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Qualitative and Quantitative Risk Assessment Method for Fire Safety Accident in Liquefied Natural Gas Storage

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ABSTRACT

Liquefied natural gas (LNG) has the characteristics of low temperature, volatile, flammable and explosive, and its safety issues are being highlighted. The probability and consequences of accident were quantitatively analyzed in combination with the possibility of LNG filling station pump or pipeline spillage. The DEGADIS and LNGFire3 models were used to determine the consequences of the accident. Based on the injury criterion data provided by relevant literature, the article concludes that the personal risk value derived from personal injury level and mortality rate, when compared with personal risk standards of United Kingdom, Netherlands and other countries and institutions, the personal risk value is much lower than the standard limit value, and shows the rationality of establishing 5kW/m2 as the safety distance from critical thermal radiation intensity.

KEYWORDS: quantitative risk assessment; liquefied natural gas; leakage; fire pool; safety

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Introduction

With the global development of socio-economy, people are paying more attention to liquefied natural gas (LNG) as a source of clean. However, due to its low temperature, volatile, flammable and explosive characteristics, the safety issues of LNG stations are being highlighted, and the safety risk assessment of LNG station is imminent. Currently, there are many kinds of engineering safety risk assessment methods which according to the degree of evaluation, can be divided into quantitative, qualitative and semi-quantitative method. Qualitative risk assessment examples: security check table method, United States MILSTD-882A standard (risk is divided into four levels and the possibility of accidents occurring is divided into six levels), analysis of accident and consequences, etc. Qualitative method is relatively easy to use and the evaluation process and results are intuitive. However, the probability and consequences of the accidents can not be quantified and the accuracy of the evaluation results depends on the experience of the operator, meticulousness of the root cause analysis, and so on. Quantitative Risk Assessment (QRA) is based on a large number of experimental results and a wide range of accident data to provide the probability and consequences of accidents. Through the probability of system failure and quantitative analysis of the consequences, it accurately describes the risk of a system [1-2], and the evaluation results are firm and quantitative. Commonly used evaluation methods are fuzzy matrix method, DOW chemical company fire and explosive risk index evaluation method, etc.

Semi-quantitative evaluation method uses a unified approach to classify risks according to levels, assess ratings for the probability and consequences of the accidents, and combining both ratings to form a relative risk rating [3].

Based on the accuracy of the three evaluation methods, the quantitative method is the best, followed by semi-quantitative and qualitative method. In the event of an accident in a LNG station, it is likely to cause serious personnel and property damage; therefore, the more appropriate method would be the quantitative risk assessment (QRA). In this paper, quantitative risk assessment method (QRA) is used to illustrate the application of the method in the accidents of LNG pump or LNG piping spillage in LNG filling stations in China.

1. Understanding of the New Energy Source Liquefied Natural Gas

1.1. Liquefied Petroleum Gas (LPG)

The basic properties of liquefied petroleum gas is the multi-hydrocarbon component, calorific value equivalent to gasoline, and mainly consist of 8 components such as propane, butane, propylene, butane, etc.

Because of its proportion is greater than air, the explosive limit range from 1.7% to 10% and it sinks easily to lower areas and burns and explodes when met with fire source.

1.2. Compressed Natural Gas

Compressed natural gas is pressurized natural gas stored in a gaseous form in a container. Similar to the composition of pipeline natural gas, its main component is methane and can be used as vehicle fuel. Natural gas is also known as oil field gas, oil gas, and oil with gas. When petroleum is mined, only the gas is called natural gas. Natural chemical composition and properties vary from place to place; the main component is methane, and containing a small amount of ethane, butane, pentane, carbon dioxide, carbon monoxide, hydrogen sulfide, etc. With density of 0.6 – 0.8 g/cm it is lighter than the air. When concentration of natural gas in the air is 15% or more, it can burn normally; when concentration is 5% to 15%, it can explode when met with flame. This concentration range is the explosive limit of natural gas. Natural gas explosions produce high pressure and temperature and its destruction and danger are very great.

1.3. Liquefied natural gas

The main component of liquefied natural gas is methane. After gasification it is lighter than air, able to spread quickly during leakage and is considered a save energy source. During the liquefaction process, sulfur, carbon dioxide, moisture and other substances have been removed, so sulfur decomposition does not occur to cause air pollution. It is considered as clean energy and has a high calorific value. The manufacturing of liquefied natural gas starts from purification of the natural gas produced from oil fields, going through a series of ultra-low temperature liquefaction, and filled into filling station by special tankers and ships. Developed countries has developed this gas a few years back and have actively promote its use; in addition as a fuel for power generation, factories, homes, and cars, it contains methane which can be used as raw materials in the manufacturing of fertilizers, methanol solvents and synthetic acetic acid. It also contains ethane and propane which can be used to produce ethylene and propylene, an important raw material for plastic products. China's PetroChina, China National Offshore Oil Corporation (CNOOC), and China Petrochemical Corporation are listed companies that produce liquefied natural gas and have made major contribution to the energy shortage in China.

2. Analysis on the Risk of New Energy Liquefied Natural Gas

At present, there are many safety issues concerning China's liquefied natural gas, from production, storage, transportation, filling, sales, usage and other aspects.

2.1. No planning support

In the early 1990s, CNOOC first introduced liquefied natural gas to China. At present, Guangdong Dapeng, Fujian and Shanghai has started operations in liquefied natural gas projects; Dalian, Jiangsu, Zhejiang, Zhuhai, Shenzhen and Hainan has begin planning and construction, and in 2020, China’s national planning and development will grow to 13 enterprises. However, this planning and development does not have legal support as basis.

2.2. Acceptance audit is unavailable

In existing specifications, GB 50156 - 2002 Automobile Refueling Station Design And Construction Specifications does not include liquefied natural gas; GB 50183 -2004 Oil And Gas Engineering Design Fire Safety Regulations does include liquefied natural gas but not specific; GB 50160 - 2008 Petrochemical Enterprise Design Fire Safety Specification clearly does not apply to liquefied natural gas.

2.3. Danger in filling stations

All across the country, there are many transport vehicles and filling stations for liquefied natural gas, and sometimes accidents occur. In Henan Province, incidents such as tanker leaks, crashes, traffic accidents, fire and explosion, and rescue operations occur up to hundreds of times in a year. Lightning current, instantaneous conversion of heat, high temperature ignition from natural gas leakage, mechanical effects, electromagnetic effects, earthquakes and other natural disasters may cause the tank and gas to expand and burst, leading to fire and explosion.

2.4. QRA method and description of accident

In the LNG car filling station, accidents on the gas pump or loading piping during filling process is the biggest risk of LNG leakage. Example of accident is as follows: flow rate of the LNG pump is 0.19 m3/min, manual filling valve with valve size 50 mm, sudden breakage of the filling pipe valve during filling process, response time of emergency valve shut-off is less than 10 s (10 s is set to ensure safety), LNG leakage turns to liquid pool, quick evaporation of the gas forms a low temperature heavy gas cloud and diffuse according to air flow direction.

2.5. Probability of accident occurrence and consequences analysis

2.5.1 Probability of accident occurrence

LNG leakage is a source of major hazards for fire and explosion. The analysis of probability of leakage is mainly based on the analysis of the probability of leakage from equipments and facilities, which is usually analyzed by historical accident statistics or accident tree analysis. At present, some foreign research institutions such as Det Norske Veritas (DNV), the British Health and Safety Administration (HSE), the US Chemical Process Safety Center (CCPS) and so on, have a similar database, and can directly provide the probability of leakage for various types of equipments [4]. It is used to determine the major hazards in the quantitative risk assessment of basic probability of leakage. The probability of the leakage from the 50mm manual valve in the table is taken as the probability of valve breakage, which is 1.4 x 10-5.

A fire may occur after the gas cloud ignites. To ensure safety, the probability of igniting the gas cloud is included in the probability of fire occurrence, and the probability of fire occurrence is calculated as the probability of fire pool occurrence.

2.5.2 Analysis of the consequences of the accident

The accident consequence analysis is based on various accident consequence models, taking into consideration the changes according to distance in heat radiation, overpressure shock wave, or concentration of diffusion of dangerous substance, etc., and compares with the corresponding injury guidelines, to determine the effects range of the accident [4]. The DEGADIS (DenseGasDispersion) model was developed by Havens and Spicer in 1989 to analyze the model of heavy gas diffusion [7] and was used as a model for NFPA 59A to evaluate the heavy gas diffusion conditions in LNG production and storage [8]. LNGFire3 is the model of NFPA59A recommended LNG fire pool thermal radiation calculation which is used to determine the thermal radiation intensity of fire at different distances.

Regarding LNG diffusion and fire safety, NFPA59A recommends that half of the methane combustion limit (volume concentration 5%) and thermal radiation intensity of 5 kW/m2 is set as a criterion for determining the safety distance of the building red line. Figure 3 shows the DEGADIS and LNGFire3 model calculations of the concentration of heavy gas diffusion and thermal radiation intensity, according to changes in distance.

For volume concentration of 5% the distance from leakage source is about 35 meters, and 215% the distance is about 56 meters;the thermal radiation intensity of 5kW/m2 (which is the critical thermal radiation intensity that the human body could bear), the distance from the fire pool of about 16 meters.

The relationship between the degree of burns and the radiation dose, and the mortality rate of different burns. If the skin is exposed (without protective clothing) in thermal radiation intensity of 5kW/m2 range of time beyond 30s, it may lead to second degree burns [9]. As LNG filling station is located away from public area, in the event of a fire, generally it is only the filling station staff members who will be danger. Assuming a fire had occurred, the probability of occurrence of third degree burn is 1%, and second degree burn is 5%.

2.6. Preliminary Hazard Analysis

The preliminary hazard analysis method includes in an engineering safety system category. It is a method in analysis of the safety system which is a summary of the risk factors, conditions and possible consequences of the accident before the start of a project (including design, construction, installation, production, maintenance, etc.). The purpose is to identify the potential risk factors of the system, determining the system's risk level, put forward the corresponding preventive measures to prevent accidents, and to avoid property damage. According to the severity of the accidents, the danger and risk factors are divided into four levels.

The basic steps of the pre-hazard analysis are as follows: Hazard identification, ie, through empirical judgment, technical diagnosis or other methodological investigation to determine the presence of dangerous and harmful factors in the system. Determine the type of accident that may occur, based on past experience and lessons (and disasters) in the production of the same industry, the impact on the system, the degree of damage, the likely situation in the system to be analyzed, failure, material loss and the risk of personal injury, then analyze the possible types of accidents (or disasters). Identify the source of the identified hazards and make a pre-hazard analysis table. Study the conditions needed for the transformation of the risk factors into dangerous conditions and the transformation of the dangerous conditions into accidents (or disasters), then further sought out the preventive measures and test the effectiveness of the measures. Conduct risk classification by classifying the main focus and classify orders such as mild, severe, slow and urgent. Conduct preventive measures to prevent accidents (or disasters).

2.7. Preliminary risk analysis of liquefied natural gas storage

The main material involved in the liquefied petroleum gas storage and distribution stations is liquefied petroleum gas which is a flammable and explosive substance and has certain toxicity. In the unloading, canning, inverted liquid and filling process, accident such as fire, explosion, and poisoning may occur due to improper management or equipment failure. Therefore, according to the relevant provisions of the petrochemical industry and 5 construction design fire safety speciation 6, with reference to similar enterprises, liquefied petroleum gas fire, explosion, and poisoning accidents are identified as the most alarming accidents in the process [5]. At the same time, lightning and electrical damage, electrical fires, transportation injuries, falling and slipping, floods and other accidents may also occur during production. According to the types of accidents identified above, the causes and risk factors of each type of accidents are analyzed and summarized, and the risk factors and the triggering events of the accident, the cause of the accident and the consequences of the accident are analyzed and determined. In this paper, only the PHA analysis results of the main accident type (fire and explosion) are listed.

2.8. Pre-risk analysis of liquefied petroleum gas storage and distribution stations

(1) Possible types of accidents in liquefied petroleum gas storage and distribution stations are fire, explosion, poisoning, lightning and electrical injury, electrical fires, factory transport injuries, object strikes, falling and slipping, floods and so on.

(2) Through the pre-risk analysis of the process, it shows: in level Ô, it is a catastrophic degree of danger and has 1 risk factor, which is liquefied petroleum gas fire explosion; in level Ó, it is a dangerous degree and has four risk factors including lightning and electrical damage, electrical fires, falling and slipping, and flooding; in level Ò, it is a critical degree and has three risk factors including poisoning, vehicle traffic accidents and object strikes.

(3) For the above mentioned possible risks factors, preliminary precautionary measures have been put forward in the preliminary hazard analysis table. If the effective control of these dangerous points in the production process is strengthened, the safety requirements can be met.

3. Prevention measures against accidents involving liquefied natural gas

3.1. Adopt foreign standards

Liquefied natural gas is certified under International Standardization Organization (ISO). As early as 1959 when the United States shipped 5000 m LNG to the United Kingdom, the British became a LNG consumption country and after 40 years, the British Standardization Committee has prepared standards. Germany has also prepared standards. Experts and scholars of 18 countries including Austria, Belgium, Denmark and others have compiled the standards of LNG characteristics, standards of equipment, installation and fire safety etc. and the standard has played an important role in the development of liquefied natural gas industry in Europe. The United States is the first country to develop the liquefied natural gas industry. Standards set by National Fire Protection Association (NFPA), American Petroleum Institute (API), and Institute of Mechanical Engineers (ASME) has formed a variety of LNG standards, covering from production to the specific aspects in the standards especially in the formation of federal government legislation pertaining safety.

3.2. To establish legislative system

On the basis of international standards, it is necessary to formulate national laws and regulations on liquefied natural gas, industry standard, and enterprise standard to form a legislative system that is suitable to China's national conditions, in line with actual production, storage, loading and unloading, sales and others aspects, in order to ensure scientific, effective and safe operation according to the law.

3.3. To develop filling station design with fire safety specification

3. 3. 1 Layout

Taking urban planning into account, the stations' location shall be away from high density areas, areas that are flammable, explosive, has important public buildings, public entertainment area, and high rise buildings. The site shall be lower than the surrounding buildings or urban roads to prevent LNG overflow or leakage to the boundary areas. Also, city with the minimum frequency of wind and where there is upstream wind direction at a relatively concentrated fire source at surrounding enterprises and fire shall be chosen.

3. 2. 2 Fire safety distances

According to the fire hazard level, specifications shall be set according to relevant critical specifications. When storage tank volume is 8 – 57 m the smallest fire safety distance away from the building is at 8 m; when tank volume is 57 – 114 m the smallest fire safety distance shall be 15 m; when tank volume is 114 – 265 m the smallest fire safety distance shall be 23 m. The distance between the above three volumes and fire source shall be controlled at 15 m or more. The distance between the tanks shall be controlled at least ¼ of the sum of adjacent tanks diameter and at least less than 1.5 m, as stated in 2010 No. 12th Fire Technology and Product Information.

3. 3. 3 Circular lanes

The station must be designed and constructed to accommodate access of fire engines; circular lanes not less than 6 m wide and 12 m x 12 m site. Especially in emergency situations, liquefied natural gas tanker can access easily. During accidents, more tanks can be loaded to facilitate the transportation of tankers.

3. 3. 4 Leakage control

Liquefied natural gas stored in tanks and pipelines are generally at 160 °C or more. Poor sealing, soaking, dripping, and leakage can easily cause the tank and pip to fracture, deform, expand and overflow. In the event of leakage or fire, the accident shall be confined to a certain area, immediately treat with fire extinguisher to prevent the formation of spreading fire.

3. 3. 5 Fire resistant

The fire-resistant grade of all buildings in the stations must be set at more than 2 h after the fire-resistant time, and all the structures, steel pipes, pipe racks and bearings in the station shall be painted with fire-resistant paint (fireproof paint).

3. 3. 6 Safety exit

The station must be set up with two safety exits. Anti-liquid flow of the storage area and operation work platform also require up two safety exits to ensure that in the event of an accident, fire engines and rescue vehicles are able to conduct rescue; to ensure the safety exit of operators during an accident.

3. 3. 7 Process flow

The core of the safety design is the operation process of the liquefied natural gas station. The safety and management of each device, pipeline, tank, instrument, valve and other factors shall be quantitatively analyzed, and then conduct qualitative and quantitative safety measures.

3. 3. 8 Safety facilities

In order to be able to quickly and effectively control during normal and abnormal operation process, the safety facility shall have a pressure control device (pressure relief device – to prevent pressure overrun, automatic and manual relief valve. Concentrated release tube – 2 m above the building within 25 m, set on upstream wind direction, divergence direction shall be facing upwards). Material storage valve – Limits the material in the tank during leaks or fires; Emergency cut-off system – When instrument cannot be repaired or malfunction, the system automatically alarms the police and cut off the hazard source; Remote shutoff system – in the event of failure of the emergency cut off system and unable to control on site, the remote system can be used to cut of the tank and tanker operation; Control programs – set effective control programs such as interlocking systems, allow highest level, cut off incoming, prevent overrun, and others.

3. 3. 9 Device layout

Layout of station equipment and pipeline is more intensive, but consideration shall also be taken on its operation, maintenance, evacuation area and channel. The risks on the arrangement of various pipelines must be considered; electrical and instruments cannot be tapped to the process pipeline to prevent leakage of natural gas and EDM contact explosion.

3. 3. 10 Instrument checking

Online real-time control shall be implemented on the tank: level gauge, pressure gauge interlock system, overrun alarm, quick cut off system; on the piping and filling machine: pressure gauge, thermometer, flow meter, etc. Leakage alarm, low temperature detectors and fire detectors can be installed for the storage area. All instruments shall be interlocked with emergency shut off system to enable immediate cut off and halt transportation in an event of an accident.

3. 3. 11 Electrical designs

In accordance with GB 50058 - 92 Explosive And Fire Hazardous Environment Electric Appliance Design Code, in explosion and fire hazard areas, explosion proof equipment shall be select according to level of explosion. Use flame retardant materials and cable to prevent the gas and liquid to enter the distribution and control room. In accordance with GB 50057 - 94 Building Lightning Protection Design Code, explosion hazard area in gas I area is divided into two categories: prevention of direct lightning, lightning induction, and prevention of lightning waves.

3. 3. 12 Fire extinguishing system

Combustible gas detection equipment – to provide early warning of gas leakage and to take preventive measures in advance; dry powder fire extinguishing system – used for control room and power distribution room, install fire extinguisher that uses carbon dioxide or other gases; High-pressure water mist fire extinguishing system – used on the station tank, trench and pipe, play a role in isolation, choking to extinguish fire; Fire hydrant system – used to cool the storage tank and facilities during fire and thermal radiation incident, but must be noted that usage of water will accelerate the gasification of liquefied natural gas thereby increasing the burning rate. Cautions shall be taken when using this water.

3.4. Strict examination and acceptance

Liquefied natural gas production, storage, transportation, and sales must be conducted in accordance with national laws, regulations, specification, and strict inspections shall be conducted on field inspection, acceptance, and management. In China, there is no clear rules and regulations, so reference to foreign specifications and neighboring specification and standards shall be made. Professional training shall be given to personnel engaged in production, management and operation of liquefied natural gas to prevent accidents due to misuses and violation of operating procedures. A set of regulation, specification and standard system shall be established and improved so that rules can be followed, accordance to law, safe operation, guaranteed, socially responsible, safe and reliable.

4. Managing liquefied natural gas accidents

At present, China's liquefied natural gas accident prevention and disposal measures are absent. There are no laws, regulations, or standard system, which will inevitably lead to a series of safety issues on production, storage, transportation, and sale. An effective management on accidents must be taken.

4.1. Establish emergency response mechanism

A level of emergency response mechanism shall be established in liquefied natural gas production, storage, transportation, and sales. Firstly, is the responsible party (referring to the production, storage, transportation, sale and other units). To establish and improve the emergency management procedures for fire safety systems, refine the countermeasures for various aspects of the process, configuration of the various types of equipment, and equipment training required to all technical staff to ensure that accidents can be managed safely, quickly and effectively. Secondly, is the government role (referring to all levels in the government). They should be the emergency center to deal with the management of liquefied natural gas leakage, explosion, fire, rescue and other aspects, schedule the emergency response mechanism, and develop contingency plans, providing unified command, integration of resources, providing practical and efficient response. Thirdly, is the professional body (referring to fire rescue, safety supervision, gas, transportation and other professional bodies). A special plan shall be devise to prevent and deal with all kinds of accidents in all areas of production, storage, transportation and sale. Process management plan, storage area management plan, the disposal management process, leakage during sales, explosion, fire, disposal measures and other programs shall be specific, operable, targeted, timely, and safe.

4.2. To establish self-rescue management system

Self-rescue management is the first element of early warning, discovery, rescue, early rescue, and to prevent further expansion of the accident. A self-removing management system shall be established. In production area, there shall be a professional team of legal person in charge, has a variety of disposal equipment, a variety of professionals, training sites, logistics and financial security, day and night patrol. Storage sites must be monitored by trained qualified personnel, location and responsibilities are well established, and familiar and proficient with operation equipments; operators in charge of transport equipments shall ensure vehicle equipment comply with the relevant provisions for transport of dangerous goods, anti-static, anti-fire, and has complete requirement of plugging equipments. At the sales site, a comprehensive management team shall be established where the station leader shall be the first response personnel. The team shall comprise of managers, engineering and technical personnel, and operators. A response team from various levels, sub team, and operation sections is established to form different management teams and method to deal with various accidents.

4.3. Implementation and specific measures of rescue and fire extinguishing

(1) Regional control. Regardless of leakage, fire, explosion, and traffic accidents, immediate action shall be taken within 500 m radius. Control on all personnel, cut off all fire and electrical source, and according to the characteristic of the accident, conduct immediate rescue according to plan.

(2) Scientific monitoring. Immediately conduct analysis on the equipment and liquefied natural gas leakage and establish the spreading rate and specific spreading location, to provide a scientific technical basis for conducting rescue.

(3) Manpower arrangement. On the basis of scientific analysis and judgment, according to the characteristics of different accidents placing safety as the main concern, grasp the main elements and confirm the location of the accident in order to develop a specific management program, and then arrange the appropriate manpower to conduct the necessary action.

(4) Quick rescue. Liquefied natural gas diffuses quickly, easily causing fire and explosion, and tts destructive power is very great. Shortest possible time shall be used to control, manage, and eliminate any accident or disaster. Regardless of production, storage, transportation, sales or other aspects, plugging is the first part, and transfer and loading is the second part. Effective implementation of cooling, fire extinguishing, covering, and isolation shall be taken within the first and second part, and it is the only way to reduce the risk to the bare minimum.

5. Conclusion

Through the preliminary risk analysis of liquefied natural gas storage station, it is possible to determine the dangerous risk factors of production process, triggering conditions of accidents caused by various hazards, and predict the possible impact of various hazards to the production. According to classification of danger level and different hazard levels, combining with various resources to put forward scientific and effective safety measures to eliminate, prevent or reduce risks. Production process plan shall be based on preliminary risk analysis of safety measures, and abide strictly to design requirements. Safety management system on construction and management shall also be strengthened in liquefied natural gas storage station. The complete implementation of safety technical measures and management measures shall be taken to prevent occurrence of accidents.

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