Research on Optimization of LNG pressure control safety accessories based on fault tree analysis

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Abstract. This paper classifies more than 20 accidents according to the main factors and types of accidents from 1994 to now. Through analysis, it is found that the safety attachment of LNG pressure control is a weak link in LNG storage system. The safety attachment of LNG pressure control is analyzed from four aspects of people, machine, Environment, and management, and the fault tree model is established. After calculation, the minimum cut set and structural importance of the safety attachment of LNG pressure control are obtained. Based on the fault tree analysis results of LNG pressure control safety accessories and the statistical results of 20 accidents, control measures and suggestions are put forward from the peripheral layout, electrical, equipment, installation, production operation, daily maintenance of LNG pressure control safety accessories, in order to prevent and reduce accidents caused by LNG pressure control safety accessories.

1. Introduction
LNG (Liquefied Natural Gas) is liquefied natural gas, which can save storage and transportation space and cost greatly after liquefaction, and has the characteristics of high calorific value and high performance. At the same time, it can remove impurities in the liquefaction process. It is a high-quality, clean, efficient and convenient green fuel, and is considered to be the cleanest fossil energy on the earth. LNG belongs to flammable and explosive dangerous chemicals, so there are always security threats in the process of production, processing, storage, transportation and operation. Especially in the process of human utilization of LNG energy, the danger of LNG tank explosion is becoming increasingly prominent. Once an accident occurs, it is very easy to cause casualties, property losses and environmental damage. Therefore, it is necessary to explore the development law of accidents, explore the key points and influencing factors of LNG fire and explosion accidents, and put forward corresponding accident prevention and control suggestions to provide support for the safety development of LNG industry[1].

2. Statistical Table Analysis of Major Accidents in the History of LNG Industry
The first major accident in the history of LNG industry was a fire and explosion accident at LNG gas storage station in Cleveland, USA in 1944. This paper makes a statistical analysis of 20 explosion accidents in LNG tank farms on land in the world since 1944. We classify major accidents of LNG...
according to the main influencing factors and types of accidents. The main factors include equipment factors, human factors, environmental factors and management factors. The major types of accidents are chemical explosion, physical explosion, LNG leakage and tank fire. The accident situation and classification are summarized in Table 1[2].

Table 1. LNG Major Accidents Statistics Table.

| Time   | Location of the accident        | Accident situation                                                                                       | Main Influencing Factors | Accident type              |
|--------|--------------------------------|--------------------------------------------------------------------------------------------------------|---------------------------|----------------------------|
| 1944   | Cleveland, USA                 | Storage Tank Material Failure, LNG Leakage Explosion 131 Deaths                                          | Equipment factor          | Chemical explosion         |
| 1968   | Portland, USA                  | Four people died in tank explosion caused by gas leakage during pressure measurement                     | Equipment factor          | Chemical explosion         |
| 1971   | Las Pezia, Italy               | Misfilling operation, 2000 t LNG leak in tank roll                                                    | human factor              | Gas leakage                |
| 1972   | Montreal                       | Workers misoperated, natural gas returned to the nitrogen pipeline, and one person died after the leak triggered an explosion. | human factor              | Chemical explosion         |
| 1973   | New York, USA                  | Burning of insulating materials during tank maintenance resulted in 40 deaths due to overpressure explosion of tanks. | human factor              | Physical explosion         |
| 1973   | Kenwick Island, UK             | Breakage of barometer leads to leakage of LNG and explosion of vapor cloud                              | Equipment factor          | Chemical explosion         |
| 1977   | Arzew                          | Aluminum valves failed, 2 x 103 cubic meters LNG leaked, 1 person died                                  | Equipment factor          | Gas leakage                |
| 1977   | Bangtan, Indonesia             | Failure of liquid level alarm, overfilling of storage tank, overpressure leakage                        | Equipment factor          | Gas leakage                |
| 1978   | Das Island, United Arab Emirates | Failure of Bottom Pipe Joint of Storage Tank and Leakage of LNG                                    | equipment factor          | Gas leakage                |
| 1979   | Maryland, USA                  | LNG pump seal failure, LNG vapor leakage caused explosion, one person died, one person was injured     | equipment factor          | Chemical explosion         |
| 1983   | Bangtan, Indonesia             | Control valve failure, heat exchanger overpressure explosion, 3 deaths                                | Equipment factor          | Physical explosion         |
| 1985   | Alabama                        | The weld of storage tank was broken, LNG leaked and ignited. Six people were seriously injured.         | Equipment factor          | Tank fire                  |
| 1987   | Nevada                         | Ignition of LNG Vapor Cloud by Unqualified Insulation Material                                         | Management factors       | Tank fire                  |
| 1988   | Massachusetts, USA             | Flange gasket failure, 114 cubic meters LNG leakage                                                   | Equipment factor          | Tank leakage               |
| 1989   | Britain                        | The vaporizer drain valve was not closed and the LNG vapor cloud was ignited after ejecting. Two people were seriously injured. | Management factors       | Tank fire                  |
| 1992   | Maryland, USA                  | The safety valve is not open. After overfilling, the tank wall breaks and 95 cubic meters LNG leaks. | Management factors       | Tank leakage               |
| 1993   | Bangtan, Indonesia             | LNG pipelines are damaged and LNG leaks are caused by line renovation                                 | environmental factor      | Tank leakage               |
| 1993   | University of Manchester       | LNG rolling, 150 t natural gas exhaust                                                                | human factor              | Tank leakage               |
| 2004   | Skikda, Algeria                | Boiler explosion caused LNG leak and gasification, triggered vapor cloud explosion, 27 people were killed and 72 injured. | environmental factor      | Chemical explosion         |
| 2007   | Shanghai China                 | One person died and 16 others were injured in an explosion caused by tank pressure test                | human factor              | Physical explosion         |

2.1. Classification of LNG Major Accidents

**Fire.** After LNG leaks, it quickly gasifies into methane vapor and mixes with air to form a vapor cloud. When the concentration reaches the explosion limit (5%-15%), the vapor cloud will produce flame when it meets the fire source: when the amount of vapor is less, flash will occur; when the leakage is more, the vapor will ignite and burn after ignition, and the vapor will burn on the surface of LNG liquid pool, resulting in pool fire; when the leakage is ignited directly, spray fire will occur. For example, in 1985, at the LNG receiving station in Alabama, the vapor cloud diffused into the control room and ignited a fire; in 1989, at the LNG peak shaving station in Britain, after the vapor cloud was ignited, the spark covered a length of 40 meters.

**Chemical explosion.** Chemical explosion in LNG tank area can be divided into the following two situations: ①vapor cloud explosion (UVCE), LNG leaking volatile air mixed with air, and with air flow, vapor cloud explosion is formed when fire source meets in a relatively closed space;② Boiling liquid extended vapor explosion (BLEVE), when the tank is baked by fire source, impacted or mechanical failure, the tank suddenly cracks, and a large number of liquefied gases come from the tank. BLEVE will occur in case of fire source, or after overpressure physical explosion of storage tank, a large amount of vapor will leak and BLEVE will occur in case of fire source. Such as: 1944 fire and...
explosion accident at Cleveland gas storage station in the United States; 1987 LNG vapor cloud explosion at Nevada test base in the United States; 2004 LNG refinery vapor cloud explosion in Algeria.

**Physical explosion.** LNG is a cryogenic liquid stored at boiling point temperature. When the pressure remains constant, it can keep constant temperature. LNG in tank belongs to the coexistence of gas and liquid phases. In the process of storing, entering and leaving liquid, the liquid in tank is prone to roll and produce the phenomenon of vortex, geyser or water hammer. When excess vapor is not discharged in time, the pressure in the tank will continue to rise, reaching the endurance limit of the tank, thus causing the overpressure physical explosion of the tank. For example, in 1971, the Italian Laspezia SNAM LNG receiving station, the LNG tank rolled inside, 20 000 tons of LNG leakage; in 1993, the British Gas LNG peak shaving station, LNG rolled over, 150 tons of natural gas exhaust, etc[2].

**LNG Leakage.** LNG is a mixture consisting mainly of methane nitrogen and saturated alkanes of C2-C5. The volume of liquefied natural gas (LNG) is about its gaseous volume, which greatly reduces the occupied volume. LNG can be stored in LNG cryogenic storage tanks at ocean transportation and receiving terminals by LNG ships or barges, which is conducive to long-distance transportation and storage. Because the explosion limit of LNG is low (5% - 16%), when the valves, pipes and containers of storage and transportation devices are damaged or not tightly sealed, LNG will leak a lot and quickly mix with air to reach the explosion limit due to the heavy gas effect. In the case of open fire or sparks, it will explode and burn violently, which will bring catastrophic impact on people's lives. In addition, the leakage of liquefied natural gas will cause low temperature frostbite and some secondary hazards. According to the accident statistics table 1, the causes of LNG leakage in major accidents are as follows: ① Overpressure leakage due to failure of valves and alarms. ② Filling is not operated in strict accordance with the standard.③ The LNG pipeline was destroyed by inadvertent construction[6].

2.2. **Statistical analysis of LNG major accidents**

For the statistics of 20 accidents from 1944 to the present, we have divided the factors leading to accidents into four aspects: equipment factors, human factors, environmental factors and management factors. The factors of LNG major accidents are statistically illustrated in Figure 1.

![Figure 1. Statistical pie chart of LNG accident factors.](image_url)

From the pie chart, we can see that equipment factors, human factors, management factors and environmental factors accounted for 45%, 30%, 15% and 10% respectively, among which equipment factors led to major accidents accounted for a larger proportion. As can be seen from Table 1, the accidents caused by pressure control accessories account for 9 out of 20 accidents (highlighted in the
table), which can cause any of the four major types of accidents, and the accidents are dangerous or catastrophic. From the comprehensive analysis of accident types and causes, it is necessary for us to further analyze LNG pressure control safety accessories in order to reduce major accidents of LNG.

3. Establishment and Analysis of Fault Tree Model for LNG Pressure Control Safety Accessories

3.1. Analysis of Influencing Factors
The top event (LNG pressure control safety accessory) can be divided into two aspects: human unsafe factors (accessory failure) and material unsafe factors (not timely maintenance). Human unsafe factors are analyzed from three aspects: norm, operation and psychology. The material unsafe factors are analyzed from two aspects of valves and instruments. The accident tree model of LNG pressure control safety accessory is established. As shown in Figure 2[3].

![Figure 2. Analysis of the Influencing Factors of LNG Pressure Control Safety Accessories](image)

3.2. Establishment and Analysis of Fault Tree Model
The event symbols in the accident tree are illustrated in Table 2.

Table 2. LNG Major Accidents Statistics Table.

| Symbol | Event                                      | Symbol | Event                                      |
|--------|--------------------------------------------|--------|--------------------------------------------|
| T      | Failure of LNG pressure control safety accessories | X4    | Mileage too high and overpressure not open |
| M1     | Attachment failure                         | X5    | Artificial deactivation                     |
| M2     | Failure to repair in time                   | X6    | Failure of chain alarm                      |
| M3     | Valve failure                              | X7    | Failure of Vacuum Meter in Vacuum Insulation Tank |
| M4     | Instrument failure                         | X8    | Damage of pressure gauge                    |
| M5     | Failure of manual relief valve             | X9    | Failure of Temperature Measuring Device for Storage Tank |
| M6     | Safety valve does not open properly        | X10   | Cryogenic freezing cannot be opened         |
| M7     | Failure of Safety Valve Moving Parts       | X11   | False shutdown of alarm                     |
| M8     | Failure of liquid level alarm device       | X12   | Pressure point error                        |
| M9     | Pressure gauge failure                     | X13   | Training defect                             |
| M10    | Illegal operation                          | X14   | Institutional irregularities                |
| X1     | Valve blockage                             | X15   | Mental and physical distress                |
| X2     | Corrosive cohesion                         | X16   | Lack of experience                          |
| X3     | Spring Corrosion and Adhesion Can't Open   | X17   | Leave one's post temporarily                |

3.3. Computation of Minimum Cut Set and Analysis of Structure Importance of Basic Events

The number of cut sets is 60, and the minimum cut sets are as follows:

X1,X14; X6,X14; X3,X14; X2,X14; X4,X14; X5,X14; X7,X14; X8,X14; X9,X14; X10,X14; X11,X14; X12,X14; X1,X13; X1,X15; X6,X13; X6,X15; X3,X13; X3,X15; X2,X13; X2,X15; X4,X13; X4,X15; X5,X13; X5,X15; X7,X13; X7,X15; X8,X13; X8,X15; X9,X13; X9,X15; X10,X13; X10,X15; X11,X13; X11,X15; X12,X13; X12,X15; X1,X17; X1,X17; X6,X16; X6,X17; X3,X16;
The following approximate formulas are used to calculate the structural importance of each basic event in the accident tree:

\[ I_{\phi(i)} = 1 - \prod_{k_j \in K_i} (1 - \frac{1}{2^{n_j - 1}}) \]

In the formula, \( n_j \) is the total number of basic events in the smallest cut set \( \{k_j \} \) where the \( j \) basic event is located, and \( I_{\phi(i)} \) is the structural importance coefficient of the \( i \) basic event. The results are as follows:

\[ I_{\phi(1)} = I_{\phi(2)} = I_{\phi(3)} = I_{\phi(4)} = I_{\phi(5)} = I_{\phi(6)} = I_{\phi(7)} = I_{\phi(8)} = I_{\phi(9)} = I_{\phi(10)} = I_{\phi(11)} = I_{\phi(12)} = 0.968750000000 \]

Structural importance:

\[ I_{\phi(13)} = I_{\phi(14)} = I_{\phi(15)} = I_{\phi(16)} = I_{\phi(17)} = 0.999755859375 \]

From the analysis results, we can see that \( I_{\phi(13)}, I_{\phi(14)}, I_{\phi(15)} \) and \( I_{\phi(16)} \) values are the largest, \( I_{\phi(1)}, I_{\phi(2)}, I_{\phi(3)}, I_{\phi(4)}, I_{\phi(5)}, I_{\phi(6)}, I_{\phi(7)}, I_{\phi(8)}, I_{\phi(9)}, I_{\phi(10)}, I_{\phi(11)}, I_{\phi(12)} \) are the second, and the values in the ranking of structural importance are relatively large, while the structural importance coefficients of other basic events are relatively small[4].

4. Measures and Suggestions

Referring to the existing norms and standards, and considering the causes of accidents in the past, the following measures and suggestions are put forward:

1. Pressure test operation, according to the working conditions of the pipeline, the design pressure of the pipeline over 0.6 MPa is not allowed to do pressure test, brittle materials are strictly prohibited to use gas for pressure test, and water or air is selected as test medium. The specific operation should be carried out in strict accordance with the standards.

2. During the pre-cooling process of storage tank and pipeline, attention should be paid to check whether the cryogenic material of the pipeline is cracked, whether there are cracks in the welding part, whether the valve is frozen or leaked, and feel the temperature of the outer wall of the tank by hand to ensure the normal operation of the components at low temperature.

3. It is suggested to replace the seat directly instead of using rubber repair after discovering that the valve seat is glued. The glued problem may occur again after the valve is repaired for a period of time. If conditions permit, the fundamental problem can be solved by changing the connection form of the seat[5].

4. During routine inspection and maintenance, the settlement of tank foundation and root pile should be checked; the accessories such as valves, flanges, safety instruments and other operating equipment should be maintained in accordance with their respective factory regulations; and the staff should do a good job of anti-corrosion inspection of pipelines and connections, and do a good job of working records.

5. The daily work of tank farm should be careful to prevent valve opening, isolation failure and pipeline moving by mistake.
6. Staff members must undergo strict training before they can take up their posts, and they need to hold regular meetings to raise their awareness of safety production and safety precautions.

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