System Dynamics Modeling and Simulation of Vapor Cloud Fire and Explosion Accidents in Liquor Storage Tanks

Yu Chenglong, Shi Xunxian, Sun Enji, Zhang Xingkai
China Academy of Safety Science and Technology
Beijing, China
ycl19880228@126.com

Abstract — In order to predict the dynamic process of the fire and explosion accident in liquor storage tanks. A system simulation flow diagram of steam cloud fire explosion accident in liquor storage tanks is established based on the principle of system dynamics. And the RAMP function was used to simulate the development process of the system, and then we obtained the process of vapor cloud fire and explosion accidents in liquor storage tanks. It can be concluded that the accident is caused by the safety awareness and behavior of the operators, the fire and explosion conditions inside the tanks, the management abilities, the external environment and the perfection of laws and regulations, which ultimately leads to the safety of the liquor storage tanks. The state is formed below the critical points at which the accident occurred.

Keywords—component; formatting; style; styling; insert (key words) Liquor Storage Tanks; Fire and Explosion Accidents; System Dynamics; Security status

I. INTRODUCTION

Liquor plays an important role in the daily life of human beings, and the Liquor producing companies are spread all over the world. As the main component of liquor, alcohol is a flammable, explosive and volatile substance. Due to the volatilization of ethanol, the flammable and explosive vapor cloud will gradually be formed in the liquor storage tanks. When the vapor cloud encounters an ignition source such as static electricity or sparks, and it will cause a fire and explosion accident in the storage tanks, which seriously threatens the safety of the whole industry [1-3]. Therefore, the fire and explosion of the vapor cloud of liquor storage tanks has always been a hot issue in the field of safety.

In order to accurately predict various types of safety accidents, Khan [4] used the method of accident tree to analyze various factors leading to accidents. Hale [5] modeled and analyzed the role of safety management from the perspective of enterprise management; Mearn [6] analyzed marine accidents from the perspective of safety management processes. In addition, there are some ways to combine the cause theory with the mathematical method to quantify the impact of a single factor on the possible accident [7-9].

However, the process of fire and explosion accidents in the steam cloud inside the liquor storage tanks is a process of coupling multiple factors, whether the vapor cloud inside the tanks reaches the explosion limit, whether there is an ignition source in the site environment, whether the staff is operating correctly, and the law. If the security of the system is only considered from a single factor perspective, it is easy to generate errors. In this regard, some scholars use the method of system dynamics to analyze various system security problems, and obtain relatively systematic and dynamic prediction results.

In this paper, the system dynamics model of the fire and explosion accidents of the liquor storage tanks was established based on the system dynamics theory and the analysis of the hazard factors. Then the process was simulated by RMP function, and finally the fire occurred in the liquor storage tanks. The time node of the explosion provides a scientific basis for timely disposal of fire and explosion hazards.

II. SYSTEM DYNAMICS ANALYSIS OF LIQUOR STORAGE TANKS VAPOR CLOUD FIRE AND EXPLOSION ACCIDENTS

The liquor storage tank's system is a complex nonlinear dynamic social technical support system that is interdependent and mutually constrained by human-machine-object-method-ring. It consists of social elements and technical elements that are interconnected and interact. According to the system dynamics feedback principle, the safety level of the liquor storage tank system is mainly affected by the level of personnel factors, management factors, equipment factors, environmental factors and legal and regulatory factors. These five factors constitute the entire liquor storage tank. The subsystems of the security system form an organic unity. There is also a certain connection between them. Any change in factors will have an impact on the overall system, resulting in changes in the safety level of the liquor storage tank system.

In order to simplify the influencing factors of the system, the above five factors can be divided into two parts: subjective factors and objective factors. According to the system dynamics feedback principle, a causal relationship loop diagram of subjective factors is constructed:

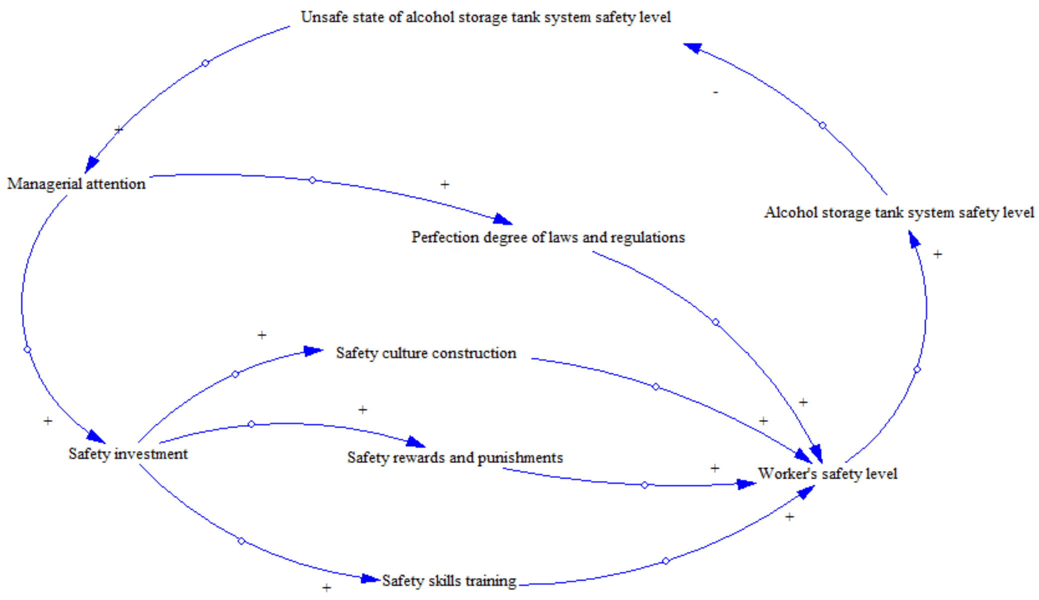

Fig.1 Causal loop chart of fire and explosion accident (Subjective factors)

The system dynamics is used to analyze the causality model, there are four loops:

1）Unsafe state of alcohol storage tank system safety level↑→Managerial attention↓→Perfection degree of laws and regulations↓→Worker's safety level↓→Alcohol storage tank system safety level↓→Unsafe state of alcohol storage tank system safety level.

2) Unsafe state of alcohol storage tank system safety level↑→Managerial attention↓→Safety investment↓→Safety culture construction↓→Worker's safety level↓→Alcohol storage tank system safety level↓→Unsafe state of alcohol storage tank system safety level.

3）Unsafe state of alcohol storage tank system safety level↑→Managerial attention↓→Safety investment↓→Safety rewards and punishments↓→Worker's safety level↓→Alcohol storage tank system safety level↓→Unsafe state of alcohol storage tank system safety level.

4）Unsafe state of alcohol storage tank system safety level↑→Managerial attention↓→Safety investment↓→Safety skills training↓→Worker's safety level↓→Alcohol storage tank system safety level↓→Unsafe state of alcohol storage tank system safety level

The causal relationship loop diagram of objective factors is shown in figure 2:

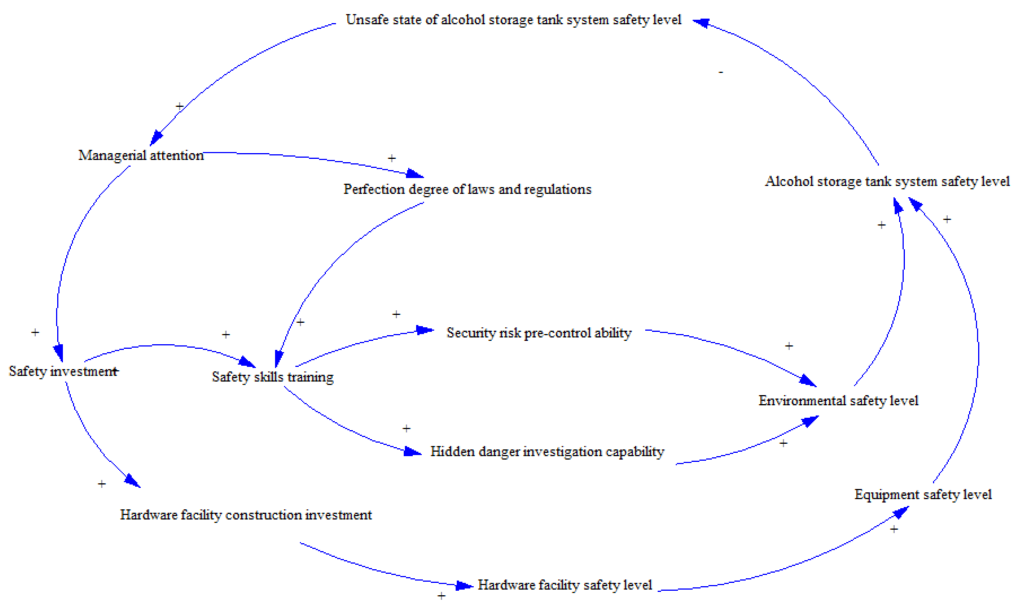

Fig.2 Causal loop chart of fire and explosion accident (Objective factors)

Using the system dynamics to analyze the causality model, there are five loops:

1）Unsafe state of alcohol storage tank system safety level↑→Managerial attention↓→Perfection degree of laws and regulations↓→Safety skills training↓→Security risk per-control ability↓→Environmental safety level↓→

Alcohol storage tank system safety level ↓ →Unsafe state of alcohol storage tank system safety level.

2) Unsafe state of alcohol storage tank system safety level ↑ →Managerial attention ↓ →Perfection degree of laws and regulations ↓ → Safety skills training ↓ → Hidden danger investigation capability ↓ → Environmental safety level ↓ → Alcohol storage tank system safety level ↓ → Unsafe state of alcohol storage tank system safety level.

3) Unsafe state of alcohol storage tank system safety level ↑ →Managerial attention ↓ →Safety investment ↓ → Safety skills training ↓ →Security risk per-control ability ↓ → Environmental safety level ↓ → Alcohol storage tank system safety level ↓ →Unsafe state of alcohol storage tank system safety level.

4) Unsafe state of alcohol storage tank system safety level ↑ →Managerial attention ↓ →Safety investment ↓ → Safety skills training ↓ → Hidden danger investigation capability ↓ → Environmental safety level ↓ → Alcohol storage tank system safety level ↓ →Unsafe state of alcohol storage tank system safety level.

5) Unsafe state of alcohol storage tank system safety level ↑ →Managerial attention ↓ →Safety investment ↓ → Hardware facility construction investment ↓ → Hardware facility safety level ↓ →Equipment safety level ↓ →Alcohol storage tank system safety level ↓ →Unsafe state of alcohol storage tank system safety level.

Considering the influence of subjective factors and objective factors on the safety of the liquor storage tank system, the circuit diagram of the whole system can be obtained:

The graph has a total of 21 feedback loops. Through the above analysis, as the unsafe behavior or unsafe state of the liquor storage tank safety system increases, the safety level of each influencing factor will decrease, thereby reducing the safety level of the entire system. When the safety level of the system is reduced to a certain level, the information is fed back to the system, reducing the unsafe behavior and unsafe state of the liquor storage tank system.

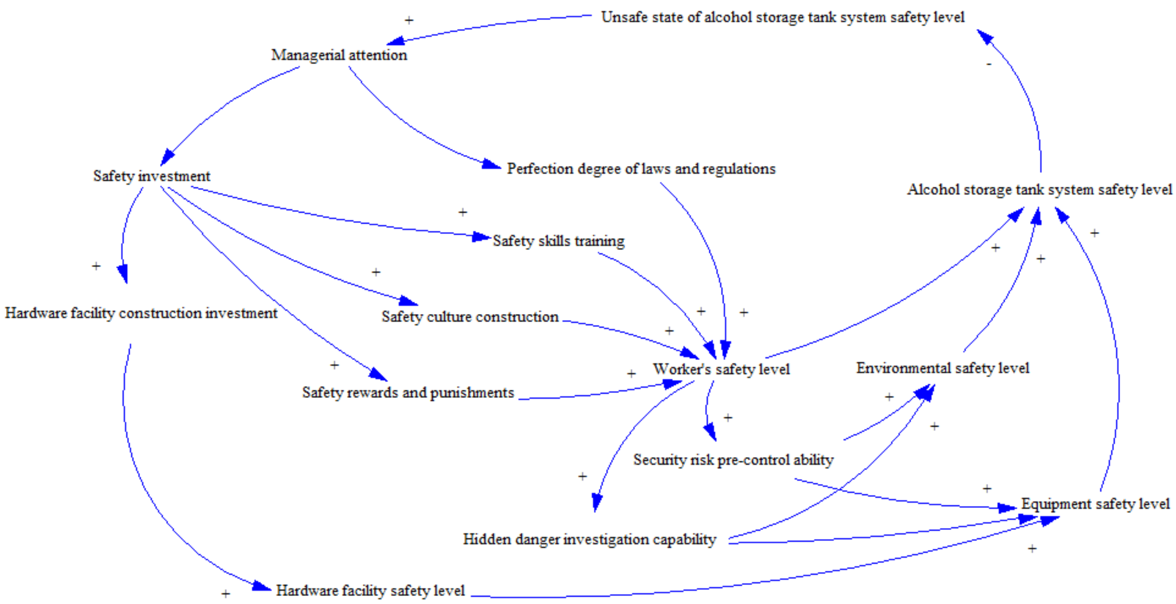

Fig.3 Causal loop chart of fire and explosion accident

III. System Dynamics Model Construction

A. Model variables

Through the analysis of the system, the main factors affecting the risk of fire and explosion of liquor storage tanks are preliminarily grasped. The variables in system dynamics mainly include state variables, rate variables and auxiliary variables. There are 33 variables in the system dynamics catastrophe model of fire and explosion accidents, of which there are 9 state variables, 10 rate variables and 14 auxiliary variables.

State variables include level of legal and regulatory construction, safety management level, safety protection investment, early detection capability of fire and explosion disasters, operator safety technical capabilities, the level of operator safety awareness, the concentration of vapor cloud inside the liquor storage tank, environmental risk factor level, safety level liquor storage tank.

Rate variables include change rate of laws and regulations level, change rate of management, change rate of safety protection input level, change rate of safety technology level, change rate of the detection capability at the beginning of a fire and explosion disaster, change rate of safety awareness, change rate of danger, evaporation rate of Liquor, safe productivity, safe loss rate.

Auxiliary changes include legal and regulatory factors, legal and regulatory factors, management factor, management factor table, penalty factor, penalty factor table, initial value of safety level, safety inspection strength, safety check factor table, employee violation factor, environmental risk factor table, environmental risk factor, alcohol concentration detection equipment failure factor table, alcohol concentration detection equipment failure factor.

B. Modeling of liquor storage tank vapor cloud fire and explosion system

After determining the various influencing variables of the system dynamics, based on the system dynamics feedback principle, based on the in-depth analysis of the interaction relationship between the main state variables, rate variables and auxiliary variables, the system dynamics flow rate is used to build the tree. Modeling method, the system dynamics simulation model of liquor storage tank fire and explosion accident is established, as shown in figure 4:

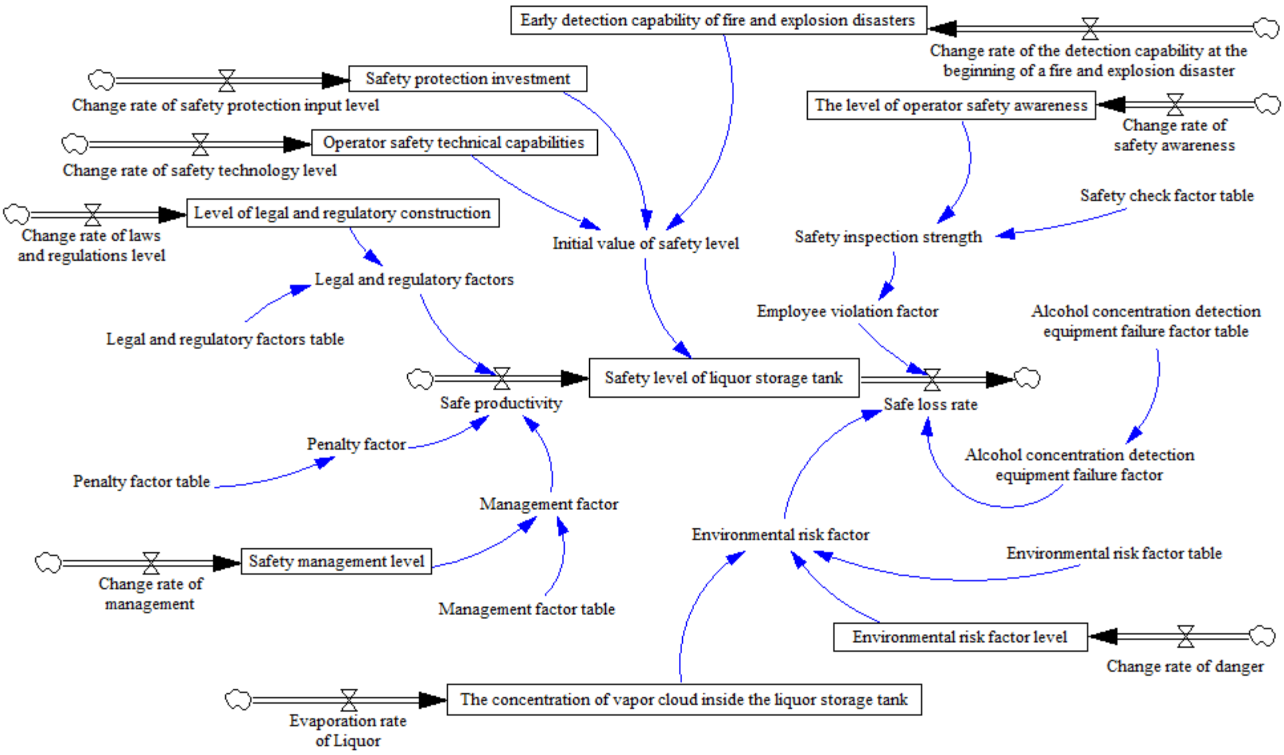

Fig.4 Simulation flow chart of fire and explosion accident

C. System Analysis

Using system dynamics, we can deeply study the information feedback system of the mutation mechanism model, and analyze the mechanism of the steam explosion of the steam storage tank in a time-varying and dynamic view, which helps to reveal the role of various elements of the liquor storage tank safety system.

Analysis of the model shows that the occurrence of fire and explosion accidents is caused by the cross-coupling between direct variables and indirect variables in the four hierarchical structures of the field operation layer, management decision-making layer, supervision specification layer and security assurance layer in the whole liquor storage tank system. When the safety level of the entire liquor storage tank system is lower than the fire and explosion warning value, this will lead to a fire and explosion accident in the steam tank of the liquor storage tank, as shown in Figure 5:

Using the unsafe behavior coupling theory combined with the relevant variables in the system to further analyze the entire liquor storage tank safety system, we can find out the root cause of the fire and explosion accident.

1) Unsafe behavior in the field work layer. For example, if the operator has violated the regulations, the safety loss rate of the liquor storage tank system will increase due to violation of the rules, which will eventually lead to the decline of the safety of the liquor storage tank. If the effective control measures are not taken in time, the final occurrence of the fire and explosion accident will occur.

2) Manage unsafe behavior in the decision-making layer. For example: command errors, inadequate safety investment, imperfect laws and regulations, etc., will lead to a decline in the level of safety management, resulting in reduced safety productivity, thereby reducing the safety level of liquor storage tanks. Over time, when the threshold (mutation point) of a fire and explosion accident is reduced, an accident will occur.

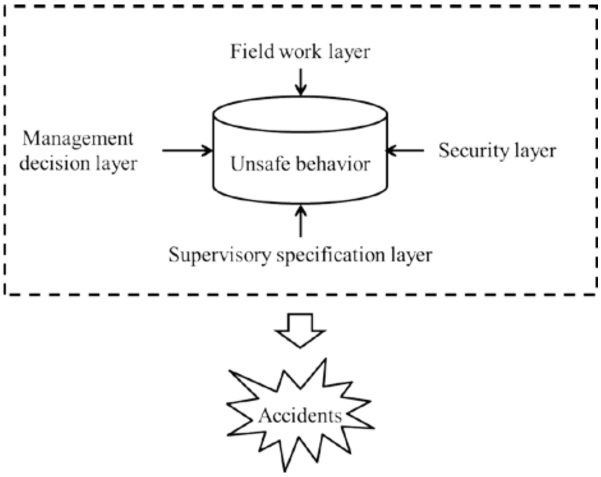

Fig.5 Coupling theory of unsafe behavior

3) Supervising the unsafe behavior of the relevant supervisory and supervision departments in the regulatory layer will cause changes in the safety level of the liquor storage tank. For example, the low intensity of supervision and inspection of safety law enforcement and the lack of effectiveness of punishment factors can lead to the consequences of various violations of employees and the reduction of employees' safety awareness. When these results accumulate to a certain extent, it will lead to fire and explosion accidents.

4) Unsafe behavior in the security layer. The initial safety level of liquor storage tanks is directly affected by the level of employee safety skills, safety protection inputs, and safety levels of environmental impact factors. As time goes by, the concentration of flammable vapor clouds inside the liquor storage tank will increase continuously. If the operator does not take effective measures in time, the operating environment safety level will be lowered. If the safety assurance layer does not invest in safety and security in the early stage, it will eventually cause a fire and explosion accident.

IV. Simulation of the Fire and Explosion Accident

A. *Simulation scheme*

Based on the established mutation mechanism model of the liquor storage tank fire and explosion accident, it is assumed that the initial safety level of the liquor storage tank is 100 (dimensionless). At this time, the entire liquor storage tank safety system has no unsafe behavior, and the whole system runs well and does not appear. However, as the behavior of the human beings changes and the volatilization of the liquor causes the density of the vapor cloud to increase, it may occur that multiple variables are sequentially or simultaneously mutated, causing a sudden increase or decrease of other factors, causing unsafe behavior. Unsafe behavior will directly or indirectly affect the safety of the liquor storage tank system, and the accumulation of equivalent weight to a certain extent will lead to fire and explosion accidents. According to the initial safety level of the safety of the liquor storage tank, the safety system is divided into three states, as shown in Table 1:

Table.1 Classification of liquor storage tanks system safety states

State	Safety level range	Possibility of accidents
Safe state I	[100,90]	Impossible
Critical state II	(90,80]	Possible
Danger state III	(80,0]	Most probably

In order to introduce unsafe behavior and state into the model, a test function is used to represent the impact of the corresponding unsafe behavior and unsafe state on the safety system of the liquor storage tank, and the variables are transformed from qualitative to quantitative. For some system variables that have a stable rate of change over a period of time and remain essentially unchanged after a certain period of time, they can be represented by the ramp function *RAMP({slop} , {start} , {finish})*, where *slop* is the slope; *start* is the ramp start time; *finish* is the ramp end time. Its mathematical expression is

$$f(t) = \begin{cases} 0 & t < 0 \\ Rt & t \geq 0 \end{cases} \tag{1}$$

The function of this function is to change linearly according to the preset slope R from the specified start time and to terminate at the specified end time. Since the cause of the safety system of the liquor storage tank is similar to the effect of the entire safety system and the ramp function, the ramp function *RAMP ({slop}, {start}, {finish})* is selected as the cause factor.

B. *Simulation results and analysis*

According to the above analysis program, the fire and explosion accident of the liquor storage tank was simulated. The dynamic system has a start time of 0 day, a step size is one day, and end time is 1000 day.

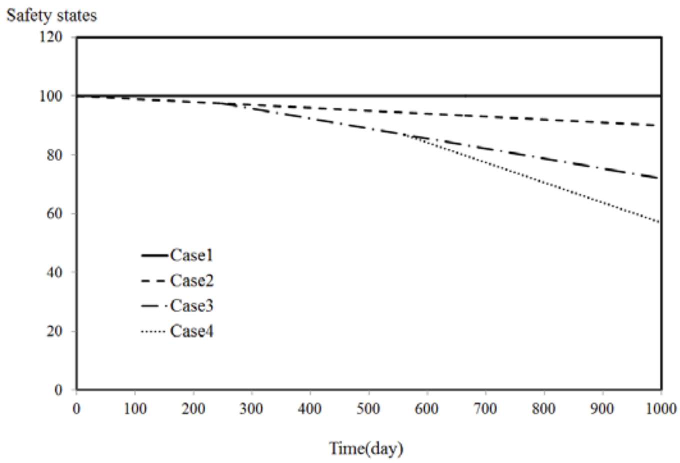

Fig.6 Simulation graph of fire and explosion accident

In order to systematically study the effect of the coupling of different causative factors on the safety level of the liquor storage tank system, four simulation environments were designed: Case1 indicates that the liquor storage tank system does not have any unsafe behavior (state). The dynamic trend of safety level; Case2 indicates the dynamic change trend of the safety level of the liquor storage tank system under the influence of only one unsafe factor; Case3 indicates the dynamic change trend of the system safety level under the condition of two unsafe factors cross-coupling Case4 shows the dynamic trend of system safety level under the condition of three unsafe factors cross-coupling.

1) Case0: The initial safety level of the liquor storage tank is 100, which means that there is no unsafe factor in all links in the whole liquor storage tank system, the safety level of the liquor storage tank remains unchanged, and it is in a safe state I, a fire and explosion accident will not be happened.

2) Case1: Over time, an unsafe factor has arisen at the first day, such as an increase in the concentration of combustible vapor clouds inside the liquor storage tank. By modifying the parameters of the test function RAMP, the effect of this unsafe factor on the safety system of the entire liquor storage tank is shown. At the 1000^{th} day, the safety level of the storage tank is lowered to 91, but the whole system is still in a safe state I, and will not A fire or explosion has occurred.

3) Case2: At the time of xxx, an unsafe factor has arisen on the basis of the increasing concentration of vapor cloud inside the storage tank. For example, the alcohol detection device inside the liquor storage tank has obstacles, which increases the safety loss rate. The safety of the tank is further reduced. Continue to modify the parameters of the function RAMP to indicate the coupling effect of two unsafe factors. At the 244^{th} day, the safety level of the liquor storage tank starts to be less than 90, and it is in the critical safety state II. If the corresponding measures are not taken, the fire and explosion accident may be occurred.

4) Case3: Over time, an unsafe behavior occurred on the basis of Case2 at 558^{th} day, such as an operator disoperation when opening the liquor storage tank. Further modify the RAMP parameters to indicate the coupling effect of the three unsafe factors. The safety of the liquor storage tank is lower than the lower limit of the safety state II, and the oil and gas well is in the safe state III. At this time, as long as static electricity sparks, etc. Sources can cause fire and explosion accidents.

V. Conclusions

Based on the system dynamics and disaster-causing theory, this paper establishes a system dynamics analysis model of steam cloud fire explosion accident in liquor storage tank, and uses this model to simulate the development process of fire and explosion accidents, and finally obtain the following conclusions:

1) Fire and explosion accidents are caused by cross-coupling of various unsafe behaviors affecting the safety level of liquor storage tanks, and cause the safety level of liquor storage tanks to drop to safety warning values.

2) The factors affecting the occurrence of fire and explosion accidents are non-linear for the safety level of liquor storage tanks. By establishing a system dynamics model, coupling analysis does not affect the system safety impact, which can effectively solve this difficulty.

3) The occurrence of fire and explosion accidents is not instantaneous. It is formed by superimposing different influencing factors. If the influencing factors can be eliminated in time before the accident occurs, the occurrence of fire and explosion accidents can be effectively controlled.

4) System dynamics can simultaneously represent and analyze multiple system variables, and describe the mechanism of fire and explosion accidents from the viewpoint of event dynamics, which has important significance in the theory of safety cause.

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