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LNG Carriers Safety: A Research Perspective

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ABSTRACT

Over the past few years, there has been substantial increase on voyages and investment in the LNG carriers systems due to high demand of the liquefied natural gas (LNG) across the globe. Maritime and offshore accidents resulting from LNG spills have resulted into catastrophic consequences with long term financial implications to operators in the industry. Therefore, the safety of the LNG value chain is very important. This research provides an insight into the background of LNG systems, analysis of safety/risk assessment of one of the component of a LNG value chain such as the LNG carrier. The analysis include properties and hazards of LNG, various safety/risk analysis techniques, overview of LNG carriers including the incidents/accidents, the regulations governing the safety of its shipping and the overview of formal safety assessment (FSA) of ships. Finally, conclusion is drawn.

Keywords*: LNG, Safety, LNG Carrier, Risk Analysis.*

1. INTRODUCTION

LNG carriers are expensive and complex engineering structures for which there is need for proactive risk assessment of their operations because catastrophic accidents such as cargo loss cannot be tolerated. Various researchers have contributed in improving safety of LNG carrier operations by carrying out risk analysis of LNG operations. The main safety concern of LNG carriers is the release of large amounts of LNG or its vapour. Risks associated with LNG hazards to people, damage to LNG carrier systems and the environment need to be estimated and reduced. A quantitative risk analysis approach has been applied to a generic LNG carrier using the formal safety assessment (FSA) principle (IMO, 2007; Vanem et al., 2008). Event Tree Analysis (ETA) method was used to identify the consequences of collision, grounding, contact, fire/explosion and loading/unloading risks of LNG carrier operations in the FSA process. Collision risk was found to be the highest when the As Low As Reasonably Practicable (ALARP) principle was applied. Other researchers have carried out qualitative and quantitative risk analysis of LNG carrier systems and LNG terminals, including the works of Bubbico et al. (2009), Hyo et al. (2005), Moon et al. (2009), Østvik et al. (2005), Pitblado et al. (2004), Vanem et al. (2006) and Nwaoha et al. (2011a, 2012b, 2013).

In bublico et al. (2009)'s work, a preliminary risk analysis of LNG carriers approaching the Panigaglia maritime terminal was conducted. The intentional damages of the containment systems of the LNG carriers by terrorist attacks caused pool fires. The consequence analysis showed that dangerous thermal effects were expected within a radius of 700-1500m in the location under examination. The impact on residential population was negligible while that of anchorage was marginal. Similarly, Pitblado et al. (2004) investigated the risk and consequence analysis of accidental failures such as terrorist attacks on LNG carriers approaching a generic LNG terminal in USA. In the works of Hyo et al. (2005), a quantitative risk assessment of the Korea onshore LNG storage tank was carried out using a Fault Tree analysis (FTA) method. The research considered events involved during the loading and unloading of LNG carriers as one of the six accident categories that could cause a LNG spill from the Korea onshore LNG storage tank. Various FTA diagrams for the identified six accident categories were developed and their failure probabilities evaluated. Also, a study by Østvik et al. (2005) revealed how a qualitative risk assessment technique was undertaken to estimate risks of a 138000m^3 membrane type LNG carrier under construction by Navantia. They considered various operational phases of LNG vessels while identifying the hazards and estimated the risks of the hazards using expert judgements.

Research conducted by Moon et al. (2009) highlighted risk assessment of different gas turbine propulsion system designs for LNG carriers with the aim of identifying hazards associated with each design and the most significant contributors to such hazards. The causes of gas release were investigated, focusing on novel features of the gas turbine propulsion systems. Further investigations were conducted to identify ways to reduce the risks and causes of gas release. Nwaoha et al. (2011a) conducted a probabilistic risk assessment (PRA) on LNG carrier systems using a FTA. The research proposes a novel Fuzzy Evidential Reasoning (FER) model for the treatment of uncertainties of failure modes of the LNG containment system and transfer arm based on the FSA methodology. Advanced computing techniques are proposed to deal with uncertain situations in Nwaoha et al. (2013). In the work, a combination of risk matrix and FER were used to carry out risk-based ranking of LNG carrier hazards.

Therefore, literature review is carried out to investigate the properties of LNG and its carriers, and the various LNG accidents/incidents. Such an investigation can assist analysts in the improvement of safety of LNG shipping operations with particular emphasis on safety/risk assessment using probabilistic and subjective approaches. The LNG accidents/incidents revealed in this study shows a rapid increase in the number of voyages per year due to high demand of LNG, support the argument that there is need to carry out regular risk assessment of LNG carrier operations using a proactive approach. In view of this, various risk assessment tools are discussed and the efficient approaches are identified and recommended for LNG carrier operational risk assessment. Formal safety assessment (FSA) is also discussed. The maritime industry adopted FSA in 1990s as a proactive tool to tackle various marine accidents. FSA has changed the traditional reactive regulatory framework toward a risk-based and goal-setting regime (Godaliyadde, 2008).

2. SAFETY OF LNG

The safety record of the LNG industry is outstanding compared to other petroleum/process industries. This is evident by the few incidents and accidents that have happened since 1912, when the first LNG plant was built in West Virginia. The research conducted by Foss (2003) revealed that the success of the LNG industry in terms of safety is based on the following factors:

- The industry has technically and operationally evolved to ensure safe and secure operations. Technical and operational advances include everything from the engineering domain that underlies LNG facilities to operational procedures and technical competency of personnel.
- The physical and chemical properties of LNG and its associated hazards and risk are well understood and incorporated into their technology and operations.
- The high standards and regulations that are applied to the LNG industry.

Safety is defined as freedom from unacceptable risk or personal harm (Wang and Trbojevic, 2007). This is applied to LNG facilities, including LNG carriers because of the potential hazards that might affect their operations. A hazard is a physical situation or condition with a potential for injuries/deaths, property damage, damage to the environment or some combinations of these (Wang and Trbojevic, 2007). Risk mitigation and hazard prevention measures are applied to a LNG value chain. Risk mitigation measures are used to reduce the consequences of hazards, while hazard preventive measures prevent the occurrence of hazards and their undesirable consequences. Risk is defined as a combination of the probability of occurrence of an undesired event and the degree of its possible consequences, or a term which combines the chance that a specified undesired event will occur and the severity of the consequences of the event (Wang and Trbojevic, 2007).

Though various safety measures secure the operations of the LNG value chain, they are still prone to accidents. An accident on a particular component of a LNG value chain can affect another component. For example, an accident/incident on the LNG carrier operations during loading/unloading of LNG can affect the LNG storage tank via the pipelines. The LNG carrier operational hazards can be identified using a brainstorming technique, after analyzing the safety features of the components that make up the LNG value chain. The LNG value chain has five main functions such as natural gas production, liquefaction of natural gas, transportation of LNG, re-gasification and distribution (Naturalgas Online, 2010). In natural gas production, the production process involves drilling and completion of natural gas well, followed by strengthening the well hole with casing, and evaluation of the pressure and temperature of the formation, before installation of the proper equipment for an efficient flow of natural gas out of the well to the liquefaction facility (Naturalgas Online, 2010). The liquefaction facility is used to convert natural gas to its liquid state in order to facilitate LNG transportation using LNG carriers. Safety features of the liquefaction facility are secondary containment of the LNG storage tanks for LNG isolation in event of an accident, automatic shutdown down and fire alarm systems for undesirable conditions. Transportation of LNG is the shipment from one containment tank to another using the LNG carriers. With the increase of LNG demands and distributions, the safety concern of LNG shipping is increasingly growing, attracting more and more attention and research. Therefore, the containment systems of LNG carriers have more than four layers that secure LNG, coupled with their double hull systems that reduce the risk of gas spills. In regasification of the LNG, vaporizers are used to convert the LNG to its gaseous state. HSE policies and industrial safety rules and regulations are practiced to avoid environmental pollution and exposure of workers to risk (HSE, 2011). Pipelines are used to transport the produced natural gas from the re-gasification process to end users. These pipelines are constantly inspected to ensure safe distribution of natural gas. Pipeline inspection reveals the safety level of the pipelines so that appropriate action or correction will be taken if anything has gone wrong. The pipeline inspection is carried out using inspection techniques such as internal (magnetic flux leakage, ultrasonic, geometry/calliper and eddy current tool), external (Remote Operated Towed Vehicle (ROTV) and Remote Operated Vehicle (ROV)) and diver inspection.

3. PROPERTIES OF LNG

LNG is natural gas that is liquefied at a temperature of approximately –256^{0}F (-160^{0}C) in order to ease the storage and transportation. It occupies 1/600th the volume of its gaseous state. The raw natural gas is mainly produced from oil, gas or condensate well. Natural gas is composed of large percentage of methane and small percentages of other compounds such as propane, ethane, pentanes, water vapour, hydrogen sulphide, carbondioxide, helium, nitrogen and rare gases. The quality of natural gas is improved using processes such as oil and condensate removal, water removal, separation of natural gas liquids, sulphur and carbondioxide removal. These processes make the LNG a clear, cold, odourless, non-corrosive, non-toxic, cryogenic liquid at normal atmospheric pressure. LNG is unique because of properties such as:

- The density of LNG is about 450Kg/m^3 compared to the density of water, which is about 1000Kg/m^3 (Foss, 2003). Thus, LNG floats on top of water if spilled, and vaporizes rapidly because it is lighter than water.
- The vapour of LNG is flammable because it is composed mainly of methane. Methane occupies about 70 to 90% of LNG.
- The LNG vapour at ambient temperature is lighter than air and its specific gravity relative to air is 0.55, once thermal equilibrium is reached (ABS Consulting, 2004).
- At a pressure of 1 atmosphere and temperature of -259ºF (-162ºC), its normal boiling point, LNG can evaporate and form vapour that has a specific gravity of 1.7 (ABS Consulting, 2004).
- LNG vapour tends to stay near the surface of the ground or water for less than a minute, until it mixes with air and warms to a temperature of approximately -162°F (-108ºC), at which it will become less dense than air and tend to rise and disperse more rapidly (ABS Consulting, 2004).
- The vapour of LNG does ignite whenever there are LNG spills and a source of ignition such as an open flame, spark or a source of heat of 540^{0}C and above (Foss, 2003).

4. HAZARDS OF LNG

The properties of LNG determine the type of hazards associated with it in onshore and offshore environments. Safety systems are used to mitigate and prevent the consequences of hazards on its value chain systems. Failures of LNG carrier operations are the main factor that results in consequences such as LNG hazards, which cause pollution of the environment. Such LNG hazards are explosion, vapour clouds, rollover, freezing liquid, rapid phase transition and pool fire. Explosion is an LNG hazard that occurs when LNG changes its chemical state by ignition or uncontrollable release from its pressurized state (Foss, 2003). The release of LNG without control is probably a result of structural failure. Structural failure mainly occurs as a result of external attack on the tank (i.e. induced failure) or the stress in the inner part of the tank. Structural failure will not lead to immediate explosion because the LNG liquid is stored at atmospheric pressure. Vapour clouds become hazardous if there is a source of ignition when the LNG is within 5-15% flammability limit. The LNG returns to a gaseous state once it leaves the container where it is stored at temperature of –256^{0}F (-160^{0}C). It mixes with the surrounding air and begins to disperse after the creation of a fog (Foss, 2003). Fire caused by a LNG vapour cloud, burns gradually until it reaches the source (LNG spills) and continues to burn as a pool fire (IMO, 2007).

Rollover occurs when loading of LNG with multiple densities into a tank causes formation of various layers. This is a result of the LNG not mixing up initially (IMO, 2007). The density of the lower layer of LNG is changed by heat applied by the normal heat leak until it becomes lighter than the upper LNG layer (Foss, 2003). During this process, liquid rollover would occur with a sudden vaporization of LNG that may be too large to be released through the normal tank pressure release valves (Foss, 2003). The pressure release valve settings depend on the designed pressure of the tank. The pressure release valve value is usually higher than the designed pressure of the tank. The stabilization of the LNG causes overpressure in the tank (IMO, 2007). The resultant effect of the overpressure may be cracks on the inner tank (primary containment). Freezing liquid is the hazardous effect of LNG spillage. Once there is LNG spillage, human beings close to the hazardous environment are at risk of being freeze. One of the ways of preventing freezing liquid is use of containment systems to surround the LNG storage tank. In addition, all personnel working on the LNG facility must wear gloves, facemasks and other protective clothing when entering potentially hazardous areas, including the areas where freezing liquid occurred (Foss, 2003). Rapid phase transition occurs when LNG is released on water. The LNG floats on top of water and vaporizes immediately if the LNG is of large volume, thereby causing rapid phase transition. Water temperature and the presence of substances other than methane affect the likelihood of a rapid phase transition (Foss, 2003). Rapid phase transitions range from small pops to blasts that can damage lightweight structures (Foss, 2003). Rapid phase transition constitutes a minor hazard to nearby people and structures, in event of LNG release (IMO, 2007). Whenever there is LNG spill in presence of an ignition source, a pool fire occurs. The spreading of the pool fire depends on the expansion and evaporation of LNG pool from its source. A pool fire on water is more hazardous than a pool fire on land due to thermal effects and the thermal radiation from a pool fire can injure unprotected people and damage property at considerable distance away from the fire (IMO, 2007).

5. OVERVIEW OF LNG CARRIERS

Maintenance of the structural integrity of the cargo containment system is the most important concern in the transportation of LNG (Moon et al., 2009). Use of the LNG carriers for transportation of LNG started in 1959. The LNG carriers are designed and constructed to carry cryogenic LNG stored at a temperature of -162ºC and at atmospheric pressure (Moon et al., 2009). LNG carriers are constructed with double hulls, which provide a significant measure of protection against LNG release in event of external damage (Nwaoha et al., 2013). In addition, the International Gas Code (IGC) requires LNG carrier tanks to be protected from damage due to collision or grounding by locating the tank at a specified minimum distance inboard from ship's shell plating (ABS Consulting, 2004). Inner tank and outer hull are more than 2m apart, so that if there is a large hole in the hull, it will result in a smaller one in the inner tank (Bubbico et al., 2009). This has contributed in keeping LNG safe. Additionally, the LNG shipping industry has been showing a remarkable safety record because of stringent safety practices in the LNG industry (Chang et al., 2009, Nwaoha et al., 2013).

Most LNG carriers have six storage compartments. The three main types of LNG carriers such as membrane tank design, structural prismatic tank design and spherical (Moss) tank design have the same features but with different tank design (Nwaoha et al., 2013). The LNG carrier tank design is either a self-supporting or supporting tank design. The self-supporting tank does not depend on ship's hull for support and has three categories such as (ABS Consulting, 2004):

- Type A. It is designed primarily using recognized standards for classical ship structural analysis procedures.
- Type B. It is designed using model tests, refined analytical tools, and analysis methods to determine stress levels, fatigue life, and crack propagation characteristics.
- Type C. It is designed for specific vapour pressure criteria and the tanks meet pressure vessel criteria (not typically applicable to the LNG carriers).

The membrane tank design type LNG carrier is classified as a supporting tank design type LNG carrier. The storage/containment tank of such LNG carrier is supported by the hold it occupies (Pitblado et al., 2004, Sandia National Laboratory, 2005). It is made up of a layer of metal (primary barrier), layer of insulation, liquid-proof layer, and another layer of insulation. The multiple layers are attached to the walls of the external framed hold. The spherical (moss) tank design type LNG carrier has a spherical shape (Pitblado et al., 2004, Sandia National Laboratory, 2005). This type of LNG carrier is classified as self-supporting tank design type. A steel cylinder is used to support the tank, which makes the tank independent of the ship's hull. Any leakage is channeled to the drip tray because of the insulation surrounding the spherical tank design channel. The structural prismatic tank is classified as self-supporting type and is similar to the spherical (moss) tank (Pitblado et al., 2004; Sandia National Laboratory, 2005). The tanks are installed in the hold of a double hull ship and are insulated. Any leakage is channel to drip trays in a similar way to spherical (moss) tank design. The prismatic tank is not popular in the LNG industry, as it accounts for only 2% of the world's LNG fleet (Foss, 2003).

The membrane and spherical tank designs are the most popular tank designs and account for 98% of the world's LNG carrier fleets (Foss, 2003). The insulation of these tanks cannot keep the LNG cold enough. To overcome this challenge, LNG is stored in the tank using auto- refrigeration. In this process, the LNG is subjected to constant temperature and pressure to keep it cold by allowing the Boil-Off Gas (BOG) to leave the tank. The BOG can be used as fuel or re-liquefied and returned to the tank. Traditionally, LNG carriers have been propelled by steam turbine, which has been proved to be a simple and reliable solution for consuming natural BOG (Moon et al., 2009). Other design options for propulsion systems have been developed due to increase in LNG carrier size and advances in technology. These include dual fuel steam mechanical, dual fuel diesel electric, dual diesel turbine electric and dual fuel diesel mechanical propulsion with reliquefaction (Moon et al., 2009).

6. LNG Carriers Accidents

Since the use of the LNG carriers in transportation of LNG, few incidents have happened and only one accident claimed 6 lives of personnel in 1996. Some notable accidents and their causes have been listed in Table 1. The accidents of LNG carriers in Table 1 are the ones that caused LNG spills. Various accidents have happened in the LNG industry that did not lead to LNG spill. Some of these accidents that involved LNG carriers are listed in Table 2.

Table 1: Incidents/Accidents of LNG Carriers that Resulted to LNG Spill

Ship Name	Description of Accident
Cinderella (Jules Verne)	Overfilling of the tank and fracture of the deck and tank cover during loading of LNG. There was a LNG spillage, but no injuries/fatalities of personnel. This accident occurred in 1965 (Østvik, et al., 2005).
Methane Princess	Leakage of the valve and deck fracture during disconnection after discharge. LNG spillage occurred but there were no injuries/fatalities. This accident happened in 1965 (Østvik, et al., 2005).
Polar Alaska (Methane Polar)	Violent sloshing of LNG in refrigerated tank en route to Alaska caused cable tray to break loose. This in turn slashed thin membrane cargo tank wall releasing contents. No fire or explosion reported. This accident occurred in 1969 (Østvik, et al., 2005).
Descartes	Gas leak from tank and faulty connection between tank dome and membrane wall caused mechanical failure. This accident occurred in 1971 (Østvik, et al., 2005).
Esso Brega (LNG Palmaria)	Rollover. Tank developed a sudden increase in pressure and LNG vapour discharged from the tank safety valves and vents. The tank roof was slightly damaged and there was a LNG spillage. No ignition source for fire to occur. This accident happened in 1971 (Østvik, et al., 2005).
Arzew	A large diameter valve ruptured during a ship loading operation, causing LNG spillage. The spilled LNG did not ignite but there was a casualty. A terminal worker on the LNG export terminal was frozen to death when the LNG sprayed on him. This accident occurred in 1977 (Østvik, et al., 2005).
LNG Aquarius	The tank was overfilled during loading operations and there was a spillage of LNG. No casualty was recorded. This accident occurred in 1977 (Østvik, et al., 2005).
Mostefa Ben Boulaid	There were valve leakage and deck fractures during unloading of LNG, which caused LNG spillage. There was no injury or fatality of personnel. This accident occurred in 1979 (Østvik, et al., 2005).
Pollenger (LNG Challenger)	There were a valve leakage and tank cover plate fractures during unloading of LNG. The spilled LNG did not cause any injury/fatality of personnel. This accident happened in 1979 (Østvik, et al., 2005).
Tellier	During loading of the LNG, there were broken moorings, hull and deck fractures. LNG spilled and explosion occurred thereafter. Several injuries were experienced. This accident occurred in 1989 (Østvik, et al., 2005).
Khannur	There was LNG leak through a vent during unloading. There were cracks in tank dome and over-pressurization of cargo in No. 4 tank. A LNG spill was experienced. This accident occurred in 2001 (Østvik, et al., 2005).
Mostefa Ben Boulaid	A spillage resulted in a cracked deck. Thought to be human error as the alarm that should alert personnel had been isolated. No one was hurt. This accident happened in 2002 (Østvik, et al., 2005).

Table 2: Incidents/Accidents of LNG Carriers that Resulted to No LNG Spill

Ship Name	Description of Accident
Methane Progress	While in port, the vessel touched bottom. There was no LNG spillage or injury/fatality recorded. This accident happened in 1974 (Østvik, et al., 2005).
El Paso Paul Kayser	The vessel was stranded at sea. There was severe damage to the bottom, ballast tanks, motors water and bottom of containment system set up. No casualty or LNG spillage was recorded. This accident happened in 1979 (Østvik, et al., 2005).
LNG Libra	While at sea, the shaft moved against rudder. Tailshaft fractured. There was no spillage of LNG or injuries/fatalities. This accident happened in 1980 (Østvik, et al., 2005).
LNG Taurus	The vessel was stranded at port and ballast tanks all flooded thus leading to listing the vessel. There was extensive bottom damage, but no spillage of LNG or injury/fatality was experienced. This accident happened in 1980 (Østvik, et al., 2005).
Melrose	There was fire in engine room at sea and no structural damage sustained. No LNG spill or fatality/injury was recorded This accident occurred in 1984 (Østvik, et al., 2005).
Gadinia (Bebatik)	Steering gear failure at the port. No LNG spill or injury/fatality was experienced This accident happened in 1985 (Østvik, et al., 2005).
Isabella	There were cargo valve failure and the cargo overflows during unloading of LNG. There were also deck fractures, though no LNG spillage or injury/fatality was experienced. This accident happened in 1985 (Østvik, et al., 2005).
Bachir Chihani	While at sea, the vessel sustained structural cracks allegedly caused by stressing and fatigue in the inner hull. There was no LNG spillage or fatality/injury. This accident happened in 1990 (Østvik, et al., 2005).
Mourad Didouche	Lifting cable broke while the turbine was lifted out of engine room, causing turbine to fall from great height at the shipyard. This accident happened in 1995 (Østvik, et al., 2005).
LNG Finima	The vessel was boarded by pirates while anchored. The pirates stole paint and broached a lifeboat. There was no spillage or casualty. This accident happened in 1996 (Østvik, et al., 2005).
Mostefa Ben Boulaid	There was electrical fire in the main engine room, while at quay discharging. This caused power lost and there was no spillage. This accident happened in 1996 (Østvik, et al., 2005).
LNG Portovenere	Fire broke out in the engine room, when the empty vessel was at sea, which killed 6 people. There was no spillage of LNG. This accident happened in 1996 (Østvik, et al., 2005).
LNG Capricorn	Sustained damage to shell plating on contact with mooring dolphin, while in port. No spillage or damage to cargo system. This accident happened in 1997 (Østvik, et al., 2005).
Northwest Swift	Had a collision with fishing vessel. The port side and bulkward were damaged. No water ingress and LNG spillage. This accident happened in 1997 (Østvik, et al., 2005).
Mostefa Ben Boulaid	Had generator problems in port, though there was no spillage or casualty. This accident happened in 1998 (Østvik, et al., 2005).
LNG Bonny	Had complete power failure while at sea. There was no spillage or injuries/fatalities. This accident happened in 1998 (Østvik, et al., 2005).
Methane Polar	Had engine breakdown and struck the Petrotrin jetty at Point Fortin, while being brought in empty for loading. There was no casualty or damage experienced. This accident happened in 1999 (Østvik, et al., 2005).
Matthew	Had tailshaft problem and overheated bearing while at sea. There was no casualty or spillage experienced. This accident happened in 1999 (Østvik, et al., 2005).
Hanjin Pyeong Taek	Had collision with bulk carrier at sea and damage occurred to shell plating. No spillage reported. This accident happened in 2000 (Østvik, et al., 2005).
LNG Jamal	Insulating materials & vinyl sheeting burnt out during welding operations on No. 3 tank cover at wharf. There was no spillage or casualty experienced. This accident happened in 2000 (Østvik, et al., 2005).

Hoegh Galleon (Pollenger)	An outbreak of fire in the yard caused damage to part of the tank insulation, which caused the death of 1 ship builder. This accident happened in 2000 (Østvik, et al., 2005).
Ramdane Abane	There was engine break down at sea and no casualty or spillage was experienced. This accident happened in 2001 (Østvik, et al., 2005).
Methane Polar	Had collision with bulk carrier at sea (in ballast), which caused minor hull damage and sustained holing to bow. There were three injuries and one fatality of the bulk carrier crew, though no spillage was recorded. This accident happened in 2001 (Østvik, et al., 2005).
Norman Lady	The LNG vessel collided with a U.S. Navy submarine, while at sea (in ballast condition). The LNG vessel suffered a leakage of seawater into the double bottom of the dry tank area. There was no LNG spillage or injuries/fatalities. This accident happened in 2002 (Østvik, et al., 2005).
Methane Princess	Had fire on board while under construction. Fire burnt part of the cargo tanks, though the damage was minor. There was no injury/fatality. This accident happened in 2003 (Østvik, et al., 2005).
Century	Sustained main engine damage offshore. There was no LNG spillage or injury/fatality of personnel. This accident happened in 2003 (Østvik, et al., 2005).
Hoegh Galleon (Pollenger)	Developed gearbox problems at sea. There was no LNG spillage or casualty. This accident happened in 2003 (Østvik, et al., 2005).
Hilli	Had a boiler tube failure at anchorage. The failure did not result to any spillage or casualty. This accident happened in 2003 (Østvik, et al., 2005).
Gimi	Softly touched bottom when approaching pier. It did not result in injuries or spillage. This accident happened in 2003 (Østvik, et al., 2005).
Fuwairit	Grounded during passage of typhoon “Maemi” while under construction. There was no casualty experienced. This accident happened in 2003 (Østvik, et al., 2005).
Galicia Spirit	Grounded after mooring ropes released during typhoon “Maemi” while under construction. The vessel sustained damage to bottom and starboard shell plating, but there was no casualty. This accident happened in 2003 (Østvik, et al., 2005).
LNG Berge Arzew	While under construction, mooring ropes broke due to typhoon "Maemi" and drifted away from berth, touching bottom. The bottom plating was damaged, but there was no casualty. This accident happened in 2003 (Østvik, et al., 2005).
British Trader	There was minor electrical fire onboard, which damaged one transformer while the vessel was at sea. No spillage or casualty reported. This accident happened in 2004 (Østvik, et al., 2005).
Methane Arctic	The vessel had minor fire breakout after being struck by lightning during discharge. There was slight damage on the vessel, but no casualty or LNG spillage. This accident happened in 2004 (Østvik, et al., 2005).
Tenage Lima	Made contact with a submerged rock due to a strong southerly current. The starboard side shell plating in way of No. 1 membrane tank was heavily damaged, though, no spillage or casualties were experienced. This accident happened in 2004 (Østvik, et al., 2005).
Hispania Spirit	The hull was damaged via contact during berthing operations, which resulted in oil spill. There was no LNG spill or casualty. This accident happened in 2005 (Østvik, et al., 2005).
Laieta	Engine breakdown while in ballast. LNG spill or casualty was not experienced. This accident happened in 2005 (Østvik, et al., 2005).
Methane Kari Elin	Suffered damaged insulation and had nitrogen leak (Gasbridge, 2010). No LNG spillage or casualty reported. This accident happened in 2005.
Catalunya Spirit	The vessel had damaged insulation (Gasbridge, 2010). No LNG spillage or casualty reported. This accident happened in 2006.
Catalunya Spirit	The vessel went adrift for hours off Cape Cod because a computer glitch caused the vessel to lose power (TimeLeyLaw, 2010). No spillage or casualty was experienced. This accident happened in 2008.
Matthew	Grounded on coral reef habitat off the south coast of Puerto Rico near Guayanilla (DARRP, 2010). No spillage or casualty reported. This accident happened in 2009.
Umm Al Amad	The vessel was boarded by six pirates while sailing. The pirates stole cash from the ship and crew members (ReCAAP, 2010). There was no spillage or casualty. This accident happened in 2010.

7. RISK ASSESSMENT OF THE LNG CARRIERS

The safety and reliability of LNG carriers have so far been outstanding in the marine industry, which is achieved as a result of the safety features that are in place to avoid unwarranted release of LNG from their containment systems and other related marine facilities such as tank farms. Risk assessment is a comprehensive estimation of the probability and the degree of the possible consequences in a hazardous situation in order to select appropriate safety measures (Wang and Trbojevic, 2007). Before carrying out a risk assessment, all parties involved should have a common understanding of the goals of the exercise, the methods to be used, the resources required, and how the results will be applied (ABS, 2000). Risk assessment of LNG carriers can be carried out using qualitative or quantitative risk analysis depending on the requirements of LNG safety analysts and the available historical LNG incidents data. The process can be proactive and includes new risks estimated based on improvement in technology of the LNG carriers.

From the previous studies, it has been seen that the risks associated with LNG carrier operations are managed/reduced to a great extent using the safety features such as double hull construction, high strength steel in critical areas, double wall walled piping system, redundant steering systems, highly trained specialized crews, gas detection systems, inert inter-barrier spaces, water spray, dry chemical, CO_2 firefighting systems and emergency cargo evacuation systems that are incorporated in the LNG carriers. Irrespective of the safety features already in place on the LNG carriers and other LNG facilities, hazards that might affect the proper functioning of the LNG carrier systems and subsystems may not be eliminated, especially with the development and implementation of new technologies. The experts in the LNG industry can conduct comprehensive risk assessment of LNG carriers and other related marine facilities using safety/risk analysis techniques such as:

- Event Tree Analysis (ETA).
- Risk Matrix.
- Fault Tree Analysis (FTA).
- Failure Mode, Effect and Critical Analysis (FMECA).
- Preliminary Hazard Analysis (PHA).
- Hazard and Operability study (HAZOP).
- What If Technique.
- Cause Consequence Analysis (CCA).

7.1. Event Tree Analysis (ETA)

ETA is a safety/risk analysis technique used in the LNG industry to deduce the consequences of an accident, unintended event or abnormal function of a system. This involves the study of the complex relationships among the subsystems of the system given the occurrence of an initiating event (Wang and Trbojevic, 2007). ETA is developed diagrammatically using inductive bottom-up logic (Halebsky, 1989; Wang and Trbojevic, 2007). ETA assigns probabilities to each branch of an event using historical data or expert judgement. For example, to determine how possible each consequence occurs when a LNG spill (initiating event) happens, involves defining the possible routes along which the consequence could occur and assign probabilities to their routes. ETA can be used to identify possible outcomes of a LNG spill occurrence. For instance, if a LNG spill occurred and there is no ignition source, the consequence will be negligible in terms of fire risk. If there is an ignition source, then check if the gas detection system failed. If not, the consequence will be minor damage, otherwise check the status of the fire alarm system. If the fire alarm system did not fail, the consequence will be major damage; otherwise injuries/deaths will be caused. ETA can be employed to investigate unknown effects from known causes (Godaliyadde, 2008; Villemeur, 1992). ETA enables quantitative analysis to be carried out to estimate the occurrence probability of each possible consequence of a LNG carrier hazard.

7.2. Risk Matrix

Risk matrix is a qualitative assessment method which can be used to estimate risk in the LNG carrier operations. It is used as a pre-comprehensive risk assessment of a LNG system because the mechanism can be used to screen high risk hazards that need to be further evaluated using other risk/safety analysis techniques. The LNG and risk/safety experts focus on those high risk hazards for facilitation of the risk assessment process. Risk matrix mostly used as a first choice for hazard identification and risk prioritization for large engineering systems as detailed failure rate values are not needed. This technique uses a tabular format to estimate risks associated with the hazards (Halebsky, 1989; Eleye-Datubo, 2006; IMO, 2007; Military Standard, 1993; Tummala and Leung, 1995). The table of a risk matrix technique has probability of failure on the horizontal axis and consequence of that failure on the vertical axis. The points of intersection of the horizontal and vertical axis are the risks of the hazards. The probability of failure is categorized and scored, as well as consequence of that failure. The summations of their scores at the points of intersection on the risk matrix table are described as estimated risks of hazards (failures). The success of this method depends heavily on the multi-disciplinary team experience of the system under investigation.

7.3. Fault Tree Analysis (FTA)

FTA is a safety/risk analysis technique commonly used to assess the probability of failure of a system. Since the early 1970s, the FTA technique has been utilised as a tool in risk assessment methodologies (Godaliyadde, 2008; Kumamoto and Henley, 1992). This technique is a process of deductive reasoning which can be applied to a system of any size for risk assessment purposes (Ang and Tang, 1984; Godaliyadde, 2008; Wang and Trbojevic, 2007). The FTA technique represents the failure logic of a system in an inverted tree structure and provides very good documentation of how the failure logic of the system is developed (Andrews and Ridley, 2002). The pathways through the Fault Tree (FT) diagram represent all the events which give rise to the top event, are known as cut sets or implicant sets. The minimal cut set is defined as the irreducible pathways leading to the occurrence of a top event (Wang and Trbojevic, 2007). It can be used in qualitative and quantitative risk assessment of LNG carrier operations. The quantitative assessment is carried out successfully on any system that the failure probabilities of the basic events are known. If the basic events probabilities are not known, a subjective method can be adopted.

7.4. Failure Modes, Effect and Criticality Analysis (FMECA)

FMECA is a safety/risk analysis technique used in HAZID and risk estimation. It was created and developed in the United States in the early 1960s and used by NASA during the development of the Apollo Project (Carmignani, 2009). It can be carried out from any indenture level required to examine the failure modes of a component (subsystem) of a LNG carrier and its possible consequences. FMECA systematically details, on a component by component basis, all possible failure modes and identifies their resulting effects on the system (Godaliyadde, 2008; Kumamoto and Henley, 1992). FMECA is an inductive process which involves the compilation of reliability data that is available for individual components (Godaliyadde, 2008; Wang and Trbojevic, 2007). It can provide regulators with insight into the system features and how they contribute to overall system safety (Buzzatto, 1999). This safety/risk analysis technique is made up of Failure Mode and Effects Analysis (FMEA) and Criticality Analysis (CAS). The performance of an FMEA is the first step in generating FMECA (Pillay and Wang, 2003). FMEA is the identification of potential failure modes of the constituent components and the effect on system performance by identifying the potential severity of the effect (Pillay and Wang, 2003). The CAS produces the criticality ranking of the components of LNG carrier under investigation. The CAS helps analysts to know which component of LNG carrier to give maximum attention. FMECA can be used in qualitative and quantitative analyses. FMECA produces information that can be used in the development of fault trees (FTs) and boolean representation tables (Godaliyadde, 2008; Wang and Trbojevic, 2007).

7.5. Preliminary Hazard Analysis (PHA)

PHA is a safety analysis technique that is performed to identify all the possible hazards that could be created by the system being designed. This is the first step used to identify the hazards of a LNG carrier starting from when the ship is about to be designed. Results of PHA enable system designers to avoid many potential safety problems (Dowlatshahi, 2001). A collective brainstorming technique is employed during which the design or operation of the system is discussed on the basis of experience of the participants (Godaliyadde, 2008). PHA is a qualitative approach which involves a mixture of inductive and deductive logic (Wang and Trbojevic, 2007). Checklists are commonly used to assist in identifying the hazards and the results are presented in a tabular format (Godaliyadde, 2008). When sufficient information is not available for particularly rigorous analyses, PHA serves as a valuable aid (Dowlatshahi, 2001). The procedures of a PHA are (Czerny et al., 2005):

- Perform brainstorming or review existing potential hazard lists to identify hazards associated with the system.
- Provide a description of the hazards and mishap scenarios associated with them.
- Identify causes of the hazards.
- Determine the risk of the hazards and the mishap scenarios.
- Determine if system hazard avoidance requirements need to be added to the system specification to eliminate or mitigate the risks.

7.6. Hazard and Operability (HAZOP) Study

HAZOP study is an inductive technique for identifying hazards and problems associated with the operation of a process plant in the LNG industry. The HAZOP technique was developed in the 1970s by loss prevention engineers working for Imperial Chemical Industries at Tees-Side UK (Godaliyadde, 2008; Smith, 2005; Villemeur, 1992). This is a collective brainstorming technique in which the system is examined systematically, component by component, to determine how deviations from the design intent can occur, the consequences of such deviations and the preventive/mitigative measures that are required (Godaliyadde, 2008). It is also an extended FMECA. The aim of the HAZOP is to carry out a qualitative analysis at the intermediate stages of the design process to predict hazards, thus it is an exploratory technique (Godaliyadde, 2008; Mauri, 2000). It is used in detailed examination of components within a LNG system to determine what would happen if the components were to operate outside their normal design mode conducted by a group of specialists headed by a hazard analyst. Each LNG component will have one or more parameters associated with its operation such as "pressure", "flow", "temperature", "composition", "relief", "level", "phase" and "instrumentation". The HAZOP study looks at each parameter in turn and uses guide words to list the possible off-normal behaviour (Wang and Trbojevic, 2007). The guide words are "no", "low", "high", "as well as", "reverse", "other than" and "part of" (Wang and Trbojevic, 2007).

An example of the combination of a parameter like "no" and a guide word like "flow" is used in loading or unloading of LNG from an onshore containment tank to a LNG containment tank through a pipeline. If LNG is not or has stopped flowing through the pipeline, the team involved in HAZOP studies will give the deviation "no flow" of LNG. The team then focuses on listing all the credible causes of a "no flow" of LNG beginning with the cause that can result in the worst possible consequences. Once the causes of "no flow" of LNG are recorded, the team lists the consequences, safeguards and any recommendations deemed appropriate. The process is repeated for the next deviation until completion of the node. Information produced from HAZOP studies can be used in CCA, FMECA and Boolean representation analysis (Wang and Trbojevic, 2007).

7.7. What-IF Analysis

What-If analysis helps to identify potential LNG hazards. It uses brainstorming techniques to ask question, "What If" in the lifecycle of any LNG system. The intention of "What If" is to ask questions which will cause a team to consider potential failure scenarios and ultimate consequences that such failures might create (CCPS, 1992; Eleye-Datubo, 2006; Wang and Trbojevic, 2007). The possible LNG hazards are identified, existing safeguards are noted, and qualitative severity and likelihood ratings are assigned to help in risk assessment. This technique assures that all hazards that may or may not occur in the future are known because well experienced personnel are involved in the HAZID process (Wang and Trbojevic, 2007). Use of experienced team, contributes immensely to the successful application of "What If" analysis on LNG carrier operations. Their experience in the LNG carrier design, operations and maintenance is important. In this technique, all the potential LNG hazards are identified before recommendations on them are made. This minimizes the chances that potential problems are not overlooked. This technique uses a mixture of inductive and deductive logic (Wang and Trbojevic, 2007).

7.8. Cause–Consequence Analysis (CCA)

CCA is the combination of ETA and FTA. The ETA shows consequence and the FTA shows causes, hence deductive and inductive analysis is combined. The CCA was developed at RISO national laboratories, Denmark, in the 1970's to specifically aid in the reliability and risk analysis of nuclear power plants in Scandinavian countries (Andrews and Ridley, 2002; Andrews and Ridley, 2001; Villemeur, 1992). Many authors have used the CCA as the main analysis tool for a safety assessment (Andrews and Ridley, 2002; Pauperas, 1991; Valaityte et al., 2009; Vyzaite et al., 2006). The purpose of the CCA is to identify chains of events that can result in undesirable consequences. The CCA diagram documents the failure logic of a system (Andrews and Ridley, 2001). It is used to identify hazards (FTA) and consequences of the hazards (ETA) for easy eradication of risk. The "consequence tracing" part of the CCA involves taking the initial event and following the resulting chains of events through the system (Wang and Trbojevic, 2007). The "cause identification" part of the CCA involves drawing the FT and identifying the minimal cut sets leading to the identified critical event (Wang and Trbojevic, 2007). The diagram of the CCA normally starts with choice of critical event. This technique is advantageous in LNG safety analysis as it can work forward using event trees (ETs) and backward using fault trees (FTs).

8. OVERVIEW OF FORMAL SAFETY ASSESSMENT OF SHIPS

Several accidents in the maritime industry prompted the International Maritime Organization (IMO) to question the safety of operations of ships. For safety of the public and environment, the IMO decided to adopt the FSA methodology after studying notable accidents that have affected the lives of people onboard vessels and caused great damage to the environment. FSA is described as a process of identifying hazards, assessing the associated risks, studying alternative ways of managing those risks, carrying out Cost Benefit Assessment (CBA) of alternative management options and finally making decisions on which option to select (MSA, 1993). FSA methodology has five steps such as HAZID (Step 1), Risk Assessment (Step 2), Risk Control Option (RCO) (Step 3), CBA (Step 4) and Decision Making (Step 5). The steps interact with each other to ensure that the best RCO is chosen based on the CBA during decision making on optimal ships and marine systems operations.

One of the notable accidents studied by IMO was the capsize of the Herald of Free Enterprise that happened on 6th March, 1987, which claimed 193 lives. The investigation of the capsize of the Herald of Free Enterprise led by Lord Carver brought changes to maritime safety related regulations as demonstrated by the adoption of the enhanced damage stability and watertight closure provisions in the Safety of Life at Sea (SOLAS'90) (Wang, 2002; Wang and Trbojevic, 2007). The introduction of the ISM Code for the safe operations and pollution prevention, and the development of the FSA framework in shipping industry are also adopted as maritime safety related regulations (Wang, 2002; Wang and Trbojevic, 2007). Introduction of a more structured risk analysis process through the FSA procedure, compelled regulators to examine potential hazards and introduce appropriate measures or standards before a catastrophic accident occurs.

The submission of Lord Carvers report on the investigation of the capsize of the Herald of Free Enterprise published in 1992, caused the United Kingdom Maritime Coastal Agency (UK MCA) to immediately improve the safety of ships by proposing to the IMO in 1993 that FSA should be applied to ships to ensure a strategic oversight of safety and pollution prevention. The IMO accepted the proposal and sanctioned the application of FSA in relation to ship design and operation. The UK MCA has proved FSA's practicability by carrying out trial applications to safety of high speed catamaran ferries (IMO, 1997a; IMO, 1998a) and bulk carriers (IMO, 1998f; IMO, 2000; IMO, 2002a; IMO, 2002b). FSA has been successfully applied to various ships and marine facilities using probabilistic and subjective (possibilistic) assessment approaches. The ship and marine facilities are fishing vessels (Pillay, 2001; Loughran et al., 2003), ports (Trbojevic, 2002; Ung et al., 2006; Ung, 2007). marine transportation (Soares and Teixeira, 2001), offshore support vessels (Sii, 2001), containerships (Wang and Foinikis, 2001), LNG ships (IMO, 2007; Vanem et al., 2008), ship hull vibration (SHV) (Godaliyadde, 2008), cruising ships (Lois et al., 2004), liner shipping (Yang et al., 2005; Yang, 2006), trial study on passenger roro vessels with dangerous goods (IMO, 1998g), trial study on high speed crafts (IMO, 1997b; IMO, 1998b; IMO, 1998c) and trial study on oil tankers (IMO, 1998d; IMO, 1998e). The applications of FSA to ship design and operation offer great incentives that could (Eleye-Datubo, 2006):

- Improve the performance of the current fleet, being able to measure the performance change and ensure that new ships are good designs.
- Ensure that experience from the field is used in the current fleet and that any lessons learned are incorporated into new ships.
- Provide a mechanism for predicting and controlling the most likely scenarios that could result in incidents.

The incentives offered by FSA have been demonstrated in Nwaoha et al. (2011b) by applying its methodology to LNG carrier operations using a subjective approach. The subjective approach is successful by employing a FER algorithm for the treatment of uncertainties associated with the failure modes of LNG carrier systems.

9. OVERVIEW OF REGULATIONS GOVERNING SAFETY OF LNG SHIPPING

The IMO was created in 1958, with the aim of functioning as a body that contributes to the standardization of the legislations and regulations related to safety of shipping. The IMO was formerly called the Inter-governmental Maritime Organization (IMCO). The international safety based marine regulations have been driven by serious marine accidents (Godaliyadde, 2008). The regulations for gas carriers concerning the construction, equipment and operations of gas carriers are contained in the IMO "Gas Codes". The three Gas Codes that have evolved for the LNG shipping industry are (Walker et al., 2003):

- The code for existing ships carrying liquefied gas in bulk (existing ship code – IMO).
- The code of construction and equipment of ships carrying liquefied gas in bulk (The GC code – IMO).
- The international code of construction and equipment of ships carrying liquefied gas in bulk (The IGC code – IMO).

The IMO has implemented international conventions for the safety of shipping such as (ABS, 2000):

- International Standard of Training, Certification and Watchkeeping (STCW), 1995. It is aimed at providing unified standards for training and certification of seafarers.

- International Convention for the Prevention of Pollution at Sea, 1973 and protocol of 1978 (MARPOL 73/78). It is aimed at preventing and minimizing pollution at sea from oil, noxious liquid substances, noxious substances in packaged forms, sewage, garbage, and air pollution.

- International Load Line Convention (ILLC), 1966. It is aimed at standardizing the procedures for assignment of load lines to ships and the conditions of assignment, such as intact and damage stability, the protection of openings in the watertight boundaries and protection of crew at sea, etc.

- Convention on the International Regulations for Preventing Collisions at Sea (COLREG), 1972. It is aimed at providing "rules of the road" at sea, such as maintaining proper lookout, safe speed, lights and signals to be displayed, etc.

- International Convention for the Safety of Life at Sea (SOLAS), 1974. It is aimed at providing adequacy in ship structural design (albeit by specifying compliance with classification rules); safety of mechanical and electrical systems onboard; damage stability; fire safety; radio communication and search and rescue; safety of navigation and prevention of collision; the provision of life saving appliances, the safe carriage of dangerous cargoes; and safety management.

The International Association of Classification Societies (IACS) was formed in 1969 and is made of 10 members and 2 associate members. The members of IACS such as Lloyd's Register, American Bureau of Shipping (ABS), Bureau Veritas (BV), Det Norske Veritas (DNV), Korean Register of Shipping, and Nippon Kaiji Kyokai classify LNG ships using the regulations of the IMO conventions and their own rules. Their rules and the IMO conventions have contributed in improving the safety of LNG carriers. Other bodies such as the Society of International Gas Tankers and Terminal Operators (SIGTTO) provide guidelines for the safe operation of gas tankers and terminals at an optimal level.

10. CONCLUSION

A thorough literature search of LNG carrier safety has been conducted in this research. Areas such as safety and properties of the LNG have been detailed. Furthermore, LNG carrier descriptions/operations and accidents have been explained, and lessons learnt from the accidents. Additionally, risk assessment of LNG carrier operations, hazards of LNG and various safety/risk analysis techniques have been analysed. Such safety/risk analysis techniques include HAZOP, PHA, FMECA, What-If-Technique, FTA, ETA, CCA and risk matrix. The FTA, CCA and risk matrix are described as qualitative/quantitative safety/risk analysis techniques, while the What-If-Technique is described as a technique that adopts a synthesis of inductive and deductive logic in this research. HAZOP study is explained as an inductive technique, while PHA is described as a qualitative approach that uses a combination of inductive and deductive logic in addressing LNG hazard identification. Other techniques such as the FMECA and ETA are described as qualitative and quantitative techniques. Both can be used in qualitative and quantitative risk assessment of LNG carrier operations due to their procedures. The FSA is reviewed and the various subjective and probabilistic applications in the maritime industry are outlined. Overviews of FSA of shipping and regulations governing LNG shipping have also been highlighted, to facilitate solving of risk assessment problems in the LNG industry. The detailed literature review in this research has provided information on the current status and way forward of LNG carrier safety with the aim of proposing a proactive approach for risk assessment of the operations of the systems.

REFERENCE

Andrews, J. D. and Ridley, L. M. (2001), "Reliability of Sequential Systems Using the Cause–consequence Diagram Method", Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, Vol. 215, Issue 3, pp. 207-220.

Andrews, J. D. and Ridley, L. M. (2002), " Application of the Cause–Consequence Diagram Method to Static Systems", Reliability Engineering and System Safety Vol. 75, Issue 1, pp. 47-58.

Ang, A. H. S. and Tang, W. H. (1984), "Probability Concepts in Engineering Planning and Design", John Wiley Sons.

ABS (2000), "Guidance Notes on Risk Assessment Application for the Marine and Offshore Oil and Gas Industries", Houston, U.S.A, June.

ABS Consulting (2004), "Consequence Assessment Methods for Incidents Involving Releases From Liquefied Natural Gas Carriers", A Report for Federal Energy Regulatory Commission Under Contract Number FERC04C40196, U.S.A, May 13.

Bubbico, R., Cave, S. D. and Mazzarotta, B. (2009), "Preliminary Risk Analysis for LNG Tankers Approaching a Maritime Terminal", Journal of Loss Prevention in the Process Industries, Vol. 22, Issue 5, September, pp. 634-638.

Buzzatto, J. L. (1999), "Failure Mode, Effects and Criticality Analysis (FMECA) Use in the Federal Aviation Administration (FAA) Reusable Launch Vehicle (RLV) Licensing Process", Digital Avionics Systems Conference Proceedings, October 24-29, Missouri, U.S.A.

Carmignani, G. (2009), "An Integrated Structural Framework to Cost-based FMECA: The Priority-cost FMECA" Reliability Engineering and System Safety, Vol. 94, Issue 4, pp. 861-871.

CCPS (1992), "Guidelines for Hazard Evaluation Procedure", Center for Chemical Process Safety (CCPS), American Institute of Chemical Engineers, 2nd Edition, New York, USA.

Chang, D., Rhee, T., Nam, K., Chang, K., Lee, D. and Jeong, S. (2008), "A Study on Availability and Safety of New Propulsion

Systems on LNG Carriers", Reliability Engineering and System Safety, Vol. 93, pp. 1877-1885.

Czerny, B. J., D'Ambrosio, J. G., Murray, B. T. and Sundaram, P. (2005), "Effective Application of Software Safety Techniques for Automotive Embedded Control Systems" SAE World Congress, April 11-14, Michigan, U.S.A.

DARRP (2010), http://www.darrp.noaa.gov/southeast/matthew/index.html. Accessed on 25/October/2010.

Dowlatshahi, S. (2001), "The Role of Product Safety and Liability in Concurrent Engineering", Computers and Industrial Engineering, Vol. 41, Issue 2, pp. 187-209.

Eleye-Datubo, A. G. (2006), "Integrated Risk-Based Modelling to Safety-Critical Marine and Offshore Applications", PhD Thesis, Liverpool John Moores University, UK.

Foss, M. M. (2003), "LNG Safety and Security", Centre for Energy Economics, University of Austin, Texas, U.S.A, October.

Gasbridge (2010), http://www.gasbridge.co.nz/index.php?page=52. Accessed on 25/October/10.

Godaliyadde, D. (2008), "Application of Formal Safety Assessment for Ship Hull Vibration Modelling", PhD Thesis, Liverpool John Moores University, UK.

Halebsky, M. (1989), "System Safety Engineering as Applied to Ship Design", Marine Technology, Vol. 26, No. 3, pp. 245-251.

HSE (2011), "LNG Terminals - Consent and Operational Issues", Health and Safety Executives, UK. http://www.hse.gov.uk/gas/supply/ingterminals.htm Accessed on 11/May/2011.

Hyo, K., Jae-Sun, K., Youngsoo, K. and Theofanius, G. T. (2005), "Risk Assessment of Membrane Type LNG Storage Tanks in Korea-based on Fault Tree Analysis", Korean Journal of Chemical Engineering, Vol. 22, No.1, pp.1-8.

IMO (1997a), "IMO/MSC Circular 829, Interim Guidelines for Application of Formal Safety Assessment to the IMO Rule-Making Process", International Maritime Organization, London, 17th November.

IMO (1997b), "Formal Safety Assessment Trial Application to High Speed Passenger Vessels", International Maritime Organization, London, UK, MSC 68/14/2 & 68/INF, May.

IMO (1998a), "Aspects of Formal Safety Assessment Methodology: Experience Gained from the Trial Application undertaken by the United Kingdom", International Maritime Organization, London, UK, MSC69/INF 14, February.

IMO (1998b), "Joint Nordic Project on Safety Assessment of HSC Operations", International Maritime Organization, London, UK, MSC70/INF15, October.

IMO (1998c), "Joint Nordic Project on Safety Assessment of HSC Operations", International Maritime Organization, London, UK, MSC70/INF15, January.

IMO (1998d), "Formal Safety Assessment Study on Disabled Oil Tankers", International Maritime Organization, London, UK, MSC70/20/2, July.

IMO (1998e), "Formal Safety Assessment Novel Emergency Propulsion and Steering Devices for Oil Tanker Analysed with the Formal Safety Assessment Method", International Maritime Organization, London, UK, MSC69/14/1, February.

IMO (1998f), "Bulk Carrier Safety", International Maritime Organization, London, UK, MSC70/4/1, September.

IMO (1998g), "Trial Application of Formal Safety Assessment to the Dangerous Goods on Passenger/Ro-Ro Vessels", International Maritime Organization, London, UK, MSC69/INF24.

IMO (2000), "Safety of Bulk Carriers – Basis of the International Collaborative Formal Safety Assessment Study", International Maritime Organization, London, UK, MSC72/INF18, March.

IMO (2002a), "International Collaborative FSA Study on Bulk Carriers – Step 2", International Maritime Organization, London, UK, MSC75/INF22, March.

IMO (2002b), "International Collaborative FSA Study on Bulk Carriers – Step 3", International Maritime Organization, London, UK, MSC76/INF8, September.

IMO (2007), "Formal Safety Assessment – Liquefied Natural Gas Carriers", MSC 83/21/1, International Maritime Organization (IMO), Submitted by Denmark.

Kumamoto, H. and Henley, E. J. (1992), "Probabilistic Risk Assessment and Management for Engineers and Scientists", IEE Press, 2nd Edition, ISBN: 0 7803 1004 7.

Lois, P., Wang, J., Wall, A. D. and Ruxton, T. (2004), "Formal Safety Assessment of Cruise Ships", Tourism Management, Vol. 25, Issue 1, pp. 93-109.

Loughran, C., Pillay, A., Wang, J., Wall, A. D. and Ruxton, T. (2003), "A Preliminary Study of Fishing Vessel Safety", Journal of Risk Research, Vol. 5, No. 1, pp. 3-21.

Mauri, G. (2000), "Integrating Safety Analysis Techniques, Supporting Identification of Common Cause Failures", PhD Thesis, Department of Computer Science, University of York, UK.

Military Standard, (1993), "System Safety Program Requirements", MIL-STD-882c, January, AMSC Number F6861.

Moon, K., Song, S., Ballesio, J., Fitzgerald, G. and Knight, G. (2009), "Fire Risk Assessment of Gas Turbine Propulsion System for LNG Carriers", Journal of Loss Prevention in Process Industries, Vol. 22, pp. 908-914.

Naturalgas Online (2010), www.naturalgas.org, Accessed on 1/April/2010.

Nwaoha, T. C. Yang, Z. Wang, J. and Bonsall, S. (2011a), "Application of Genetic Algorithm (GA) to Risk-based Maintenance Operations of Liquefied Natural Gas (LNG) Carrier Systems", Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, Vol. 225, No. 1, pp. 40 – 52.

Nwaoha, T. C. Yang, Z. Wang, J. and Bonsall, S. (2011b), "A New Fuzzy Evidential Reasoning Method for Risk Analysis and Control of Liquefied Natural Gas (LNG) Carrier Containment System", Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for Maritime Environment, Vol. 225, No. 1, pp. 206 – 225.

Nwaoha, T. C. Yang, Z. Wang, J. and Bonsall, S. (2013), "Adoption of New Advanced Computational Techniques in Hazard Ranking of LNG Carrier Operations", Ocean Engineering, Vol. 72, 2013, pp. 31-44.

Østvik, I., Vanem, E. and Castello, F. (2005), "HAZID for LNG Tankers", SAFEDOR Report D.4.3.1.

Pauperas, J. (1991), "Cause-consequence Analysis of a Generic Space Station Computer System", Reliability and Maintainability Symposium, Orlando, Florida, U. S. A.

Pillay, A. (2001), "Formal Safety Assessment of Fishing Vessels", PhD Thesis, Liverpool John Moores University, UK.

Pillay, A. and Wang, J. (2003), "Technology and Safety of Marine Systems", Elsevier Ocean Engineering Book Series, Vol. 7, ISBN: 0 08 044148 3.

Pitblado, R. M., Baik, J., Hughes, G. J., Ferro, C. and Shaw, S. J. (2004), "Consequences of LNG Marine Accidents", CCPS Conference, June 29-July 1, Orlando, U.S.A.

ReCAAP (2010). http://www.recaap.org/incident/pdf/reports/2010/August%202010%20Report%20(O).pdf. Accessed on 25/October/2010.

Sandia National Laboratory (2005), "Guidance on Risk Analysis and Safety Implications of a Large Liquefied Natural Gas (LNG) Spill Over Water", A Report Prepared for U.S. Department of Energy, SAND2004-6258, California.

Sii, H. S. (2001), "Marine and Offshore Safety Assessment", PhD Thesis, School of Engineering, Liverpool John Moores University, United Kingdom.

Smith, D. J. (2005), "Reliability, Maintainability and Risk", Butterworth Heinemann, 7th Edition, ISBN 0 7506 6694 3.

Soares, C. G. and Teixeira, A. P. (2001), "Risk Assessment in Maritime Transportation", Reliability Engineering and System Safety, Vol. 74, pp. 299-309.

TimeLeyLaw (2010), http://www.timrileylaw.com/LNG_TANKERS.htm. Accessed on 25/October/2010.

Trbojevic, V. M. (2002), "Risk Based Methodology for Safety Improvements in Ports", Journal of Hazardous Materials, Vol. 71, pp. 93-109.

Tummala, V. M. R. and Leung, Y. H. (1995), "A Risk Management Model to Assess Safety and Reliability Risks", International Journal of Quality and Reliability Management, Vol. 13, No. 8, pp. 53-62.

Ung, S. T (2007), "The Development of Safety and Security Assessment Techniques and their Application to Port Operations", PhD Thesis, School of Engineering, Liverpool John Moores University, UK.

Ung, S. T., Williams, V., Chen, H. S., Bonsall, S and Wang, J. (2006), "Human Error Assessment and Management in Port Operations using Fuzzy AHP", Marine Technology Society Journal, Vol. 40, No. 1, pp. 73-86.

Valaityte, A., Dunnett, S. J. and Andrews, J. D. (2009), "Development of an Algorithm for Automated Cause-consequence Diagram Contruction", International Journal of Reliability and Safety, Vol. 4, No. 1, pp. 46-68.

Vanem, E., Antão, P., Østvik, I and De Comas, F. D. C. (2008), "Analysing the Risk of LNG Carrier Operations", Reliability Engineering and System Safety, Vol. 93, Issue 9, pp. 1328-1344.

Villemeur, A. (1992), "Reliability, Availability, Maintainability and Safety Assessment", John Wiley & Sons, Chichester, UK.

Vyzaite, G., Dunnett, S and Andrews, J. D. (2006), "Cause–consequence Analysis of Non-repairable Phased Missions", Reliability Engineering and System Safety Vol. 91, Issue 4, pp. 398-406.

Walker, A. H., Scholz, D., Boyd, J. and Burns, G. H. (2003), "LNG Transportation, Risk Management, and Maritime Security", International Oil Spill Conference Proceedings, April 6-10, Vancouver, British Columbia, Canada.

Wang, J. (2000), "A Subjective Modelling Tool Applied to Formal Ship Safety Assessment", Ocean Engineering, Vol. 27, Issue 10, October, pp.1019-1035.

Wang, J. and Foinikis, P. (2001), "Formal Safety Assessment of Containerships", Marine Policy, Vol. 25, No. 2, pp. 143-157.

Wang, J. and Trbojevic, V. M. (2007), "Design for Safety of Marine and Offshore Systems", Institute of Marine Engineering, Science and Technology, London.

Yang, Z. (2006), "Risk Assessment and Decision Making of Container Supply Chains", PhD Thesis, School of Engineering, Liverpool John Moores University, United Kingdom.

Yang, Z., Wang, J., Bonsall, S., Fang, Q. and Yang, J. B. (2005), "A Subjective Risk Analysis Approach for Container Supply Chains", International Journal of Automation and Computing, Vol. 2, No. 1, pp. 85-92.