

Application of fault tree analysis in LNG fire risk assessment of LNG fueled ships

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Abstract. Assess the risk of LNG fire of LNG fueled ships navigating in the middle reaches of Yangtze River of China according to the acceptable risk criteria so that support technically to design, building and shipping safety management of LNG fueled ships and also to marine safety administration. “Fault tree analysis” was used to analyze the contribution of factors for LNG fire of LNG fueled ships. Statistical analysis base on the Normal distribution was carried out to reveal the confidence intervals of the probability of ships collision, touch and general fire. Quantitative assessment showed that LNG fuel is not suitable for passenger ships and chemical cargo carriers. It was found that ship length is the key to people onboard evacuating in case of LNG fire, so that LNG valid volume above 20M³ was unsuitable for a ship with length less than 80 m as well as that more than 10M³ was very dangerous for crew onboard a ship with length less than 45 m. Factors of bridges over river, berths along banks and anchorages in river, which would aggravate the consequences of LNG fire, were taken into consideration during risk assessment. In view of navigation condition in the middle reaches of Yangtze River, measures were suggested for LNG fire risk control of LNG fueled ships.

Keywords: fire, risk assessment, LNG fueled ship, Yangtze river.

1. Introduction

As a clean energy to substitute fuel oil, liquefied natural gas (LNG) for shipping power has broad prospects in “the green developing” of Yangtze River. Presently, there have been more than 280 LNG fueled ships operating in the inner water of China and about 1000 are planning to build [1], which implies a potential appreciate market. With the rapid developing, risk control of LNG transportation should be strengthened due to risk raised highly. The high temperature of flame, strong radiant heat, rapid spread and huge mass burning rate of LNG, make LNG fire very dangerous and too much difficult to extinguish. Furthermore, crowd navigating route, many bridges over river and limited space onboard ship, which would aggravate significantly people’s death or injure and property loss in an accident. Therefore, fire should be a primary object of the risk control of LNG fueled ships. Vanem E. analyzed the risk of LNG carrier operations. Vianallo C. made quantitative assessment of gas distribution network in Italian. Guo researched the safety of LNG transportation in rivers of south-China. Wang assessed the quantitative risk of leakage accidents of LNG carriers in inland rivers of China. Dai indicated the probability of water pollution accidents forcing live water intake stopped in Yangtze River. Li put forward acceptable risk criteria of industries of China. However, the quantitative risk assessment (QRA) particular for LNG fueled ships has not developed. Considering the special arrangement onboard LNG fueled ships and fire requirements, a detailed QRA is necessary, which would provide helpful information and knowledge not only for design, building and shipping safety management of LNG fueled ships but also for marine safety administration.

2. The risk of LNG fire on LNG fueled ships (below abbrev. as LNG fire)

In this paper, LNG fueled ships are those ships operated only in the inner water of China

including Yangtze River. LNG fire is the accidental combustion of LNG fuel caused by such basic accidents as damage of tanks, breakage of pipes, leakage of valves of the LNG system onboard, or the ship collision, touch, normal fire, etc. The risk of LNG fire R_0 is the product of the accident frequency F and the accident consequence C , i.e. $R_0 = F \times C$.

To analyze and reveal the relation between the LNG fire and the basic accidents of LNG fueled ships, “fault tree” is a typical method of analysis [2], as shown in Fig. 1.

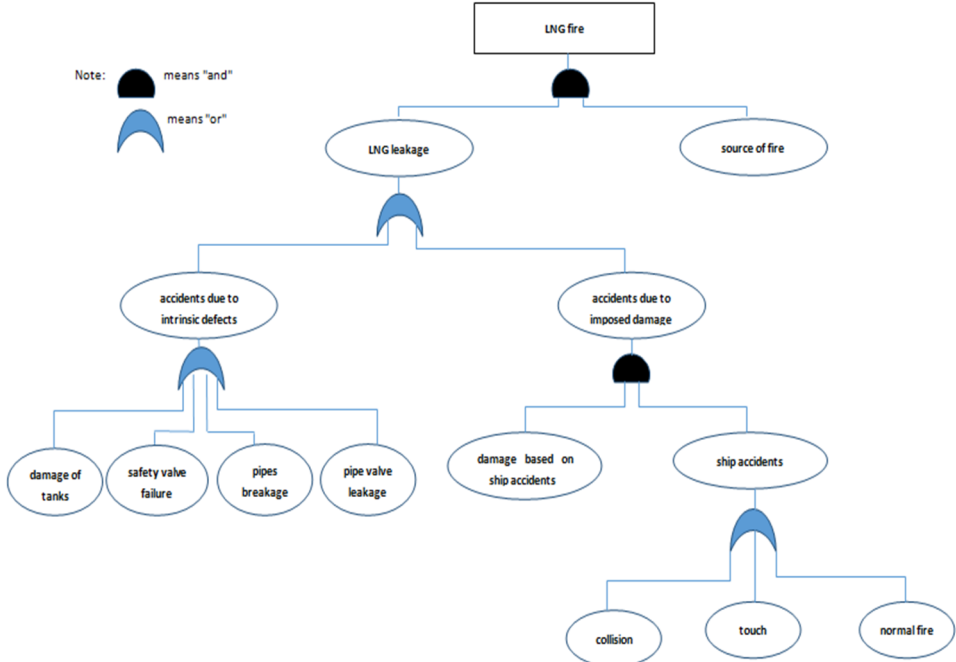


Fig. 1. “Fault tree” analysis of LNG fire

3. The frequency of LNG fire, F

Based on the “fault tree” analysis, the frequency of the LNG fire F is calculated by the formula as below:

$$F = p' \times \sum_{i=1}^n (p_i \times q_i), \quad (1)$$

In the Eq. (1), p' is the frequency of accidental sparks occurring on board a LNG fueled ship, usually taken as 0.24 [3, 4]. p_i is the probability of basic accidents. q_i is the probability of LNG leakage onboard caused by basic accidents.

3.1. The LNG leakage caused by damage of tanks, breakage of pipes, leakage of valves of the LNG system onboard. It is seen in Table 1 that the probability of such basic accidents as the damage of tanks, breakage of pipes, leakage of valves [5].

Table 1. probability of such basic accidents as damage of tanks, breakage of pipes, and leakage of valves

Basic accidents	Damage of tanks p_1	Failure of safety valves p_2	Breakage of pipes p_3	Failure of pipe valves p_4
The probability p_i , / year	3.0×10^{-6}	9.0×10^{-6}	3.1×10^{-5}	4.4×10^{-5}

LNG fuel leaked definitely in case of tanks damaged, pipes broken or valves failed, which means the respective probability $q_1 = q_2 = q_3 = q_4 = 1$.

3.2. The LNG leakage caused by ship collision, touch, normal fire. It is seen in Table 2 that data of ship collision, touch or normal fire happened during 2011-2018 in the middle reaches of Yangtze River [6, 7].

Data of ship collision in Table 2 is samples of statistic totality which generally obeys to Normal distribution. Because the sample average \bar{A} obeys to 't-distribution', the confidence interval with $1 - \alpha$ credibility level of the average of statistic totality u is able to be described as:

$$\bar{A}t_{\alpha/2}(n-1) < u < \bar{A} + \frac{S}{\sqrt{n}}t_{\alpha/2}(n-1). \quad (2)$$

Table 2. Ship collision, touch or normal fire happened in the middle reaches of Yangtze River (2011-2018)

Year	Navigating ships	Ship collision		Ship touch		Ship normal fire	
		Collided ships*	Collision frequency	Touched ships	Touch accident frequency	Fired ships	Fire frequency
2011	82976	182	0.00220	13	0.00016	7	0.00008
2012	81151	156	0.00192	11	0.00014	11	0.00014
2013	78718	132	0.00168	16	0.00020	8	0.00010
2014	80312	112	0.00140	9	0.00011	14	0.00017
2015	82064	112	0.00136	14	0.00017	8	0.00010
2016	87478	268	0.00306	33	0.00038	22	0.00025
2017	81869	214	0.00262	39	0.00048	19	0.00023
2018	82499	192	0.00233	23	0.00028	15	0.00018

*Note: the numbers of collided ships equal to the numbers of collision accidents plus 2

In Eq. (2), S is the sample standard deviation, n is sample numbers, and α is generally taken as 0.05. Furthermore, because the sample variance obeys to χ^2 -distribution, the confidence interval with $1 - \alpha$ credibility level of the standard deviation of statistic totality σ is able to be described as:

$$\frac{S\sqrt{n-1}}{\sqrt{\chi_{\alpha/2}^2(n-1)}} < \sigma < \frac{S\sqrt{n-1}}{\sqrt{\chi_{1-\alpha/2}^2(n-1)}} \quad (3)$$

For the above example, the average of ship collision frequency \bar{A} is 2.07×10^{-3} , the standard deviation S is 0.6×10^{-3} . The confidence interval with 95 % credibility level of the average of p_c is $(1.57 \times 10^{-3}, 2.57 \times 10^{-3})$ as shown in Fig. 2(a), and it is $(0.40 \times 10^{-3}, 1.22 \times 10^{-3})$ for the standard deviation of p_c .

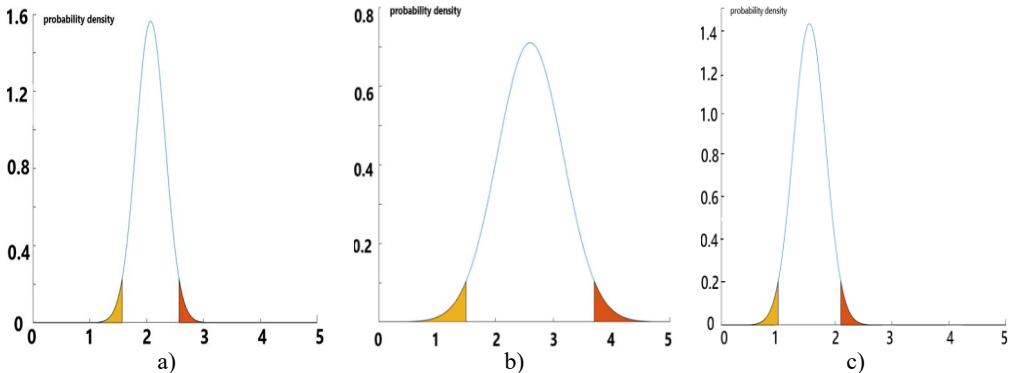


Fig. 2. The confidence interval with 95 % credibility level of the average of p_c , p_t and p_f

In the same way, for the samples of ship touch accidents the average value is 2.6×10^{-4} , and the standard deviation is 1.3×10^{-4} . The confidence interval with 95 % credibility level of the average probability of ship touch p_t is $(1.5 \times 10^{-4}, 3.7 \times 10^{-4})$ as shown in Fig. 2(b), and it is $(0.86 \times 10^{-4}, 2.65 \times 10^{-4})$ for the standard deviation of p_t .

For the samples of ship normal fire, the average value is 1.55×10^{-4} , and the standard deviation is 0.6×10^{-4} . The confidence interval with 95 % credibility level of the average probability of ship normal fire p_f is $(1.0 \times 10^{-4}, 2.1 \times 10^{-4})$ as shown in Fig. 2(c), and it is $(0.40 \times 10^{-4}, 1.22 \times 10^{-4})$ for the standard deviation of p_f .

Damage of LNG fuel tanks, pipes or valves caused by ship collision, touch or normal fire. The research of inner water ships crashworthiness [8-10] claims that the colliding force between ship and rigid structure is connected with the ship tonnage and colliding speed. Approximately, the connection could be prescribed as below:

$$F_{mean} = \frac{1}{1 + \beta} \times 0.0705 \times V^{0.75} \times W^{0.55}, \quad (4)$$

where V is colliding speed, m/s; W is ship tonnage, t; β is a corrective coefficient, taken as 0.75 for a ship of tonnage less than 1000 t and 0.09 for a ship of tonnage above 1000 t but not more than 3000 t.

LNG fuel system onboard inner water ship is ordinarily located at stern, as a result it would be stroke at a low speed in collision. Tanks and pipes of LNG fuel system are arranged so carefully that any part of them is of the distance no less than 0.8 m to ship hull boundaries according to the present Regulations [11, 12]. Therefore, the probability of damage of LNG fuel tanks, pipes or valves caused by ship collision, touch, p_d , is not above the level of 10^{-2} .

LNG fuel tanks, pipes or valves would fail by massive heat in a normal fire onboard. At the level of risk protection according to present Rules, however, either the probability of tanks failure p_j or the probability of pipes and valves failure p_v is not above the level of 10^{-2} .

LNG fuel leaked definitely in case of tanks, pipes or valves failed in ship safety accidents, which means the respective probability $q_d = q_j = q_v = 1$.

3.3. Uncertainty of the decision support system. As a decision system based on statistic data, there are inevitably uncertainties existed in natural variability of objects, imperfect of measuring, assumption of modeling, sampling, etc. For example, the history data of eight years is too finite to obtain a precise probability of shipping accidents totality, and then it has to accept some wider confidence intervals. The confidence intervals with 95 % credibility level of the average probability of p_c , p_t and p_f , gave description of the uncertainties. Due to accumulating and transferring of uncertainty, its impact demonstrates eventually in the frequency of LNG fire according to the Eq. (1). Therefore, it is able to calculate out the uncertainty of the frequency of LNG fire which display as the sum of variance in the following process:

$$F = 0.24 \times \{(p_1 + p_2 + p_3 + p_4) \times 1 + [(p_c + p_t) \times p_d + p_f \times (p_j + p_v)] \times 1\}. \quad (5)$$

4. The consequences of LNG fire, C

LNG fire appeared mainly in two ways: pooled fire and vapor cloud explosion. Different way is of different consequences [13, 14]. Setting $\{C_f\}$ as people death in pooled fire, and $\{C_e\}$ as people death in vapor cloud explosion, then the consequences of LNG fire is prescribed as $\{C\} = \{C_f\} \cup \{C_e\}$. The calculation of $\{C_f\}$ is based on the heat radiation of pooled fire in which people suffered onboard. For $\{C_e\}$, the basis is shock wave overpressure of vapor cloud explosion. Models and formulas of these calculations are omitted because of few connections with the subject of this paper.

5. Risk assessment of LNG fire

$$R_c = N \times R_0 = N \times F \times C, \quad (6)$$

where R_c is the calculated risk. N , namely safety coefficient, is taken as 5 with considering that accidents frequency and consequences rise up with over-speed or overload of ship, flood, and intense heat of summer, strong wind, and damage aggravating if accidents happened in which bridges, ports or anchorages located.

5.1. Criteria of acceptable individual risk, Z_p . In the light of safely developing idea, it is determined that the acceptable individual risk of inner water shipping of China should not be lower than developed countries [15]. According to the guidance notes of IMO [16], the maximum acceptable individual risk of ship crew is 10^{-3} /year, and the maximum acceptable individual risk of passengers onboard is 10^{-4} /year.

5.2. Criteria of acceptable social risk, Z_g . Criteria of acceptable social risk of LNG fire, Z_g , referred to the "F-N" curve recommended by IMO [17], as shown in Fig. 3.

5.3. The risk of LNG fire is acceptable only if it complies with the requirement $R_c < Z_p$ as well as R_c lying in "acceptable area" or "as low as reasonably practicable (ALARP) area" of the "F-N" curve.

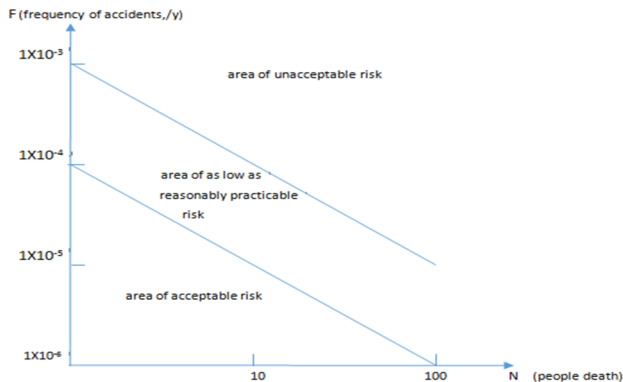


Fig. 3. Criteria of acceptable social risk of LNG fire (F-N curve)

6. Measures and recommendations for LNG fire risk control

Yangtze River is the busiest inland waterway of shipping in the world [18]. Presently, the average tonnage of general cargo ships in Yangtze River is more than 1500 t [19], the average fuel consumption of a ship operating at economical speed is about 4.1 kg/kt·km [20]. It is necessary that 8 tons of fuel oil for one voyage of the ships. If it used LNG fuel, the liquid volume of LNG fuel what it need would be about 8.9M^3 with consideration of the 50 % substitute rate of LNG fuel of the present dual fuel engines [21]. Therefore, the LNG fuel tanks onboard LNG fueled ships in the middle reaches of Yangtze River are designed as their total volume not more than 10M^3 . By the above analysis, the confidence interval of the probability of LNG fire is $(2.71 \times 10^{-5}, 2.79 \times 10^{-5})$. Taking the maximum into consideration, the calculated risk of LNG fire R_c is 6.98×10^{-4} p/y (one people death per year). The risk value does not exceed present criteria of acceptable individual risk of inner water shipping of China, and as well lie in the "ALARP" area of "F-N" curve of criteria of acceptable social risk [22-24].

In case of LNG fire, crew onboard needs enough space to evacuate. The more violent combustion or explosion is the more safe distance onboard needs. Obviously ship length is the key. For a ship with length less than 80 m, it is not permit to employ LNG with valid volume above 20M^3 , and for a ship with length less than 45 m valid volume more than 10M^3 are unallowable. Measures and recommendations are given to enhance LNG fire risk control of

present LNG fueled inner water ships [25]. For example, recognition of outlook, signal and communication of LNG fueled ships, painting visible and light-reflected color on surface of LNG tanks, pipes and ship hull above water, increasing special signal lights, etc.

Risk assessment of LNG fire in Yangtze River shipping is of typical meaning to make safe use of the clean fuel, which offers a mirror for other rivers. Although it differs significantly among different rivers that accidents statistic data performing essentially in quantitative analysis of risk, the way to improve intrinsic safety of LNG fuelled ships is the same. From this point, such measures as fuel volume limited according to ship length are useful not only for projects in China but all over the World.

7. Conclusions

Application of QRA in LNG fire of the LNG fueled ships laid the groundwork to improve safety level of LNG transportation in river. By QRA, based on analyzing of failure models, data and ship accidents statistics as well, it is predicted that the most likely area of the probability of LNG fire of LNG fueled ships in the middle reaches of Yangtze river is $(2.71 \times 10^{-5}, 2.79 \times 10^{-5})$. For a general cargo ship fueled by LNG, with tonnage of 1500 t, the quantified risk of LNG fire is 6.98×10^{-4} p/y, which is acceptable at present. To prevent and control the risk of LNG fire, such managerial measures as ship recognition, navigation rules, etc. are indispensable.

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