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Facilitating Hazard Analysis of LNG Carrier Operations via Risk Matrix Approach

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ABSTRACT

System failures and catastrophic accidents are being experienced in various industries in recent time. Experiencing such accident in gas industry will result to loss of lives, loss of billions of dollar investments and damage to the environment. To subdue occurrence of such accidents in the LNG industry, this study aims at demonstrating how risk matrix approach and experts' judgement can be incorporated in hazard analysis of the LNG carrier operations. The study revealed that the mechanism of the risk matrix technique can be used to reveal the risk levels of various hazards of the LNG carrier operations.

Keywords: *LNG Carrier, Risk Matrix, Risk, Hazard*

1. INTRODUCTION

The recent interest in increasing fleet of LNG carriers and expansion or building of new LNG facilities to accommodate the carriers, along with increased awareness on potential terrorist threats has caused stakeholders to raise questions about the potential consequences of incidents involving LNG carrier operations (ABS consulting, 2004). Therefore, hazard identification (HAZID) needs to be carried out on a generic LNG carrier. The greatest concern of LNG carriers is hazards that could cause LNG spills. Some of these hazards are regarded as high risks to the LNG carrier operations. Expert judgment is used to estimate the high risks hazards due to uncertainties of their failure rates. HAZID of a generic LNG carrier will proactively ensure the safety of LNG vessels and their systems/subsystems if acted upon, as well as provide a basis of analysing the measures of their pollution prevention to the maritime environment.

In this study, the safety of LNG carriers is introduced and various types of the carrier are identified and described. All relevant hazards that might affect the proper functioning of LNG carriers and their systems and subsystems are identified using a brainstorming technique. The above process is proactive and not confined only to the hazards that materialised in the past. Previous experience is properly taken into account and background information such as applicable regulations and codes, list of hazards of LNG carriers, hazardous substances and ignition sources are used. The failure rate values of the generic LNG carrier systems may be difficult to achieve because of the high level of uncertainties associated with the historical data. Therefore, use of expert judgment and a risk matrix technique can provide an alternative solution of revealing high risk hazards of LNG carriers.

2. LITERATURE REVIEW

The usefulness of risk matrix technique has been demonstrated in various industries. A risk matrix technique has been adopted in the fishing industry to prioritize issues across the seven most valuable Western Australian commercial fisheries (Fletcher, 2005). The brainstorming technique is used by stakeholders to identify issues across three ecological areas such as retained species, non-retained species and the broader ecosystem for each fishery. The risk associated with each issue is assessed using one of the five sets of consequence criteria specifically developed to cover fishery-related impacts. The risk score for each issue is revealed using the mechanism of the risk matrix technique. Identification of the group of worst issues in 115 issues across the three ecological areas, improved their entire fish management processes.

Other usefulness of the risk matrix technique has been revealed in the defence industry to estimate the risks of hazards associated with military defence systems (Military Standard, 1993). Their experts carried out the HAZID using the brainstorming technique. The experts applied the risk matrix technique to the hazards of the defence systems by using four categories of occurrence likelihood of hazards and four consequence levels on the systems.

In the process industry, the risk matrix technique has also been used in the selection of accident scenarios of an ethylene oxide storage system which needed to be modelled in the calculation of the severity of hazards (Delvosalle, 2006). The usefulness of the risk matrix technique has been proven in management science (Haifang, et al., 2009). In the authors' work, a risk matrix technique is adopted in identification of the key risk factors of the use of private capital in a government project. The work of Zhu et al. (2003) demonstrated the effectiveness of risk matrix technique in technical project risk management.

Eleye-Datubo (2006) and Loughran et al. (2002) have proved the relevant of the risk matrix technique in the maritime industry. In Loughran et al. (2002), the risk matrix technique is used to prioritized hazards of a fishing vessel, while in Eleye-Datubo (2006), the technique is used in qualitative risk analysis of bulk carrier. Since the International Maritime Organization (IMO) recommended the risk matrix technique in their rule making process (IMO, 2002), it is applied in this study. The LNG carrier hazards are identified and their risk levels are revealed using the expert judgement and the risk matrix technique in this study. The high risk hazards are represented with FT diagrams for detailed risk analysis in future studies.

3. SAFETY OF LNG CARRIERS

The LNG carrier has an exemplary safety record in terms of cargo loss in the maritime industry. Few accidents have occurred since the first converted freighter delivered a Lake Charles, Louisiana cargo of LNG to the United Kingdom in January 1959, none involved a major release of LNG (CLNG, 2008; Nwaoha et al. 2011). The safety record of the LNG carrier is attributed to the safety design of systems and sub-systems operation. The effectiveness of the LNG shipping industry in handling accidents that happened in the industry is also a contributing factor. The LNG shipping industry adopts four levels of awareness in addressing safety issues. These are (Chauvel, 1997):

- Discovering. Associated with curiosity on what went wrong, which results in development of better ideas for improvement.
- Learning. Once new and better ways of doing things have been discovered, this knowledge has to be accepted and passed to future generations and other colleagues in the LNG shipping industry.
- Understanding. Once new ways of working have been established, research and reflection facilitate the level of understanding of the principles based on scientific methods.
- Developing. This is the final stage of the cycle based on the understanding. A new system can be developed with confidence because the outcome can be safely controlled.

The containment tank of a LNG carrier stores LNG at a temperature of about –256^{0}F (-160^{0}C) (California Energy Commission, 2003). All LNG carriers are constructed with double hulls (Sandia National Laboratory, 2005). This construction method improves the integrity of the hull system and provides protection for the cargo containment tanks in the event of an accidental collision (Sandia National Laboratory, 2005). The LNG carrier has cargo handling, ship handling and safeguard systems that have the ability to ensure safe delivery of LNG from source to the destination (Foss, 2003). The major sections, operations and functions of the LNG carrier is illustrated in Figure 1. LNG carriers are built with three major cargo containment tanks such as (Foss, 2003).

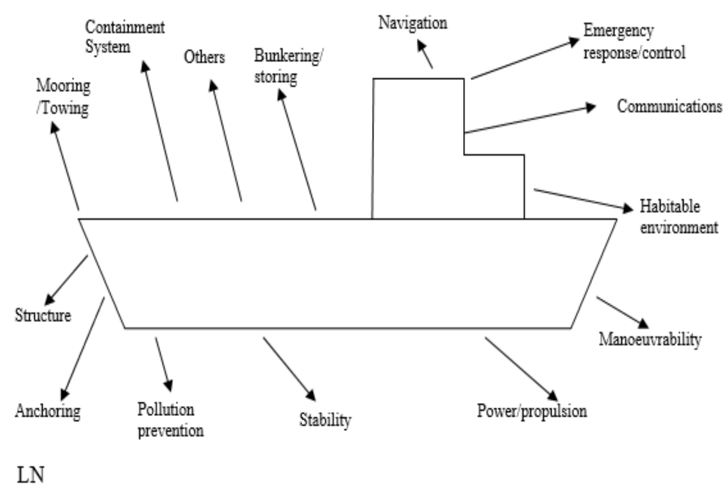

Figure 1: A Generic LNG Carrier

- Membrane tank design.
- Spherical (moss) tank design.
- Structural prismatic tank design.

3.1. Membrane Tank Design

Most LNG carriers are built with membrane tanks that have double containment. The double containment is made up of primary and secondary containment. The primary containment holds LNG while the secondary containment secures the LNG whenever there is leakage. The inner shell consists of thin stainless steel called a membrane that is about 0.7-1.2millimeters (mm) thick (Pitblado et al. 2004). It is capable of containing the hydrostatic load of LNG, though relies on the vessel for structural support (Pitblado, et al. 2004;

Sandia National Laboratory, 2005). Plywood and thick perlite or polyurethane insulation separates the membranes and the space between them is filled up with nitrogen. The membrane tank design has almost zero stress and its structure is below the main deck of the LNG carriers. Such features protect the carriers from external/terrorist attacks (Foss, 2003). A large cofferdam separates each membrane tank so as to reduce the potential of an event in one tank affecting the other (Pitblado, et al., 2004).

3.2. Spherical (Moss) Tank Design

Some of the LNG carriers have spherical (moss) containment tanks. Spherical (moss) tank design has double containment as membrane tank, but with different tank shape. Any LNG carrier containment tank that has a spherical shape, maintains its own structural integrity, without depending on the vessel for support. The LNG carrier containment tank is exposed to external/terrorist attack because the covers of spherical tanks are above the carrier deck, though the tanks are separated with barriers. Aluminium with thickness of 29 to 57mm is used to construct the spherical tanks (Pitblado et al. 2004). The secondary barrier of a spherical (moss) tank is a splash barrier with a drip pan at the bottom from which accumulated liquid evaporates, because the tank does not depend on the vessel for support (Foss, 2003). The holds collect spilled LNG and the vessels contain equipment capable of recovering LNG (Sandia National Laboratory, 2005). The tanker uses nitrogen to purge some below decks spaces to aid in preventing fires (Sandia National Laboratory, 2005).

3.3. Structural Prismatic Tank

The structural prismatic tank design is similar to a membrane tank. It has the same secondary containment and primary containment safety systems. The tank is also similar to the spherical (moss) tank because it is a self-supported tank that does not rely on the vessel for support (Sandia National Laboratory, 2005). Prismatic tanks are designed to conform to the shape of the LNG carrier's hull, thereby occupying much of the internal area of the carrier. It minimizes the areas in which LNG from a tank rupture or spills can be diverted (Sandia National Laboratory, 2005).

4. HAZARDS OF LNG CARRIERS

Despite all the safety features of LNG carrier systems and subsystems, there are still potential hazards that might impair the proper functioning of the LNG carrier operations. Most of these hazards seem to be unavoidable during the operational mode of the LNG carrier systems and subsystems. These hazards are identified and screened using a brainstorming technique by experienced marine professionals. Four experts such as marine risk analyst, marine safety engineer, marine chief engineer and ship captain employed in this study are considered to have equal experience of the LNG carrier operations. The identified hazards of the LNG carriers are the ones associated with their operations and external events. These include overfilling of tanks, structural damage due to incorrect loading, overpressure of tanks, unignited leak in the cargo system, fire in cargo handling, fire in forward storage area, explosion in engine room due to crank house failure, explosion in cargo handling, earthquake, lightning, sabotage, war action, collision, workplace accident, crane operations, working in tanks/enclosed spaces, operating error, leak from LNG loading arm, loss of instrumentation during the LNG loading operations, unignited leak from the LNG tank, ignited leak from the LNG tank, gas freezing and waves.

5. Methodology of Risk Matrix

In the LNG carrier operational environment, risk is defined as the occurrence likelihood of a LNG hazard and the consequence of such occurrence. A risk matrix technique is a method that combines occurrence likelihood of a hazard and its possible consequence in matrix form for estimation of the risks of that hazard. Its effectiveness has been demonstrated in Eleye-Datubo (2006); Helebsky (1989); Pillay and Wang (2003); Tummala and Leung (1995). The risk matrix technique are used to screen out low risk hazards and identification of high risk ones in the LNG carrier operations. Table 1 can be used to facilitate such exercise. Information in Table 1 is employed in development of Table 2, which is the risk matrix table. In the application of the risk matrix technique, the services of experts are employed in the estimation/judgment of hazards of any system/operations under investigation, including the LNG carrier operations. Figure 1 illustrates various part and operations of the LNG carrier that can facilitate identification and screening of the hazards of the system for optimal operations of the vessel.

Table 1: Risk Parameters and Levels of the LNG Carrier Hazard

Parameters	Levels/linguistic terms	Numerical ratings	Meanings
Consequence of a LNG carrier hazard	Negligible	1	Less than minor system damage, less than minor injury/illness of personnel or negligible environmental damage.
	Marginal	2	Minor system damage, minor injury/illness of personnel or minor environmental damage
	Critical	3	Major system damage, severe injury/illness of personnel or major environmental damage
	Catastrophic	4	System loss, death of personnel or severe environmental damage.
Occurrence likelihood of a LNG carrier hazard	Less possible	1	The LNG carrier hazard is unlikely to occur compared to other LNG carrier hazards.
	Possible	2	The LNG carrier hazard is likely to occur compared to other LNG carrier hazards.
	More possible	3	The LNG carrier hazard is reasonably likely to occur compared to other LNG carrier hazards.
	Most possible	4	The LNG carrier hazard is highly likely to occur compared to other LNG carrier hazards.
Risk of a LNG carrier hazard	High	6-8	LNG carrier operations have to be prohibited until the risk is reduced to an acceptable level.
	Moderate	5	LNG carrier operations can continue while risk reduction measures are being applied at an acceptable cost.
	Low	3-4	LNG carrier operations continue while efforts are being made to reduce the risk, but the cost of prevention should be carefully measured and limited. Risk reduction methods should be implemented within a defined time period.
	Very Low	2	Actions are required on the LNG carrier while in operation, if there is no additional cost burden.

Table 2: Risk Matrix Table

Consequences of hazards with scores that are expressed in $\log_{10} 10$	Occurrence likelihoods of hazards with scores that are expressed in $\log_{10} 10$			
	1. Less possible	2. Possible	3.More possible	4.Most possible
1. Negligible	2	3	4	5
2. Marginal	3	4	5	6
3. Critical	4	5	6	7
4. Catastrophic	5	6	7	8

In Table 2, each of the scores of the occurrence likelihood and consequence of the hazards are expressed in a logarithmic scale. For example, a score of 2 is equivalent to $\log_{10} 10^2$. In Table 2, the risks associated with the hazards are the areas of intersections of the rows and the columns. Thus, 2, 3, 4, 5, 6, 7 and 8 are the scores of the risks associated with the hazards. The risk levels are revealed in Table 1. From the Table 1, high, moderate, low and very low risk levels are associated with 6-8, 5, 3-4 and 2 risk scores respectively. Mathematically, risk is defined as:

Risk (R) = Occurrence likelihood of a Hazard × Consequence of the Hazard (1)

Log (Risk) = Log (Occurrence likelihood of a Hazard) + Log (Consequence of the Hazard)

6. A TEST CASE

The qualitative risk assessment of the hazards of generic LNG carrier operations using a risk matrix technique is carried out in this study. The risks of hazards of a generic LNG carrier are estimated by expert judgement using the risk matrix table (i.e. Table 2). The experts involved have been described in Section 4.

The experts estimated the risk of a hazard (i.e. overfilling of LNG tanks) using the information in Tables 1, 2 and Equation 2. The experts estimated occurrence likelihood and consequence of "overfilling of LNG tanks" as "more possible" and "marginal" respectively. In Tables 1 and 2, "more possible" and "marginal" have scores of 3 and 2 respectively. Therefore, application of Equation 2, implies that the risk score of "overfilling of LNG tanks" is 5. This value indicates a moderate risk level as evidenced in Table 1.

In a similar way, occurrence likelihoods, consequences, risk scores and risk levels of structural damage due to incorrect loading, overpressure of tanks, unignited leak in the cargo system, fire in cargo handling, fire in forward storage area, explosion in engine room due to crank house failure, explosion in cargo handling, earthquake, lightning, sabotage, war action, collision, workplace accident, crane operations, working in tanks/enclosed spaces, operating error, leak from the LNG loading arm, loss of instrumentation during LNG loading operations, unignited leak from the LNG tank, ignited leak from the LNG tank, gas freezing and waves are revealed as (possible, critical, 5, moderate), (less possible, catastrophic, 5, moderate), (less possible, critical, 4, low), (possible, critical, 5, moderate), (possible, critical, 5, moderate), (less possible, marginal, 3, low), (less possible, critical, 4, low), (less possible, catastrophic, 5, moderate), (less possible, marginal, 3,low), (Less, possible, critical, 4, low), (less possible, catastrophic, 5, moderate), (possible, critical, 5, moderate), (less possible, marginal, 3, low), (less possible, critical, 4, low), (less possible, catastrophic, 5, moderate), (more possible, marginal, 5, moderate), (most possible, catastrophic, 8, high), (less possible, marginal, 3, low), (possible, critical, 5, moderate), (most possible, catastrophic, 8, high), (more possible, marginal, 5, moderate) and (possible, critical, 5, moderate) respectively.

From the hazard and risk assessment exercise, it has been revealed that the "ignited leak from the LNG tank" and "leak from LNG loading arm" are the high risk hazards. This information is very important in the risk management of the LNG carrier operations and resource allocation. Therefore, attention should be focused on the high risk hazards. A fault tree analysis (FTA) can be employed in comprehensive risk analysis of these high risk hazards. Thus, the top events of the two high risk hazards of a generic LNG carrier are represented using the FT diagrams with undeveloped events in Figures 2 and 3 to facilitate future studies. In Figure 2, a LNG containment system fails when structural defect, corrosion, fire and explosion, structural potential pressure difference (PD) or failure of supporting structure happens. In Figure 3, a LNG spill from transfer arm occurs when transfer arm failure, material defect or failure of piping happens.

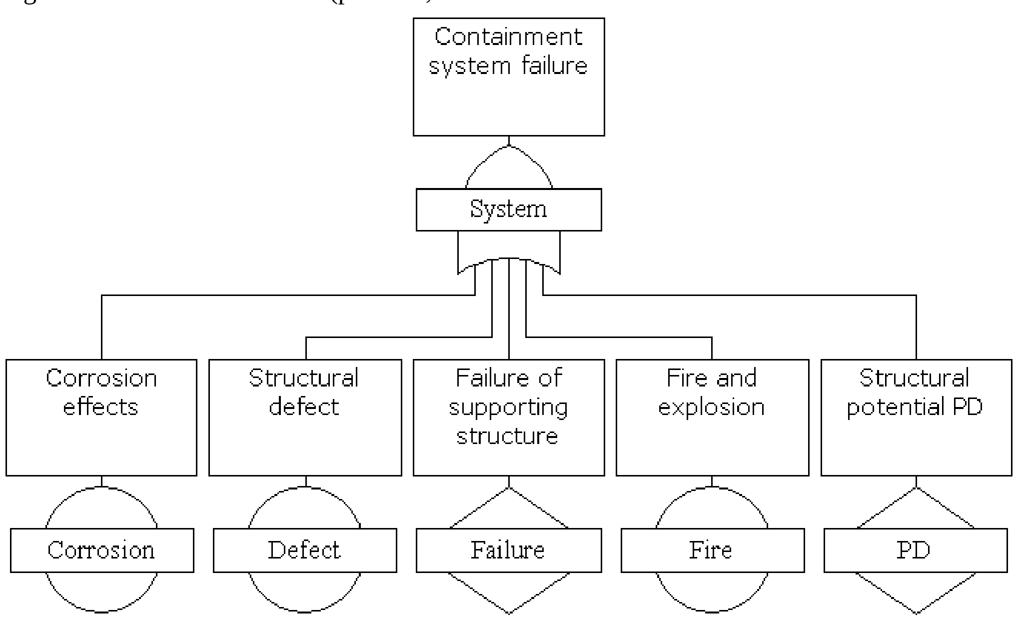

Figure 2: Fault Tree of a LNG Containment System Failure

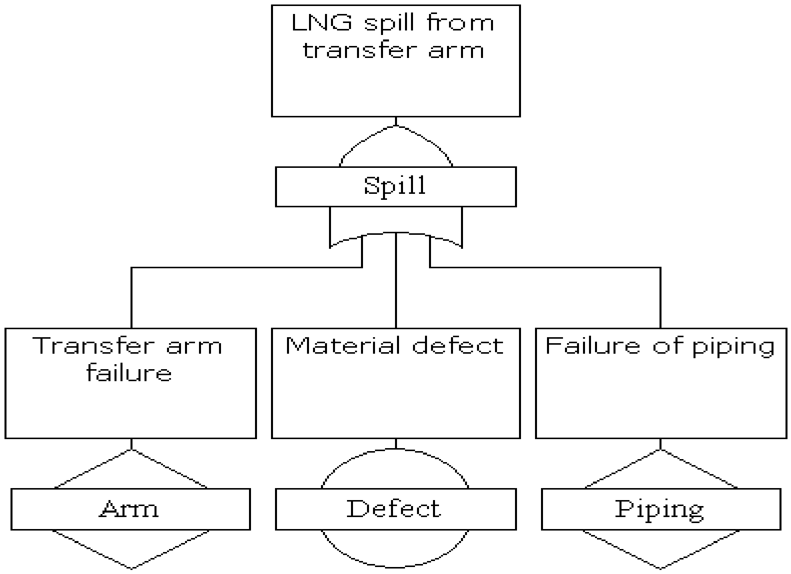

Figure 3: Fault Tree of a LNG Spill from Transfer Arm

7. Conclusion

The paper presents a structured framework for capturing needed information during hazard analysis of LNG carrier operations. The use of risk matrix technique in hazard analysis of the LNG carrier operations has been demonstrated in this study. Experts' judgement, risk matrix table and risk formula are used to calculate the risk scores of hazards of the LNG carrier, thereby revealing their risk levels. High risk is associated with high score and vice versa, as defined in the risk matrix table. The study revealed "ignited leak from LNG tank" and "leak from LNG loading arm" as the high risk hazards. The occurrence and consequence of these hazards cannot be tolerated in the LNG industry. Therefore, further investigation is needed on their causes. In view of this, the FT diagrams with undeveloped events are used to represent these high risk LNG carrier hazards for detail risk analysis using advance techniques in future studies. The proposed methodology in this study is most beneficial during the earliest stage of risk assessment of the LNG carrier operations, due to its ability to reveal high risk hazards and screen out low risk ones. This can optimize oil and gas company's resource allocation, as less attention will be given to low risk hazards.

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