Safety Risk of Flammable and Explosive Dangerous Goods through the Ship Lock

Tiansheng Xie, Chao Han, Guobo Wang and Chen Fengyun*

Safety and Emergency Technology Center, China Waterborne Transport Research Institute, No.8 Xitucheng road, Haidian District, Beijing 10088, China
Email: xts@wti.ac.cn

Abstract. Based on the analysis of the current situation on flammable and explosive dangerous goods passing through the Three Gorges ship lock, evaluate leakage, fire, and explosion hazards through typical accident simulation calculations to find out the hazardous characteristics and safety risks of flammable and explosive dangerous goods through the Three Gorges ship lock. The study indicates the main safety risks of flammable and explosive dangerous goods passing through the ship lock are ship collision, grounding, leakage, fire and explosion, as well as the facilities strength declining in lock chamber, cracks or other structural destrucions due to the long-time high temperature under flame or overpressure of the explosion.

1. Introduction
In recent years, the ships, cargos, especially the ships with dangerous goods that pass through the Three Gorges ship lock have shown a rapid growth trend [1]. The Three Gorges possesses the features of high political sensitivity, high safety risk, high association with people’s livelihood, and high social attention and so on [2]. Once the accidence occurs to dangerous goods ship, it is easily to cause the consequences such as burning explosion, water contamination, casualty and property loss and so on, raising up a series of social problem at the same time, which impacts substantially on navigation management in the Three Gorges [3]. Relevant research has been carried out at home and abroad to address the safety risks of the navigation in the Three Gorges. Based on the characteristics of collision accident in the Three Gorges ship lock, Li et al., used the risk analysis and interpretation structural model (ISM) to obtain a hierarchical distribution map of the risk factors of collision accident in the Three Gorges ship lock, and propose countermeasures for ship collision avoidance [4]. In view of the safety management status of dangerous goods through the ship lock, Huan analyses the main problems and puts forward relevant solutions [5]. Lan et al. analyzed the safety risks of lockage from the aspects of traffic organization and emergency response of dangerous goods ships, and put forward related suggestions [6]. Yi proceeds the ship lockage risk evaluation based on Bayesian network and clarified that explaining structural model is an effective method for analyzing the causes of ship collision accidents. Introducing Bayesian network to establish a safety evaluation system, and propose risk prevention and control measures for security inspection, lockage organization, and other transportations distributary [7]. During the lockage process of the ship which carries the flammable and explosive goods, with limited ship chamber and difficult rescue conditions, once the leakage or fire explosion occur, it imposes harms on ships, ship lock, even to the Three Gorges Dam and Yangtze River eco-environment. A systematic analysis and quantitative risk assessment of the safety risks of
flammable and explosive dangerous goods passing through the Three Gorges ship lock is needed to take targeted risk prevention and control measures to ensure the safety of the Three Gorges Ship Lock.

2. Situation Analysis of the Flammable and Explosive Passing through the Three Gorges Ship Lock

The dangerous goods which going up the ship lock mainly toward Sichuan, Chongqing. The dangerous goods which going down the ship lock mainly export chemical products to the middle and lower reaches of the Yangtze River, with 5:1 ratio between the upper and down supply quantity. The flammable and explosive dangerous goods passing through the Three Gorges ship lock are 16 categories in total. There are gasoline, methanol, vinyl acetate, methyl acetate, phenol, ethyl acetate, ethanol, acetone, N-butyl acetate, carbon disulfide, naphtha, octane isomer, methylbenzene, ethyl benzene, dichloroethane. The largest transporting volume is gasoline, followed by methanol.

According to the statistics, total quantity of dangerous goods passing through the ship lock in 2017 is over 100 million-dwt, of which 3.29 million-dwt were flammable and explosive dangerous goods. The total quantity of dangerous goods is keeping with quick increasing trend. The dangerous goods passing through the Three Gorges Ship Lock are subject to safety supervision by the navigation management agencies, maritime agencies, and fire agencies of the Three Gorges.

In recent years, with the increase of the total of inflammable and explosive dangerous goods, the safety pressure also increases. The Three Gorges ship lock has formed a joint management force through continuous improvement of laws and regulations, and innovative management, such as fire truck monitoring along with the ship, the linkage control plan of the ship waiting for lockage and so on. These managements have effectively promoted the safety level for ships with flammable and explosive dangerous goods passing through the Three Gorges ship lock.

3. Dangerous and Jeopardized Characteristics of Flammable and Explosive Dangerous Goods Passing through the Ship Lock

Chemical dangerous goods possess the characteristics of explosive, flammable, poisonous, infection, corrosion, radioactive, etc. During the transportation, storage, production, operation, usage, and disposition, it is easily to cause personal injury or death, property damage and environment contamination [8]. Among them, flammable and explosive dangerous goods are the most dangerous among chemical dangerous goods, and they are also the most concerned goods in the Three Gorges ship lock [9]. The main flammable and explosive dangerous goods passing Three Gorges ship lock are 16 categories, and different categories expose various harm on human and environment [10]. Through the analysis on physiochemical properties of these 16 categories, flash point of gasoline and carbon disulfide are the minimum, as well as the most flammable ones among those 16 categories. Meanwhile, the burning heat of the gasoline is the highest among those 16 dangerous categories. As it is shown in figure 1, the spheres indicate the 16 dangerous categories, the size of the sphere represents the burning heat of flammable and explosive dangerous category. The larger the sphere, the higher the burning heat, and vice versa. It can be seen from the figure that the burning heat of gasoline and octane isomers is the highest, and the minimum explosive concentration is lower, and once it explodes, it causes greater harm. Naphtha has a lower flash point and minimum explosive concentration, but its combustion heat is lower, causing less harm. Dichloroethane and methanol have high flash points, high minimum explosive concentration, and low burning heat. It is the least dangerous of the 16 flammable and explosive dangerous goods that pass through ship lock.

Based on the analysis of the physical and chemical characteristics of flammable and explosive dangerous goods passing through the ship lock, if two kinds of goods that have contradictory properties leak at the same time when they pass through the ship lock, they will be mixed and react after the goods are leaked, which will easily cause secondary disasters and cause more serious consequences. Therefore, the cargos with the contradictory properties cannot pass through the ship lock at the same time. Among the 16 flammable and explosive dangerous goods, carbon disulfide is a strong reducing agent, and acetone contraindications are strong oxidants, strong reducing agents, and
alkalis. Therefore, carbon disulfide and acetone are mutually incompatible substances and cannot pass through the ship lock at the same time.

![Figure 1. Physiochemical properties analysis of 16 Dangerous categories.](image)

On basis of the toxicity analysis of the dangerous goods passing through the ship lock, it can be known that 16 categories except methyl chloroformate, are of low toxicity. Methyl chloroformate is of moderate toxicity, and has also been included in the Catalogue of Inland River Embargo Dangerous Chemicals (2019 Edition) as the embargo dangerous chemical in Inland.

According to the dangerous characteristics analysis on the 16 flammable and explosive dangerous categories, and combining the lockage quantity within the past years, only a small amount of octene isomers, methyl chloroformate, and ethylbenzene was transported through ship lock in 2015. It is recommended to be included in the embargo lockage list first. Parcel lots such as carbon disulfide, naphtha, n-buty acetate, methylbenzene, etc. should be restricted in time. Bulk cargoes such as gasoline, methanol, and vinyl acetate should adopt comprehensive transportation schemes to implement effective lockage management. In addition, carbon disulfide and acetone are mutually incompatible substances and are not allowed to pass the lock at the same time.

4. Safety Risk of Flammable and Explosive Dangerous Goods Passing through the Ship Lock

The ship lock system is composed of the approach channel, the lock head, the lock chamber, the filling and emptying system, the centralized control system, and the ship lockage system, which makes the ship lock system complicated. The security risks of lockage are analyzed from the perspective of human-machine-environment-management. The main risks are as shown in table 1.

The coupling of multiple components of a ship lock makes it sensitive and fragile. Different from normal risk resources, its risk sources have the characteristics of intense dynamic variability, wide distribution, numerous trigger element with low trigger energy, high concealment and potential hazards, and difficulty in management. The above-mentioned risk sources and their characteristics have formed the safety risk of flammable and explosive dangerous goods passing through the ship lock.

Ships collision: water level flow variation, securing infirm, strong wind, heavy fog and other factors account for the collisions between the ships or the collisions between the ship and the securing facilities, human factors account for the collisions between the ships entering and leaving the anchorage area. Ships grounding: when ships enter or leave the anchorage area, several ships are not familiar with the surrounding water environment, and accidents such as ship grounding may occur. Cargo leakage, fire, and explosion: the collision or grounding accidence of the ships cause the leakage of the loading cargos on the ship, which results in fire or explosion accidence, or purely the leakage of the cargos with self-reasons results in the fire or explosion accidence.
There are plenty of ships berthing within the anchorage area, and the docking area the ships loading dangerous goods are concentrated. The fire and explosion accident would easily cause accident on other ship. Therefore, ships grounding, ships collision, leakage of the loading cargos, fire, and explosion constitute the main safety risk of the flammable and explosive dangerous goods passing through the ship lock.

Table 1. Main risk resources of ship passing through the Three Gorges ship lock.

| Risk classification | Human | Environment | Ship | Management | Cargo |
|---------------------|-------|-------------|------|------------|-------|
| Risk resource       | Loading intensity; Professionalism; Qualification; Violation of navigation management regulations, etc. | Wind speed; Visibility; Ship mooring in the lock chamber, etc. | Ships aging; Manipulation failure; High-risk cargos, etc. | Information misrepresentation and concealment; Violation of navigation management regulations; Information communication implementation effect, etc. | Dangerous property; Package disqualified; Over loading; Ship securing infirm, etc. |

5. Quantitative Risk Evaluation

Containing the database of nearly thousands of common dangerous chemicals, ALOHA accident consequence simulation software is able to forecast the leakage dangerous areas of the chemicals, as well as the poison’s concentration of the sensitive points, and classify the dangerous areas according to the three-level statistics provided by American AEGLS (Acute Guideline Levels). In recent years, chemical leakage accidents happen frequently, ALOHA software plays an important role for enterprises emergency and government planning and gradually becomes the essential tool for the emergency rescue, planning, training and academic research of the dangerous chemical accidents.

5.1. Accidence Scenario and Parameter Selection

For the dangerous goods ships, “IPO Risk Calculation Methodology” based on statistics of the relevant accident, should choose the most harmful leakage scenario of the ship (maximum leakage). Selecting the most harmful leakage scenario for the dangerous-goods ship in the lock chamber at Three Gorges: the dangerous goods ships in the lock-chamber during lockage are 4 boats of 5,000 DWT (t) gasoline ship with all dangerous goods on the ship releasing off to the internal lock-chamber and igniting time at 10 min after the leakage occurrence, to simulate the most dangerous scenario of the fire and explosion accident.

Selecting the typical meteorological condition based on the meteorological statistics in the Three Gorges region: Annual average wind speed 5.0 m/s; prevailing wind direction N; Perennial mean air temperature 17 ℃; Perennial mean relative humidity 66%; Atmosphere stability level D.

5.2. Simulation Consequence

After selecting the leakage model, it simulates the leakage accident on the dangerous cargos ship inside the ship lock, the calculation consequences are shown in table 2.

After the dangerous goods within the ship in the ship lock are leaked off, it is flowing above the water inside the lock chamber and thus forming into the liquid pool, the area that has been ignited forms into the pool fire. The distribution of the thermal radiation in the pool fire and its influence is shown in figure 2.

As it is shown in the figure 2, once the large-scale pool fire accident happens, the distances of the crew mild burn, serious burn, and death are reaching out as far as 337 m, 226 m, and 132 m respectively by the heat radiation of the flame. It equals to say, the crew, without protection, who is at the location of down-wind direction of the liquid pool with the distance written above and is under exposure continuously for more than 1 min, will suffer from mild burn, serious burn, and death; if
under exposure continuously for more than 10 s, will suffer from high temperature heating, mild burn, and serious burn.

**Table 2.** Results list of simulation on accident consequences of dangerous cargos ships.

| Danger resource       | Leakage model            | Accidence type            | Classification standard | Influential range (down-wind direction distance (m)) |
|-----------------------|--------------------------|---------------------------|-------------------------|-----------------------------------------------------|
| Dangerous cargos ship | Complete leakage         | Pool fire                 | 4.0 kW/m²               | 377                                                 |
|                       |                          | 12.5 kW/m²                | 226                     |                                                     |
|                       |                          | 37.5 kW/m²                | 132                     |                                                     |
|                       |                          | Vapor cloud explosion     | 1.0 psi                 | 90                                                  |
|                       |                          |                           | 3.5 psi                 | 41                                                  |
|                       |                          |                           | 8.0 psi                 | /                                                   |

**Figure 2.** Thermal radiation range of the pool fire.

Accordingly, lock-chamber wall within the 132 m of the down-wind direction, which are under the long-time high temperature under flame, will be decreased in its strength and even cause the grave consequence; And for the lock gate, which is under longtime high temperature under fire, its steel structures, sealing materials, hydraulic control equipment circuit and other equipment would probably be damaged. Once the lock gate is destructed, the water level at the lower-level ship lock chamber changes substantially, which influence the lower-level ship lock safety.

The influential range of the shockwave overpressure of the vapor cloud explosion by the ship leakage inside the lock-chamber is shown in figure 3.
For the dangerous goods ship leakage inside the lock-chamber, once the vapor cloud explosion happens, the crews who are within the certain range from the explosion center will be hurt even to death. As it is shown in figure 3, the crew within the range of 41 m from explosion center will be suffered from serious harm even the death; the crew within the range of 90 m from explosion center will be suffered mild harm.

At the same time, the overpressure within the range of 41m from explosion center is above 3.5 psi (0.024 MPa), the wall of the lock-chamber within such range may generate cracks under the shockwave, declining in its intensity strength and may cause the grave consequence; For the lock gate, its steel structures, sealing materials, hydraulic control equipment circuit and other equipment may go out of control under the shockwave. Meanwhile, the lock gate bears the risk of destruction under the explosion shockwave, and influences the lower lever ship lock safety accordingly. Under the extreme situation, explosion and detonation shockwave would probably destroy the Three Gorges ship lock structures, especially the destructions on the herringbone lock gate, seriously affecting the whole ship lock safety and the Three Gorges Dam safety subsequently.

6. Conclusion
Through the syntaxic analysis on the characteristics of the flammable and explosive dangerous goods passing through the Three Gorges ship lock, gasoline and octane isomer impose the comparatively higher danger, naphtha imposes relatively lower danger; carbon disulfide and acetone are mutually incompatible substances and should be prohibited for passing through the lock at the same time; Methyl chloroformate has been listed in the Catalogue of Inland River Embargo Dangerous Chemicals (2019 Edition). The main risks for flammable and explosive goods passing through shop lock are ships collision, grounding, cargos leakage, fire, and explosion. The typical accident simulation results show that high temperature and longtime affection of the flame and explosion overpressure affection would deduct the intensity strength of the equipment in lock chamber, generate the cracks or cause other structural destruction. In extreme cases, the structure of the Three Gorges Ship Lock may be damaged. Complete safety prevention and control measures need to be taken to prevent accidents such as leakage, fire and explosion, and effectively guarantee the safe operation of the Three Gorges Ship Lock.
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