0 kW/m^2 or above, while 50% and 10% fatalities are considered for 12.5 kW/m^2 and 5kW/m^2 respectively (Jeong et al. 2017b). Therefore, the total number of fatalities can be estimated based on the density and distribution of population provided.

For estimating flash fire, a neutral weather condition with a wind speed of 5 m/s was assumed in accordance with the prevalent annual weather records of Kuta/Bali, Indonesia (Windfinder, 2016).

Fig. 13. Estimated leak rates.

3.3.3. Assessment results

For convienience of analysis, the subject area was divided into several discrete zones according to the radius from the source: Zone 1 (below 5m), Zone 2 (5-15 m), Zone 3 (15-25 m), Zone 4 (25-50 m), Zone 5 (50-100 m), Zone 6 (100-200 m) and Zone 7 (over 200 m). These zones were then populated based on the actual data at the site as shown in Fig. 14. It was assumed that the population was evenly distributed within each discrete zone.

Fig. 14. Terminal population (*by courtesy of JSK Shipping Co., Ltd*).

Using the population distribution, the number of fatalities was estimated for each accident using Eqs (3) to (10). The results are presented as F-N graphs as shown in Fig. 15. It shows the process of risk assessment using hierarchical system modelling as well as the overall risk of the whole system (summation of Sub-Systems 1 and 2). It is a common practice to show the upper and lower limits of tolerable risk on the same graph (Norway, 2000; Vanem et al., 2008), to allow judgement of tolerability of the risk. The range of tolerable level was taken from the IMO MSC Circular 72/16.

The assessment results show that, although the risk of Sub-System 1 is well within the tolerable limit, the risk level of Sub-System 2 exceeds the limit, making the overall risk intolerably high. It was decided, therefore, that some safety measures had to be introduced to improve the safety.

Fig. 15. Process of risk assessment and risk of overall system in F-N graph.

3.4 . Risk assessment with safety measures

Given the result of intolerably high risk, an action to enhance the safety of the system is necessary. Gas detection systems fitted with an automatic alarming and valve cut-off systems were introduced for this purpose. A number of configurations were devised and the risk assessment was carried out for each. It was assumed that the initial leak is detected by the gas detector, not the crew, because there is no mandatory requirement for the presence of engineers at the site.

3.4.1. Modification of frequency analysis

An automatic gas detection system detects the presence of hydrocarbon in spaces where it is not normally expected and an alarm can be triggered when the concentration exceeds a threshold value. An emergency shut-off system is then activated to isolate the leak. The isolation can also be effected manually if the automatic isolation malfunctions.

Taking into account these mitigation measures, a modified ET was developed as shown in Fig. 16. The limited leak scenario represents the case where the safety measures prevent an initial leak from developing into unfavourable outcomes. On the other hand, the late isolated leak scenario unfolds when both automatic and manual isolation processes fail.

The failure of manual isolation can be caused by the failure of the gas detector or the alarm system, or the operator not taking or being able to take appropriate action when the alarm sounds. This leads to the emergency shut-off valve failing to close in time. Where automatic isolation is used, a failure of either the leak detector or the shut-off valve leads to the failure of the automatic shut-down. In both cases of failure the isolation of the leak is at least prolonged, possibly for some time.

In order to examine the probability of the late isolated leak scenario, the present paper adopted FTA (fault tree analysis) method using the generic data about safety system failure from various sources as showin in Table 3.

The failure rate per year, λ, was calculated from the upper failure rates given by the named sources. The reliability of each equipment was then estimated using Eq. (12) (Santamaria and Brana, 1998).

$$R(t) = e^{-\lambda t} \tag{12}$$

Table 3 Reliability data for safety systems.

	Safety system list	λ	Reliability R(t)	Unreliability (1-R(t))	References
1	Gas detector	3.67E-01	0.6930	0.3070	(ORADA, 2009)
2	Alarm	2.50E-04	0.99975	0.00025	(EPRI, 1995)
3	Operator to obey alarm	-	0.97	0.03	(KletzT, 1991)
4	Cut-off V/V	1.86E-02	0.9816	0.0184	(CCPS, 1989)

Fig. 17 shows the result of FTA when one gas detection system was used for the safety system (referred to as Case 1 hereafter) while Fig. 18 is for two gas detection systems used (referred to as Case 2 hereafter). It was found that the probability of the late isolation associated with Case 2 was 0.014, far less than Case 1 that was 0.113. Given that the consequence of the hazards are closely related to the leak duration, two gas detection systems will guarentee higher reliability to limit the leak duration, thereby reducing the consequece of hazards, than one gas detection system. The estimated probabilities of successful gas detection and appropriate action taken are applied to the ETs. Examples of modified ETs for Cases 1 and 2 are shown in Fig. 19.

Fig. 16. Modified ET.

Fig. 17. FT for late isolation with one gas detector.

Fig. 18. FT for late isolation with two gas detectors.

Fig. 19. Modified ETs for 3mm leak hole for Sub-Group 1 of Sub-System 2.

3.4.2. Assessment results

The initial HAZOP study recommended the installation of gas detection systems into three points: LNG storage tank, regasification unit and BOG process unit. In this context, the idea of the present study is to investigate the optimum arrangement of gas detection systems from the safety point of view. Firstly, one or two safety measures was applied to Sub-System 1 only and the risk assessment was carried out with the result shown below. The same safety measure was applied to Sub-System 2 only and the overall risk level was evaluated in the same manner. The results were then compared with the tolerable risk level to find out the optimum solution.

Safety measures applied to Sub-System 1

Fig. 20 shows the assessment results when the safety measures (both Cases 1 and 2) were applied to Sub-System 1. It is plain that this use of the safety measures did nothing to reduce the overall risk of the entire system. In both cases, the frequency of the entire system in accordance with the number of fatalities exceeds the upper limit of tolerable level in some areas in the graph. This result is as expected because the risk of Sub-System 1 was low enough to be tolerable to begin with. This confirms that introducing safety measures to areas of low risk is ineffective.

This result indicates that one of the safety recommendations from the original HAZOP study (i.e. installation of gas detectors with automatic isolation system at the LNG storage tank) would have been ineffective.

Fig. 20. F-N graphs of risk with safety measures incorporated in Sub-System 1.

Safety measures applied to Sub-System 2

Fig. 21 shows the outcomes of the gas detection systems incorporated in Sub-System 2, suggesting that this addition to Sub-System 2 will be effective. In both cases, the F-N curve was seen to have been brought down to below the tolerable limit. Furthermore, a single gas detection system is seen to be sufficient, while two detection systemss lower the risk further.

Given this, it can be concluded that at least one gas detection system applied to Sub-System 2 can constitute 'the appropriate number of gas detectors' as mentioned in the original HAZOP recommendations.

Fig. 21. F-N graphs of risk with safety measures incorporated in Sub-System 2.

3.4.3. Comparison with selective quantitative risk assessment

In order to investigate the effectiveness of the hierarchical quantitative method proposed in this paper, the same system was studied using the selective quantitative analysis for comparison. Three accidental scenarios identified through the HAZOP study were used for this selective quantitative risk assessment (Korean Register, 2015).

- Scenario 1 - Liquid leak between LNG feed pump and regasification unit

- Scenario 2 - Vapour leak from BOG processing unit
- Scenario 3 - Liquid leak from LNG storage tank

A leak from manual valves and pipes attached to the systems were reckoned as the most probable case through the HAZOP study. For a stringent analysis, the leak was assumed to take place at the parts subjected to the highest pressure and the biggest piping system. In this context, the list of equipment involved in Scenario 1 is identical to Sub-Group 2 of Sub-System 2 while those of Scenarios 2 and 3 are the same as Sub-Group 4 of Sub-System 2 and Sub-Group 4 of Sub-System 1 respectively. The analysis results are summarized in Fig. 22 and Table 4. As can be seen, the risks of all scenarios are within the tolerable zones in the F-N graphs, implying that enhancing the safety of FRU is unnecessary.

Fig. 22. F-N graphs of risk from selective quantitative risk assessment.

Table 4 Results of selective quantitative risk assessment.

	Scenario 1	Scenario 2	Scenario 3
Frequency of outcomes	1.75E-4/year	1.21E-5/year	2.75E-5/year
Consequence of outcomes	Multiple fatalities	Multiple fatalities	Multiple fatalities
Safety system	Unnecessary	Unnecessary	Unnecessary

This conclusion is somewhat at odds with the conclusions of the HAZOP study and the hierarchical quantitative assessment. It is to be noted that the risk levels obtained from the selective quantitative assessment are far lower than the results obtained from the current study. This suggests that the selective assessment can underestimate the risks of safety-critical complex systems.

4. Discussion

The history of FRUs is very short indeed, and consequently there is no accumulated historical failure data available. While there are many publications associated with the safety of LNG processing systems on-shore in chemical industries, only a few publications deal with FRUs. It is hoped that the work presented in this paper show a way of tackling the safety of FRUs.

The principle of the hierarchical modelling method is a process of analysing and synthesising: the system is 'analysed' to the component level and the frequency of the system is then 'synthesised' from the failure frequencies of the basic components. We believe that this principle can be applied to any situation where the overall risk consists of multiple hazard factors such as collision, excessive ship motions, harsh weather conditions and human failure.

The frequency analysis presented in this paper had to rely on available generic data compiled for investigating the safety of LNG process equipment in offshore and chemical industries. It is inevitable, therefore, that some of the quantitative results obtained from this study may not reflect reality. This may have to be carefully examined in the future, but effort has been made to be realistic using available data by breaking down the system to component level for which such data exist. It is thought that the hierarchical method goes considerable way towards generating realistic frequency data.

It is recognised that the impact and consequences of accidents can vary widely depending on such factors as the structural arrangement within the FRU and the weather conditions at the time of the accidents. One way of dealing with this problem is to carry out the analysis for a number of conditions and attach the probability of occurrence of such conditions. Of course, such exercise will have to use 'state-of-the-art' numerical tools, such as CFD and FEA, to analyse the consequences. It is important to point out here is that this paper is the record of a generic study, primarily to discover if the current practice of safety or risk assessment is adequate and can be relied upon to identify high risks.

5. Concluding Remarks

The present paper investigated the potential risk of the topside units fitted on an FRU using a hierarchical method. The results were compared with those obtained by the initial qualitative risk assessment and the selective analysis. This is summarised in Table 5.

Table 5 Summary of study results.

Analysis	Qualitative risk assessment (HAZOP)	Selective quantitative risk assessment	Proposed quantitative risk assessment (with system hierarchy)
Frequency analysis	Up to once a year	1.75E-4/year (Scenario 1)	2.14E-3/year
Consequence analysis	Multiple major injuries or single fatality	Multiple fatalities (All cases)	Multiple fatalities
Safety measures	Appropriate number of gas detection systems is to be fitted to; 1) Regasification unit 2) BOG processing unit 3) LNG storage tank	Not necessary (All cases)	Minimum one gas detection system is to be fitted to regasification unit space (Group 2)

The initial HAZOP study identified fire/explosion caused by leak from pipe and valves as the most intolerable scenario, which may occur between once a year and once per ten years, causing multiple major injuries or a single fatality. It was recommended that the safety measures be independently applied to regasification unit, BOG processing unit and LNG storage tank.

A selective risk assessment on major hazardous scenarios already identified by the initial HAZOP study was conducted. The results show that the risk of Scenario 1 with the accidental frequency of 1.75E-4/year was the most critical case. Although the consequence of fire/explosion was assessed as multiple fatalities, the estimated risk levels for all scenarios were found to be tolerably low, obviating the need for further safety measures.

The present paper, on the other hand, assessed the individual risk of all sub-systems under different working conditions and, based on this, evaluated the overall risk of the whole system. In this way no part of the system was allowed to be disregarded. The probability of the occurrence of an accident was 2.14E-3/year which is far higher than the one obtained by the selective quantitative risk assessment, but somewhat lower than the results from the HAZOP study.

The outcome of the initial iteration suggested that some form of safety measures was necessary. It was subsequently found that one gas detector with the automatic isolation unit applied to the regasification unit space only is sufficient to bring the overall risk to an acceptable level.

Last but not least, the present study also shows the hierarchical system modelling method as implemented in an in-house integrated quantitative risk assessment software is effective and can be used as a general investigative tool in the safety matters of complex systems.

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