RISK ASSESSMENT OF LEAKAGE FAILURE OF KEY FACILITIES AT OIL AND GAS GATHERING AND TRANSPORTATION STATIONS

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ABSTRACT

Leakage of key equipment in oil and gas gathering and transportation stations may trigger major accidents such as fires and explosions, making risk assessment crucial for ensuring safe production. This paper proposes an integrated risk assessment method based on event tree analysis and numerical simulation to quantify the probability and impact range of leakage accidents. First, an event tree analysis is used to establish a leakage failure mode model, identifying pool fires and vapor cloud explosions (VCEs) as the primary accident types and calculating their occurrence probabilities under different leakage scenarios. Next, PyroSim and ALOHA software are employed to simulate accident progression, quantitatively analyzing hazard parameters such as thermal radiation and overpressure to determine the affected zones. Finally, combining failure probability and severity of consequences, a risk assessment matrix for critical equipment leakage at oil and gas gathering and transportation stations was constructed to enable dynamic assessment of risk levels. The research results indicate that the proposed risk assessment method can quantify the probability of leakage accidents and their potential consequences, providing reliable decision support for risk prevention and control of critical equipment leakage at oil and gas gathering and transportation stations.

Keywords: Oil and gas gathering and transportation stations; Quantitative risk assessment; Key equipment leakage; Numerical simulation

I. INTRODUCTION

With the rapid development of oil and gas pipeline construction in China, oil and gas gathering and transportation stations, as critical nodes in energy transmission, face significant challenges in ensuring safe operation. These stations, characterized by the handling of flammable and explosive media, complex process flows, and densely arranged equipment, pose significant accident risks.

Currently, risk assessment of key equipment at oil and gas gathering and transportation facilities primarily relies on traditional methods such as fault tree analysis (FTA) [1], fuzzy comprehensive evaluation (FCE) [2], Layer of Protection Analysis (LOPA) [3], and Hazard and Operability Analysis (HAZOP) [4]. While these methods are effective for static risk assessment, they have significant limitations: they struggle to reflect the dynamic interactions between system elements and the real-time propagation of risks, and they cannot assess the cascading loss effects triggered by a single event.

To overcome these limitations, this study innovatively proposes an event tree-failure simulation model. By analyzing the leakage model, the leakage size and leakage rate can be determined, and the probabilities of various failure consequences can be calculated, enabling a quantitative analysis of the overall risk level. This assessment framework can accurately quantify the consequences of accidents and achieve a comprehensive assessment of risk levels.

II. LEAKAGE FAILURE ANALYSIS OF KEY FACILITIES AT OIL AND GAS GATHERING AND TRANSPORTATION STATIONS

II.A. Station Key Equipment Leakage Event Tree

Leaks in critical equipment at oil and gas gathering and transportation stations facilities are categorized into four types: process equipment leaks, pipeline connection leaks, pipeline rupture leaks, and pipeline perforation leaks. Oil and gas gathering and transportation facilities primarily include equipment such as oil-gas separators, heaters, crude oil electrostatic dehydrators, towers, pumps, valve assemblies, pipelines, temperature gauges, and pressure gauges. These devices and instruments are connected via flanges, threads, or welds. The most common locations for leaks are static seals, such as flanges and threaded joints.

Based on whether the critical equipment ignites after a leak, whether it ignites immediately, and the speed of the flame front, several different failure consequence patterns are obtained, and a failure consequence event tree model for critical equipment at the station is established, as shown in Fig. 1.

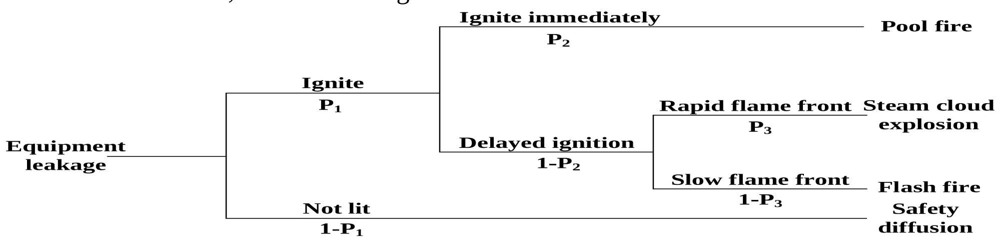


FIGURE 1. Event Tree Model for the Consequences of Failure of Key Station Equipment

II.B. Analysis of the Consequences of Leaks in Key Station Facilities

II.B.1 Leakage Model Analysis

(1) Determine leak size and leak rate

Leakage size is categorized into four types in API 581[5], the state of oil in the gathering station field is generally liquid, so the Bernoulli equation is utilized to obtain the formula for calculating the leakage rate of the liquid, as in Eq. (1).

$$Q = C_d A \rho_1 \sqrt{\frac{2\left(p_s - p_0\right)}{\rho_1}} \tag{1}$$

Where Q is the liquid leakage rate, kg / s; C_d is the aperture leakage coefficient, ranging from 0.61 to 0.65; A is the leakage aperture area, m^2; ρ_1 is the liquid density, kg/m^3; p_s is the medium pressure in the container, Pa; p_0 is the atmospheric pressure, Pa.

(2) Calculate the upper limit of total leakage

The upper limit of leakage of key equipment in the station needs to be determined by considering the total amount of media in the equipment subsystem and the amount of replenishment that the subsystem can obtain from other places when leakage occurs[6].

II.B.2 Probability of Failure Occurrence

(1) Probability of immediate versus delayed ignition

According to API581, the probability of ignition of a liquid at room temperature can be calculated according to Eq. (2).

$$P_{1,a} = \begin{pmatrix} 1.00982 - 0.70372 \cdot \ln \mathrm{M} - 0.013045 \cdot \ln\left(C_1 \cdot Q\right) + 0.18554 \cdot \ln\left(\mathrm{M}^2\right) - \\ 0.0014619 \cdot \ln\left(C_1 \cdot Q\right)^2 + 0.022131 \cdot \ln \mathrm{M} \cdot \ln\left(C_1 \cdot Q\right) - 0.016572 \cdot \ln \mathrm{M}^3 + \\ 0.00011281 \cdot \ln\left(C_1 \cdot Q\right)^3 + 0.00050697 \cdot \ln \mathrm{M} \cdot \ln\left(C_1 \cdot Q\right)^2 - \\ 0.0035535 \cdot \ln \mathrm{M}^2 \cdot \ln\left(C_1 \cdot Q\right) \end{pmatrix} \tag{2}$$

Where $P_{1,a}$ is the probability of ignition under specific temperature conditions; M is the relative molecular weight of the leaking liquid, g/mol; Q is the leakage rate, kg/s ; C_1 is the constant, generally taken as 2.205.

If the current ambient temperature reaches the automatic ignition of the leaking substance, the ignition probability at this time reaches the maximum value of 1. Therefore, the ignition probability of the leaking substance at this time is determined according to Eq. (3).

$$P_1 = P_{1,a} + \left(P_{1,b} - P_{1,a}\right)\left(\frac{T_s - C_2}{T_b - C_2}\right) \tag{3}$$

Where P_1 is the ignition probability of the leaking liquid under the current operating conditions; $P_{1,b}$ is the ignition probability when the leaking ambient temperature reaches the ignition point; Ts is the current operating temperature, K; T_b is the automatic ignition point, K; C_2 is the constant, generally taken as 303.89.

According to the time of ignition can be divided into immediate ignition and delayed ignition, according to API581 it can be seen that the time of ignition is related to the leakage state of the leaking substance, the temperature of the leaking environment and the type of leakage, the probability of immediate ignition occurring when the leakage state is a liquid, P_2can be obtained by calculating in Eq. (4).

$$P_2 = P_{2,a} + \left(P_{2,b} - P_{2,a}\right)\left(\frac{T_s - C_2}{T_b - C_2}\right) \tag{4}$$

Where $P_{2,a}$ is the probability of immediate ignition; $P_{2,b}$ is the probability of ignition when the temperature of the leaking environment reaches the ignition point.

Therefore, the probability of a pool fire $P_{pool} = P_1 \cdot P_2$.

(2) The probability of vapor cloud explosion

It can be seen that after delayed ignition, when the flame front is fast, a vapor cloud explosion will occur, the probability of P_{VCE}. Like the pool fire, the probability of a VCE incident depends on the type of leakage and the fluid phase state.

Therefore, the probability of a vapor cloud explosion is $P_{\text{VCE}} = P_1 \cdot (1 - P_2) \cdot P_3$.

II.B.3 Accident Hazard Consequences

(1) Pool fire hazard model

① Determine the radius of the liquid pool

Assuming that the liquid pool is a circular pool with a radius of *r*, when the hazardous area for the tank, according to the area of the liquid pool surrounded by the fire breakwater to determine its radius as shown in Eq. (5).

$$r = \left(\frac{S}{3.14}\right)^2 \tag{5}$$

② Determine the flame height

Assuming that the site is a windless environment, the application of Thomas empirical formula to calculate the flame height *H* as shown in Eq. (6).

$$H = 84r\left[\frac{dm/dt}{\rho_0\sqrt{gr}}\right]^{0.61} \tag{6}$$

Where *H* is the combustion flame height, m; *r* is the leakage area pool radius, m; ρ_0 is the air density, generally taken as 1.293kg/m^3; g is the free-fall acceleration, generally taken as 9.8s/m^2; *dm/dt* is the combustion rate, $kg/(m^2 \cdot s)$, crude oil taken as 0.022 $kg/(m^2 \cdot s)$.

③ Determine the heat radiation flux

The total thermal radiation flux generated during the combustion of the liquid pool is *Q*, which is calculated by Eq. (7).

$$Q = \left[\left(\pi r^2 + 2\pi r H\right)\left(dm/dt\right)\eta H_c\right] / \left[72\left(dm/dt\right)+1\right] \tag{7}$$

Where *Q* is the thermal radiation flux generated during combustion [7], W; H_c is the heat of combustion of the liquid, J/kg, typically taken as 4.954× 10^{7}J/kg for crude oil; η is the efficiency factor, typically in the range of 0.13 to 0.35.

④ Calculate the incident intensity

For the convenience of calculation, it is set that all the thermal radiation caused by combustion comes from the center of the liquid pool, then the incident intensity received by a certain location *x* away from the center of the liquid pool is I, which is calculated by Eq. (8):

$$I = Qt_c / 4\pi x^2 \tag{8}$$

Where *I* is the incident intensity, KW/m^2; t_c is the thermal conductivity [8], generally taken as 1; *x* is the the distance from the target point to the center of the liquid pool, m .

⑥ Consequences of fire

The consequences of a pool fire are mainly transmitted outward by thermal radiation, and the effects of different thermal radiation intensities on the surrounding personnel and equipment are different.

(2) Cloud explosion hazard model

When the vapors generated by the crude oil spill after diffusion, encountered a fire source to form a vapor cloud, when the vapor cloud combustion rate is relatively low, its pressure will not exceed 5KPa, the personnel and equipment will not have an impact, but the station is often a compact layout, in the small space, the pressure value rises rapidly.

Using the TNT equivalent method for the shock wave pressure caused by the VCE accident, the overpressure equation at *r* from the explosion center is as follows:

$$P = 0.145e^{9.097-\sqrt{25.13\ln\left(\frac{0.397r}{m_{TNT}^{1/3}}\right)-5.267}} \tag{9}$$

Where *P* is the shock wave overpressure value, MPa; *r* is the target point to the explosion center distance, m; m_{TNT} is the equivalent TNT mass, kg. where m_{TNT} is calculated according to Eq. M_C is calculated using Eq.

$$m_{TNT} = 2.07 \times 10^{-7} Y_f M_c H_c \tag{10}$$

$$M_c = \frac{Q_c}{u_a} min\left(x_c, u_a t_a\right) \tag{11}$$

Where Y_f is the yield factor, taken as 0.03; M_C is the total mass of combustible gas in the cloud, kg; Hc is the heat of combustion of gas, J/kg; Q_c is the equivalent release rate, kg / s; x_c is the limit of combustible gas diffusion distance, m; u_a is the wind speed, m/s.

Vapor cloud explosion are generally in the form of shock waves affecting people and the surrounding environment, the impact of the shock wave range of influence according to the shock wave overpressure damage guidelines.

II.B.4 Accident Damage Area Size

According to the event tree analysis of the consequences of key equipment failure at the oil and gas gathering station site shown in Fig. 2, the integrated area of personnel casualties and the integrated area of equipment damage are S_p and S_s, respectively, which can be obtained by probability-weighted summation according to the occurrence of pool fires and the area of VCE hazards as shown in Eq. (12) and Eq. (13).

$$S_P = P_{pool} S_{pool,P} + P_{\mathrm{VCE}} S_{VCE,P} \tag{12}$$

$$S_s = P_{pool} S_{pool,S} + P_{\mathrm{VCE}} S_{VCE,S} \tag{13}$$

Where S_p is the total area of casualties, m ^{2}; $S_{pool,P}$ is the area of casualties caused by the pool fire area, m ^{2}; $S_{vce,P}$- is the area of casualty area due to VCE, m^2; S_s is the total area of equipment damage area; $S_{pool,S}$ is the area of equipment damage area due to pool fire, m^2; $S_{vce,S}$ is the area of equipment damage area due to VCE, m^2.

III. RISK ASSESSMENT OF LEAKAGE FAILURE OF KEY FACILITIES AT STATIONS

III.A. Quantification of Failure Consequences

Leaks, fires, or explosions involving critical equipment at oil and gas gathering and transportation stations will inevitably result in casualties and property damage. The losses incurred are as follows[9]:

$$t_s = 10^{1.242+0.585\cdot \lg\left[S_s/\left(6.214 \cdot 10^2\right)\right]} \tag{14}$$

Thus, the total economic loss is C , which is expressed in Eq. (15).

$$C = \rho_s \cdot S_s + t_s \cdot D \tag{15}$$

Where ρ_s is the equipment failure around the property density, million yuan / m ^{2}; D is the number of days of production interruption losses due to fire and explosion accidents, days.

III.B. Risk Matrix Establishment

A risk matrix is a tool used to assess and categorize risks. It usually consists of two axes, one representing the probability of failure and the other the severity of the consequences of failure. By cross-combining the probability of failure and the consequences of failure in a matrix, different levels of risk ratings are formed to better identify high-risk areas and prioritize issues.

Based on the failure assessment of a certain oil and gas gathering and transportation station, the maximum quantified failure value is 15 million yuan. Taking every 3 million yuan as one level, the failures are classified into five levels, as shown in Table I.

TABLE I. Classification of Failure Consequences

Classification of failure consequences	Quantitative value of consequences (million yuan)	Remarks
A	0 - 3	The loss is very small and the resulting impact is not serious
B	3 - 6	There is some equipment damage, minor casualties
C	6 - 9	There are casualties and more serious equipment damage
D	9 - 12	With more serious casualties and serious equipment damage
E	12 - 15	With serious personnel casualties and serious equipment losses

Combined with the probability of failure, the final risk matrix of oil and gas gathering and Transportation Stations are shown in Table II.

TABLE II. Risk Matrix of Oil and Gas Gathering and Transportation Stations

Risk evaluation matrix		Failure consequence level				
		A	B	C	D	E
Failure Probability	$0\text{-}10^{-5}$					
	$10^{-5}\text{-}10^{-4}$					
	$10^{-4}\text{-}10^{-3}$					
	$10^{-3}\text{-}10^{-2}$					
	$10^{-2}\text{-}1$					

In Table II, the green zone is classified as Risk Level I, indicating a low-risk condition under which the facility can operate normally. The blue zone corresponds to Risk Level II, representing a relatively low-risk state where normal operations are possible, but heightened vigilance and preventive measures are required. The yellow zone is designated as Risk Level III, reflecting a moderate risk level; the facility remains operational, though certain areas have already exhibited significant issues. The orange zone is categorized as Risk Level IV, indicating a relatively high-risk condition where most systems within the station are no longer functional. The red zone is assigned Risk Level V, denoting a high-risk state in which the Oil and gas gathering and transportation stations are largely inoperable and immediate control measures must be taken.

IV. CASE STUDY - RISK ANALYSIS OF LEAKAGE FAILURE OF KEY FACILITIES AT AN OIL AND GAS GATHERING AND TRANSPORTATION STATION

Given that the failure of critical equipment poses the most significant risk to the functioning of the oil and gas gathering and transportation station, this section presents an analysis of the leakage failure risk of such equipment.

IV.A. Calculation of Failure Consequences

(1) Determine the leakage rate and the total amount of leakage

When the aperture leakage is 5mm, the system pressure is 0.1MPa, the leakage rate Q = 0.74kg / s, the total amount of leakage W = 967.5kg, calculated by Eq. (1).

(2) Determine the probability of occurrence of various types of consequences

According to Section *II.B.2*, we can get P_{pool}= 0.016, P_{VCE}= 0.001.

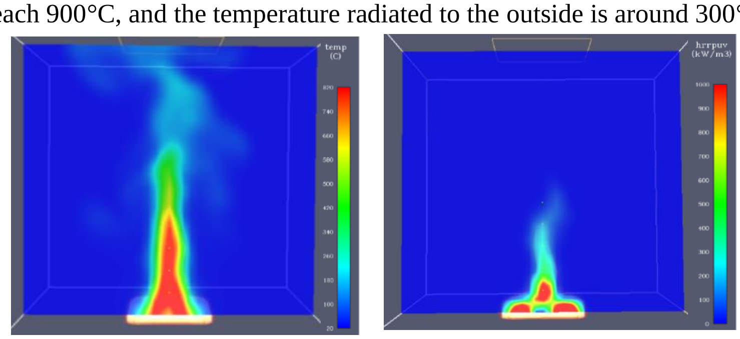
IV.B. Calculation of Impact Scope

The PyroSim software was used to simulate the consequences of a pool fire caused by a crude oil leak from key equipment, and five thermocouples with a spacing of 0.5 were set up on the centerline of the simulation area. The basic parameters of the leakage medium used in the simulation are shown in Table III, combined with the previous calculations, are used to simulate the consequences of failure when the leakage aperture is 5mm. The simulation results are shown in Fig. 2.

TABLE III. Basic Parameter Table

Basic parameter	Numerical value	Basic parameter	Numerical value
Heat of combustion (KJ/kg)	49540	Density (Kg/m^3)	890
Burning rate (kg/(m^2-s))	0.045	Hydrocarbon ratio	0.43
Boiling point (℃)	200	Relative Density (Kg/m^3)	0.75~0.95
Constant pressure specific heat (KJ/(kg-k))	2.4	Heat of vaporization (KJ/kg)	350
Molarity (g/mol)	290	Explosive limit (ppm)	41.24%-141.01
Amount of substance (m^3)	530		

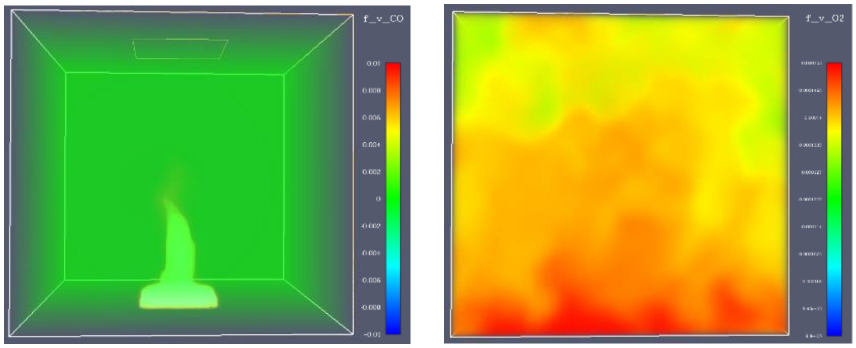
From the analysis of Fig. 2, it is concluded that the maximum temperature at the center of the flame produced by the leakage combustion can reach 900°C, and the temperature radiated to the outside is around 300°C.



1) Temperature 2) Heat release rate per unit area

FIGURE 2. Simulated Pool Fire Aftermath Diagram

Fig. 3 shows the concentration of CO and O_2in the air during the simulated 10s.



1) CO_2 concentration 2) CO concentration

FIGURE. 3 The Change of Gas Concentration After Pool Fire Combustion

Fig. 4 and 5 show the heat release rate per unit area and heat flux, respectively. It can be analyzed from the figure that the highest value of heat release rate per unit area of combustion reaches 1257KW/s, and the highest value of heat flux reaches 936KW.

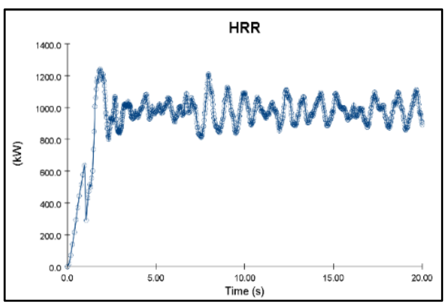


FIGURE. 4 Heat Release Rate per Unit Area

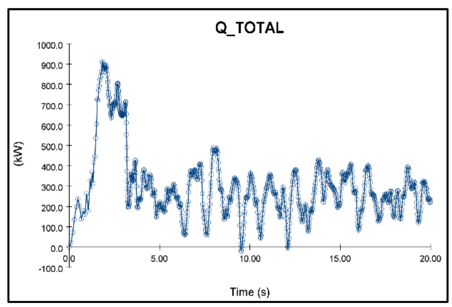
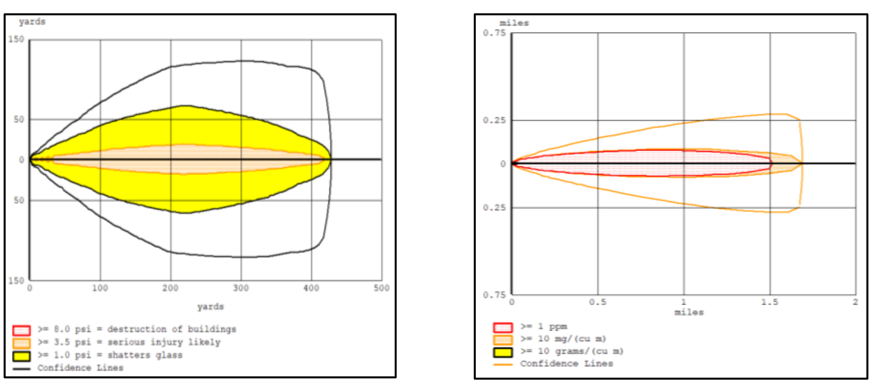


FIGURE. 5 Change in Heat Flux

The VCE accident is simulated using ALOHA software. The parameters of the simulation scenario are set as follows: southeast wind speed 5m/s, measurement height 3m, cloudiness 20%, humidity 25%, ambient temperature 15℃, tank diameter 16m, height 10m, tank capacity 70%, leakage hole diameter 5mm, leakage height 3m.

If crude oil leakage is not immediately ignited, it will form a vapor cloud. When the vapor cloud accumulates to a certain concentration in the air, it will explode upon encountering an ignition source, as shown in Figure 6. This is the flammable zone of the vapor cloud when the leakage diameter is 5 mm. The impact range of the vapor cloud explosion can reach 390 meters, and the dispersion range of toxic fumes is 2,655 meters.



1) The explosive range of vapor cloud explosion 2) Toxic gas dispersion range

FIGURE. 6 Range of Vapor Cloud Explosion Consequences

The casualty and equipment damage areas from pool fire and VCE were obtained using Eq. (3) - Eq. (9) and simulations from PyroSim and ALOHA, as shown in Table IV.

TABLE IV. Area of Casualties and Equipment Damage

Pool fire hazard area/m^2		Vapor cloud explosion hazard area/m^2	
$S_{pool,P}$	$S_{pool,S}$	$S_{VCE,P}$	$S_{VCE,P}$
92.06	31.87	189.31	106.94

TABLE V. Different Leakage Aperture Damage Area

Leakage aperture size	Personnel casualty area S_P/m^2	Equipment damage area S_s/m^2
5mm	1.66	0.62
25mm	21.78	8.34
140mm	190.90	54.04

From Eq. (12) - Eq. (13), *the* S_P and S_s of the crude oil dewatering station can be obtained when the leakage aperture diameter is 5mm, and similarly, *the* S_P and S_s of the leakage aperture diameters of 25mm and 140mm can be obtained according to the above steps, as shown in Table V.

According to API581 failure database, it is known that the ratio of the occurrence of three kinds of leakage apertures is 4:10:1, so according to Eq. (10) and Eq. (11), it can be obtained that the leakage from critical equipment leads to casualty area S_P=27.68m^2, and the area of equipment damage Ss=9.32m^2.

IV.C. Quantification of Failure Consequences

Utilizing the same process and calculation method, the quantified values of the consequences of several other moments are calculated, but due to some changes in the influencing factors at different moments, the results need to be corrected, and according to the empirical method, the corrected results are shown in Table VI. According to the corrected results, the total economic loss of each moment is obtained as shown in Table VII.

TABLE VI. Consequence Value Correction Table

Correction factor	Moment	Before correction	After correction	Correction Factor	Moment	Before correction	After correction
Leakage rate (kg/s)	t_1	0.76	0.77	Casualty area (m^2)	t_1	28.34	29.65
	t_2	0.80	0.79		t_2	29.57	30.91
	t_3	0.79	0.80		t_3	30.48	30.36
	t_4	0.82	0.80		t_4	29.66	30.14
	t_5	0.84	0.79		t_5	30.76	29.95
	t_6	0.83	0.78		t_6	31.25	28.73
	t_7	0.82	0.78		t_7	29.68	26.64
	t_8	0.79	0.77		t_8	27.63	25.38
	t_9	0.78	0.76		t_9	26.47	24.87
Total amount of leakage (kg)	t_1	970.8	971.1	Equipment damage area (m^2)	t_1	10.24	11.24
	t_2	974.3	973.4		t_2	11.92	10.87
	t_3	972.6	972.6		t_3	10.34	10.51
	t_4	977.2	972.5		t_4	9.76	10.03
	t_5	973.4	971.8		t_5	9.14	9.44
	t_6	971.4	971.4		t_6	8.94	8.76
	t_7	970.5	969.3		t_7	8.39	8.23
	t_8	969.8	967.1		t_8	9.57	7.68
	t_9	965.7	965.4		t_9	9.05	7.14

TABLE VII. Table of Total Economic Losses at All Times

Table of total economic losses at all times	t_0	t_1	t_2	t_3	t_4
Total Economic Loss (million dollars)	452.59	498.64	512.76	501.95	494.71
Moment	t_5	t_6	t_7	t_8	t_9
Total Economic Loss (million dollars)	477.32	458.86	437.65	409.78	376.65

IV.D. Determination of Failure Consequence Levels

According to the risk consequence level in Table I, the economic loss of each moment in the table is represented in the risk radar diagram as shown in Fig.7.

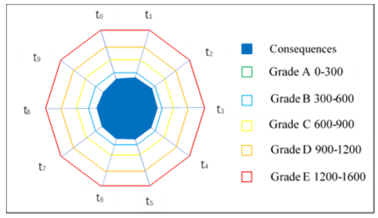


FIGURE. 7 Failure Consequence Level Diagram

V. COMPREHENSIVE RISK LEVEL

According to the risk matrix in Table. II, the comprehensive risk levels at various times for leaks from key equipment at a certain oil and gas station are shown below.

TABLE VIII. Comprehensive Risk Level at All Times

Moment	t_0	t_1	t_2	t_3	t_4
Risk level					
Moment	t_5	t_6	t_7	t_8	t_9
Risk level					

From Table VIII, it can be seen that the risk level of the first two moments is III, which is in medium risk, and the other moments are II, which is in lower risk, and with the change of time, the risk value is decreasing.

VI. CONCLUSION

(1) Establish an event tree model based on the ignition conditions following key equipment leakage, identifying failure modes such as pool fires and vapor cloud explosions. Analyze the leakage size and rate in accordance with API 581 standards, establish a quantitative calculation model, quantify the accident damage area and economic losses to personnel, and establish a risk evaluation matrix.

(2) Taking a 5mm leak diameter as an example, the leak rate W is calculated to be 967.5 kg/s, with a pool fire probability of 0.016 and a P_{VCE} probability of 0.001. Using PyroSim and ALOHA software to simulate the accident impact range, the comprehensive risk levels at each time point in the key facility leak are determined based on the probability and consequence quantification results, achieving dynamic risk level evaluation for the key facility.

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