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APPLYING THE QUANTITATIVE RISK ASSESSMENT (QRA) TO IMPROVE SAFETY MANAGEMENT OF OIL AND GAS PIPELINE STATIONS IN CHINA

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ABSTRACT

The oil and gas pipeline companies in China are facing unprecedented opportunities and challenges because of China's increasing demand for oil and gas energy that is attributed to rapid economic and social development. Limitation of land resource and the fast urbanization lead to a determinate result that many pipelines have to go through or be adjacent to highly populated areas such as cities or towns. The increasing Chinese government regulation, and public concerns about industrial safety and environmental protection push the pipeline companies to enhance the safety, health and environmental protection management.

In recent years, PetroChina Pipeline Company (PPC) pays a lot of attention and effort to improve employees and public safety around the pipeline facilities. A comprehensive, integrated HSE management system is continuously improved and effectively implemented in PPC. PPC conducts hazard identification, risk assessment, risk control and mitigation, risk monitoring. For the oil and gas stations in highly populated area or with numerous employees, PPC carries out quantitative risk assessment (QRA) to evaluate and manage the population risk. To make the assessment, “Guidelines for quantitative risk assessments” (purple book) published by Committee for the Prevention of Disasters of Netherlands is used along with a software package.

The basic principles, process, and methods of QRA technology are introduced in this article. The process is to identify the station hazards, determinate the failure scenarios of the facilities, estimate the possibilities of leakage failures, calculate the consequences of failures and damages to population, demonstrate the individual risk and social risk, and evaluate whether the risk is acceptable. The process may involve the mathematical modeling of fluid and gas spill, dispersion, fire and explosion. One QRA case in an oil pipeline station is described in this article to illustrate the application process and discuss several key issues in the assessment.

Using QRA technique, about 20 stations have been evaluated in PPC. On the basis of the results, managers have taken prevention and mitigation plans to control the risk.

QRAs in the pipeline station can provide a quantitative basis and valuable reference for the company’s decision-making and land use planning. Also, QRA can play a role to make a better relationship between the pipeline companies and the local regulator and public. Finally, this article delivers limitations of QRA in Chinese pipeline stations and discusses issues of the solutions.

INTRODUCTION

Rapid and stable economic development in China needs sustained and reliable energy supply. The social development and improvement of the people's living also make a particularly strong growth in energy demand for oil and natural gas. Due to non-coordination of the regional development and uneven distribution of oil and natural gas resources in China, it is necessary to transport oil and gas in a long distance and distribute them to the market and end users. Pipeline is one of the most important and economical ways to transmit oil and gas. This is a great opportunity for Chinese pipeline companies.

At the same time, China's economic, social development and population growth lead to great changes in cities, towns and the rural areas. The shortage of land resources and the rapid urbanization lead to a determinate result that many places around the existing pipelines become towns from the deserted locations and a lot of new pipelines have to go through or adjacent to the highly populated areas such as cities or towns. The increasing Chinese government regulation, and public concerns about industrial safety and environmental protection push the pipeline companies to enhance the safety, health and environmental protection management. This is a serious challenge for Chinese pipeline companies to face.

PetroChina Pipeline Company (PPC) operates 14,228 km transmission pipelines now, including 4,954 km natural gas pipelines, 5,125 km crude oil pipelines and 5,226 km product pipelines. These pipelines are located in 17 provinces of China. In PPC, 20% pipelines are built in 1970s, 3% pipelines are built in 1980s, 0.08% pipelines are built in 1990s, 77% pipelines are built since 2000. Therefore, most of them are old or new pipelines. According to the bathtub-curve principle, both old and new pipelines are accident-prone.

The proportion of pipelines in high consequence areas (HCAs) to the total mileage in PPC is shown in Figure 1. Product and crude oil pipelines have higher percentage of HCA and the overall HCA proportion is 29.5%. High HCAs percentage increases the risk of pipeline failure and raises difficulties in risk control and emergency management.

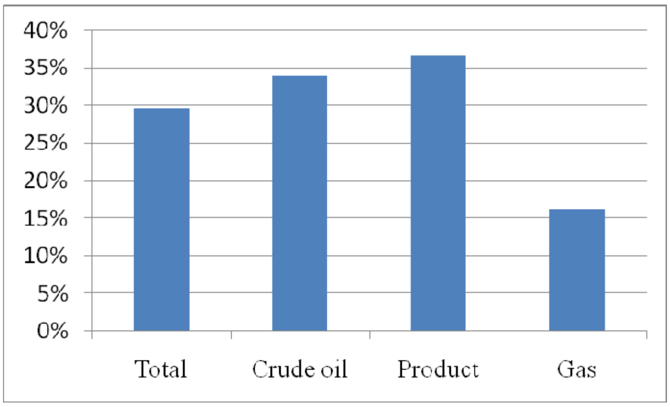

Figure 1. HCAs Proportion in PPC

In order to address these issues, PPC actively carries out pipeline integrity management, pipeline risk assessment, the station risk assessment, and makes tremendous efforts to control the threats, reduce the risks and achieve a good performance.

In recent years, PPC pays a lot of attention and effort to improve employees and public safety. A comprehensive, integrated HSE management system is continuously improved and effectively implemented in PPC. PPC conducts hazard identification, risk assessment, risk control and mitigation, risk monitoring. For the oil and gas stations in highly populated area or with numerous employees, PPC carries out quantitative risk assessment (QRA) to evaluate and manage the population risk.

QRA technology plays a practical role in many aspects such as risk management, emergency aid, land use planning, etc[1]. Risk assessment (RA) technology was introduced since 1960’s and achieved great contribution in the planning and management of chemical and petroleum industry. QRA has been developed widely since Professor Rasmussen successfully applied it in the safety assessment on American business nuclear station in 1974[2]. Other examples of the application of QRA are from governments as following. In 1976, British government conducted risk assessment on the storage, transportation, and production installations of petroleum in Canvey island[3]. Netherlandish government carried out risk evaluation on Rijinmond industrial area[4].

The high frequency of leakage, fires and explosion accidents leads the petroleum and chemical companies emphasize more on the risk management on pipelines and stations. Research on QRA in China is relatively less[5]. QRA technology has been introduced to the oil and gas pipeline station in China for several years[6]. More than 20 stations have been assessed using QRA technology in PPC. On the basis of the results, managers have taken a plan for prevention and mitigation to control the risk.

This article will deliver an introduction of the useful practice of QRA in pipeline stations and show how PPC improve safety management of oil and gas pipeline stations with QRA application.

METHODOLOGY OF QRA

QRA analyses and calculates the accident’s frequency and consequence of the industrial installations or operations. It works out the quantitative risk value and judges the acceptability of the risk according to the acceptable risk criteria that is set, as Figure 2 shows.

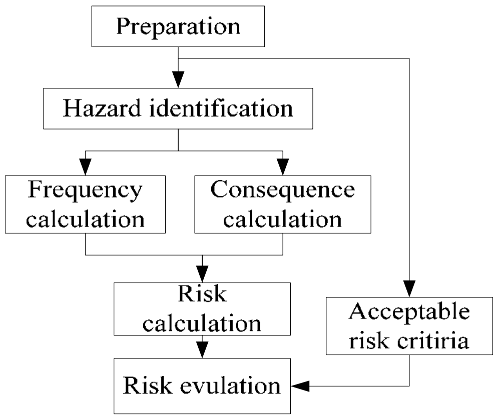

Figure 2. Procedure of QRA

The assessment experts then give the suggestions on how to control or mitigate the unacceptable risk. QRA usually answers the following questions: (a) What kind of accidents will happen in the installations? (b) How often will the accidents happen? (c) What kind of consequences will the accident lead to? (d) Is the risk acceptable?

In PPC, RA engineers carry out QRA projects according to “Guidelines for quantitative risk assessments” (purple book) published by Committee for the Prevention of Disasters of Netherlands[7].

Acceptable Risk Criteria

In the risk assessment of the industrial installations, three kinds of risk are usually taken into account, namely population risk, environmental risk and business risk. QRA focuses on evaluating the population risk in the industrial location, including individual risk and societal risk.

Individual risk is defined as risk on a location outside the establishment, expressed as a frequency per year for a person dying, whilst standing continuously and unprotected, due to an incident in the establishment with hazardous materials. Typically individual risk is presented on a map showing the risk contours. Figure 3 gives an example of individual risk contours. Societal risk is defined as the cumulative frequency per year that a number of persons would die due to an incident in the establishment with hazardous materials and their presence in the influence area of the establishment. The result is presented in an F-N curve with frequency on the y-axis and the number of fatalities on the x-axis. Figure 4 gives an example of a societal risk curve.

Usually, the as low as reasonable practice (ALARP) principle is used as the acceptable risk criteria in QRA. It sets the high and low threshold of the acceptable risk and then distinguishes the risk level to three grades, see Figure 5. The risk over the high threshold is not acceptable, while that lower than the low threshold is acceptable and negligible. The middle grade which is called is ALARP area, indicates that economical and practical measures should be taken to control or mitigate the risk level. Many national governments have released the acceptable risk criteria that can be alternative reference to QRA application in China[8].

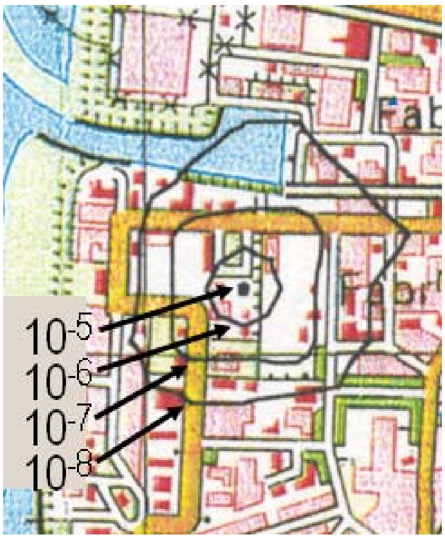

Figure 3. Example of individual risk contours

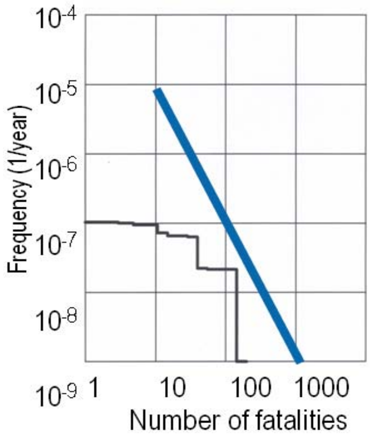

Figure 4. Example of societal risk curve

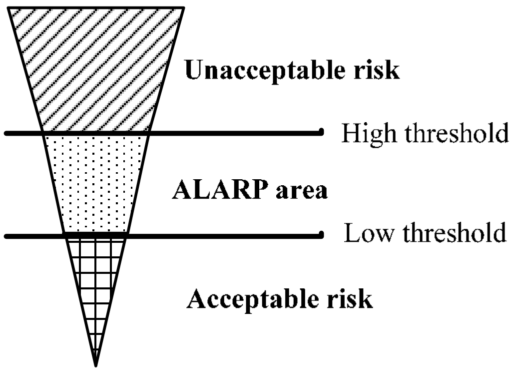

Figure 5. Risk grades under the ALARP principle

Calculation Model

When conduct a QRA, firstly hazards should be identified based on the station/plant’s facilities. Secondly, the credible leakage scenarios are set and the failure frequency of each leak scenario is estimated. Then engineers can analyze processes of the leakage by using the Event-tree method. At the same time, consequences (dispersion model, fire, and explosion) of the leakage and damages to people should be simulated. Finally, the individual risk and social risk are calculated and mapped. “Guidelines for quantitative risk assessments” gives the instruction of the processes.

For each hazard, its risk can be calculated by formula (1) as follows[6].

$$R(x,y) = \sum_{n=1}^{N} F_n U_n(x,y) \qquad (1)$$

Where,

$R(x, y)$: the individual risk that the specific hazard leads to at the location (x, y).

F_n: the accident frequency of No. n scenario.

$U_n(x, y)$: the individual death likelihood that No. n accident leads to at location (x, y).

N: the number of accident scenarios.

The value of F_n can be obtained from the event tree analysis. The accident consequence simulation can lead to fire thermal radiation flux, over pressure or toxicant concentration of No. n accident scenario at location(x,y). Then the results can be transferred to the individual death frequency U_n (x,y) by the damage model. The consequence models include leakage model, dispersion model, thermal radiation model, fire model, explosion model, etc. For the damage model, the criteria of harms to human and buildings is thermal radiation flux, over pressure or toxicant concentration.

Total individual risk of all hazards at location (x, y) can be obtained by the gird division. Calculate the individual risk of each hazard to each one grid, and then by adding the values, the total individual risk of each gird can be calculated. The individual risk contours are formed by connecting the grids that have equal individual risk values. Multiplying the population in the area, the societal risk curves can be obtained.

All above models and processes are packaged into the software, so that it is easy to calculate and assess.

Failure Frequency Estimation

In QRA, the failure frequency of the installations' scenarios depends mainly on the statistics of history data. Many countries or petroleum and chemical companies have accumulated the statistic failure data of decades, for instance, Britain HSE, Netherlands VROM[3]. The failure data of Chinese pipelines are not enough at present. Although we can refer to the international data and modify them according to the specific equipment and management, it needs us much caution when using the data as the substantial difference between China and other countries.

APPLICATION CASE OF QRA

A QRA case applied to a pump station of a crude oil pipeline is introduced as follows. It is one of the 20 stations that have been carried out QRA in PPC. The main function of the station is to receive crude oil, after heating the station pumping to next station. The station consists of two main sections: processing section and storage tank section. There are 7 tanks in the tank section, each having a volume of $10\times10^4m^3$. The processing section includes pump unit, power unit, heating unit, heat exchanger unit, metering unit, piping system, etc. The office, dormitory, dining-room are all outside of the gate in the south, as Figure 6 shows.

Hazard Identification

The first thing of QRA application is to identify the hazard, i.e. to identify the assessment objects, with the consideration of the layout of the stations and the characteristics of production. Although there are many types of equipments in crude oil stations, it is not necessary that each one be assessed by QRA. Only those that have great safety influence or high risk are taken into account, such as tanks, pipes, heat exchangers, pumps, pigging system, etc. Hazard identification is carried out by PPC experts and station operators together.

The crude oil is flammable, with its flash point at -6.67~32.2℃, and the explosion limit between 1.1~8.79%. In this case, the leakage of the tank, pipes, pumps and heat exchanger are considered as important hazards, and divided into units in the failure scenarios.

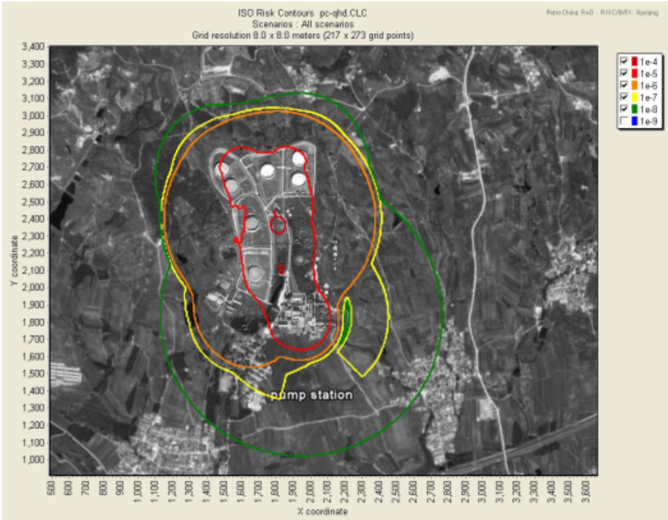

Figure 6. Layout and individual risk contours of the station

Scenario Setting and Consequence Analysis

In the case, both leakage and rupture are considered as the failure scenarios to the different equipments. Totally, 25 failure scenarios (see Table 1) are set and the corresponding failure frequencies is obtained from "Guidance of Quantitative Risk Assessment" [7].

The crude oil leakage/rupture Event-tree was analyzed as Figure 7. The crude oil can be ignited directly once a leakage happens. At the condition of non-direct ignited, the crude oil can evaporate to form flammable vapor cloud. If the consistency of the cloud exceeds the low explosion limit (LEL), the ignited source will lead to flash fire or vapor cloud explosion (VUCE).

The probability of direct ignition is 0.065, according to "Guidance of Quantitative Risk Assessment" [7]. To calculate the delayed ignition probability, two different ways are applied in the QRA. One is a calculation with actual ignition sources, namely, the specific locations at the establishment and outside the establishment and distribution of ignition sources at in the environment should be known or can be anticipated. The other is free field calculation using the specific locations of the known ignition sources at the establishment. If the cloud is not ignited at the establishment, ignition is assumed to take place at maximum cloud area, with cloud area defined as the surface area of the LEL-footprint of the cloud. If an LFL-contour is not resent outside the establishment, e.g. the spill of a flammable liquid in a bund, and if ignition does not occur at the establishment, ignition is assumed not be take place. On the basis of ignition source investigation and analysis in the field, the likelihood of delayed ignition is estimated.

The consequences (pool fire, vapor dispersion, flash fire VUCE) are simulated using the software tool.

Table 1. Leakage scenarios of the station

Equipment	Description
Tanks	Continous-10 mm hole, directly to atmosphere
	Continous-10 min, directly to atmosphere
	Instantaneous- directly to atmosphere
Pipes	Inlet pipe-Leak-effective diameter 10% of nominal diameter, maximum of 50 mm
	Inlet pipe- Full bore rupture- two sided outflow
	Pipe in tank-Leak-effective diameter 10% of nominal diameter, maximum of 50 mm
	Pipe in tank-Full bore rupture-two sided outflow
	Outlet pipe-Leak-effective diameter 10% of nominal diameter, maximum of 50 mm
	Outlet pipe-Full bore rupture- two sided outflow
Pumps	Leak-effective diameter 10% of nominal largest connection diameter, max.50 mm
	Catastrophic failure- full bore rupture
Heat exchangers	Leak-effective diameter 10% of nominal diameter, maximum of 50 mm
	Full bore rupture- 1 pipe, two sided outflow

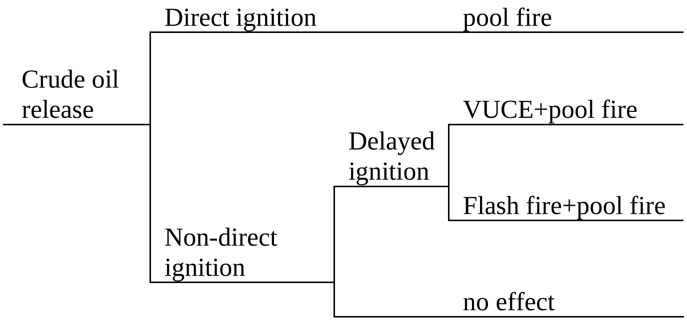

Figure 7. Typical leakage event tree of crude oil

Damage Modeling

The damages to people due to exposure to fire and explosion are simulated using the software tool. In the damage model, the hazard to human is represented by the lethality and injury rate.

The parameters, Probability of death (P_E) and Fraction of the population dying (F_E), are to be used in the calculation of the risk. Probability of death, P_E, indicates the probability of an individual dying from exposure. The individual is assumed to be outdoors and to be unprotected. Fraction of the population dying, F_E, indicates the fraction of the population dying at a certain location due to a given exposure. At least part of the population is protected by staying indoors and wearing protective clothing. For this reason, two values are used, $F_{E,in}$ and $F_{E,out}$ to denote the respective fractions of the population dying indoors and outdoors.

The probability of death due to a flash fire, P_E, and the respective fractions of people dying indoors and outdoors, $F_{E,in}$ and $F_{E,out}$ are given in Figure 8.

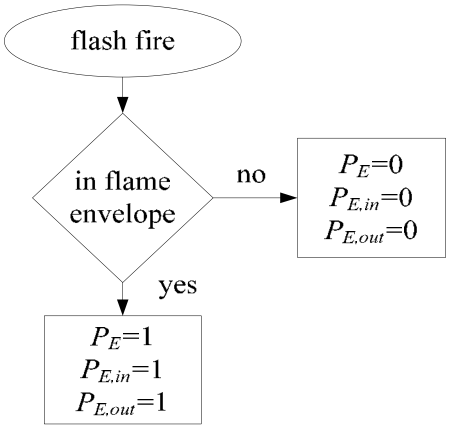

Figure 8. Calculation of the probability of death for exposure to a flash fire

The probability of death due to a pool fire, P_E and the respective fractions of people dying indoors and outdoors, $F_{E,in}$ and $F_{E,out}$, is given in Figure 9. It is assumed the people indoors are protected from heat radiation until the building catches fire. The threshold for the ignition of buildings is set at 35 kW/m^2. If the building is set on fire, all the people inside the building are assumed to die. If the heat radiation intensity is less than 35 kW/m^2, the peoples in the building can survive. It is assumed that people outdoors are protected from heat radiation by clothing before it catches fire. The protection of clothing reduces the number of people dying by a factor of 0.14 compared to no protection of clothing. The threshold for the ignition of clothing is set at 35 kW/m^2 and people die if clothing catches fire at this threshold.

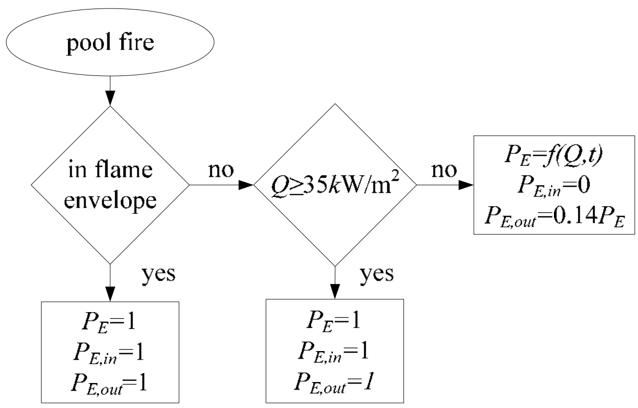

Figure 9. Calculation of the probability of death for exposure to a pool fire

The probability of death due to the exposure to heat radiation is calculated with the use of a probit function (2) and relation (3).

$$p_r = -36.38 + 2.56\ln(Q^{4/3} \times t) \quad (2)$$

$$P = 0.5 \times \left[1 + erf\left(\frac{P_r - 5}{\sqrt{2}}\right)\right] \quad (3)$$

Where,

P_r: probit corresponding to the probability of death.

Q: the heat radiation intensity, in W/m^2.

t: exposed time, in seconds.

P: the probability of an effect.

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt \quad (4)$$

The probability of death due to a VUCE, P_E and the respective fractions of people dying indoors and outdoors, $F_{E,in}$ and $F_{E,out}$, is given in Figure 10. The pressure that is bigger than 0.03MPa can lead to complete destruction or displacement of building and 100% lethality of people. The pressure at 0.01MPa can make parts of building collapse that can cause 1% lethality.

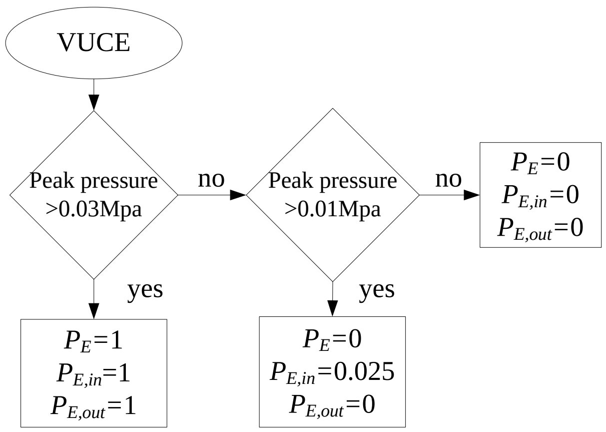

Figure 10. Calculation of the probability of death for exposure to a VUCE

Meteorological Data and Population Data

Meteorological data in term of the representative weather classes and wind speeds are collected for dispersion calculation from the local bureau of meteorology.

The presence of the population is used for the calculation of both the societal risk and the ignition probability. That varies with time, as people travel out of the area to work, attend schools and the like. Therefore different values are set for the population during daytime and night-time. The population inside and outside the station is surveyed as detailed as possible (see Table 2).

As it is assumed that at least part of the population is protected by staying indoors and wearing protective clothing, different values in Table 3 are set for the fractions of the population dying indoors and outdoors on basis of the survey.

Table 2. Presence of population in the environment

Position	Daytime	Night-time
Fire pump room	2	2
6 sentries	1 per sentry	1 per sentry
Armed police station	100	100
Control room	1	2
Power station	2	2
Pump room	3	2
Valves room	1	0
Heat exchanger area	3	2
Boiler room	4	4
Metering room	1	0
Maintenance office	17	0
Fire station	30	0
Gate guard	1	1
Dormitory	10	10
Office building	12	0
Others	70	0
Village A	760	950
village B	1120	1400
Village C	96	120

Table 3. Fraction of population indoors in the station

Population	Fraction of population indoors	
	Daytime	Night-time
Employees	93%	99%
Farmers in village	80%	100%

Assessment Results

In the case, the assessment mainly analyses the frequency, the release amount of all kinds of leakages and the corresponding fire and explosion consequence of the various processing units in the station.

In PPC, for the individual risk criteria of the employees, the high threshold is set as 1.0×10^{-3} per year, and the low threshold is set as 1.0×10^{-5} per year. For the individual risk of the residents around, the high threshold is set as 1.0×10^{-4} per year, while the low threshold is set as 1.0×10^{-6} per year.

The individual risk contours have been worked out (see Figure 6), the position risk of employees (see Figure 11) and the societal risk F-N curve (see Figure 12).

Referring to the risk criteria, the individual risk of the employees in the station is in the ALARP scope. Employees in fire pumping room, pump area and control room take higher risk, and the risk to the residents around the station (farmers) is negligible.

The societal risk criteria are shown as Table 4, which refers the acceptable risk criteria released by other nations and HongKong since Chinese government has not determine them.

Referring to the risk criteria, the societal risk out of the station is in the ALARP range. Higher contribution to the societal risk of the station is the failure scenarios of pump and heat exchanger (52%), tank rupture (17%).

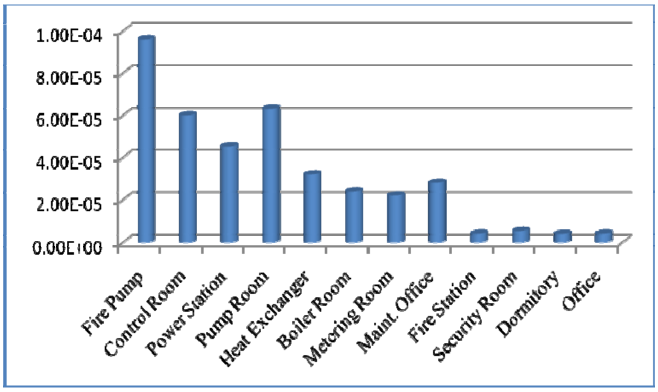

Figure 11. Position risk of employees, per year

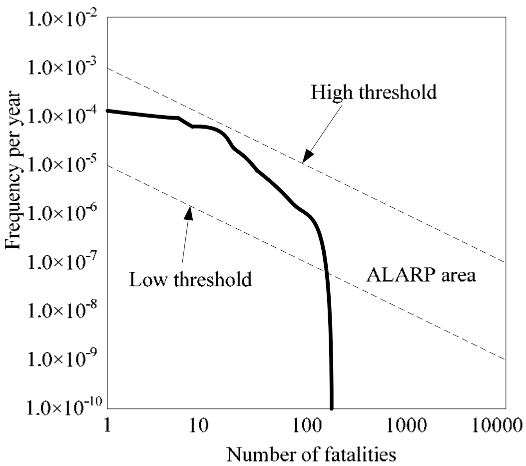

Figure 12. Societal risk F-N curve of the station

Table 4. Societal risk criteria of QRA

High threshold (fatalities number/ accumulated frequency per year）	Low threshold (fatalities number/ accumulated frequency per year）
$1/10^{-3}$	$1/10^{-5}$
$10/10^{-4}$	$10/10^{-6}$
$100/10^{-5}$	$100/10^{-7}$

Based on the result, QRA reports give many recommendations to the managers. The main points for the station are: (a) safeguard measures to fire pump room, pumping stations and control room should be strengthened and implemented to control of the individual risk in these positions, (b) in order to reduce the societal risk, maintenance and repair of pump, heat exchanger and tank should be put great effort to manage their integrity and decrease the failure likelihood of these devices.

PRACTICE OF RISK MANAGEMENT IN PPC

PPC has developed a comprehensive and integrated risk management plan for pipeline stations and petroleum terminals. This plan will carry out hazard identification, risk assessment and risk control management in more than 100 stations and petroleum terminals. Improvements and measures based on evaluation results will be taken and implemented in accordance with the magnitude of the risk and the failure consequences. As the QRA of 20 pipeline stations has been completed, the HSE department is to verify and review the processes and results of each assessment. The recommendations are discussed and appraised by PPC experts and HSE department. Many proposed measures have been adopted to be applied to reduce the risk of the involved stations and improve the safety performance. HSE department make a screening of major high-risk items on basis of QRA reports to monitor routinely.

Nowadays, PPC has established a risk-oriented allocation system of resources. In the system, QRA technology is a key method to evaluate population risk in the station. Other techniques such as HAZOP, Safety checklist, Safety integrity level and Risk-based inspection are also used in PPC. The top managers arrange the financial, human and management resources in accordance with the risk level. The management system and practices have effectively controlled the risk of employees and residents around the stations or pipelines.

CONCLUSION

As a scientific, reasonable and practical assessment technology, QRA can be used for pipeline station land safety planning and risk management. With it, PPC has gained an evident improvement in station safety management and obtained a good achievement in operational performance of oil and gas pipelines.

However, considerable limitations during the QRA application on Chinese pipeline station are waiting to be solved. First, failure database of petroleum pipeline industry needs to be developed. Secondly, national/industrial risk acceptable criteria should be established in order to provide reference for the assessment. Thirdly, a systematic quantitative risk assessment method that is suitable to pipeline station should be researched.

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