3D QUANTITATIVE RISK ASSESSMENT ON A HYDROGEN REFUELING STATION IN SHANGHAI

Yang Liang[1], Xiangmin Pan[2] , Hong Lv[1], Wei Zhou[1], Bin Xie[3]

[1] School of Automotive Studies，Tongji University, Caoan Road 4800,Shanghai,201804, P.R.China, liangyang0218@tongji.edu.cn

[2] Shanghai Motor Vehicle Inspection Certification & Technology Innovation Center, No.68 Yutian South Road,Shanghai,310000, P.R.China, xiangminp@smvic.com.cn

[3] GexCon China,No.18 Taolin Road, Shanghai, Shanghai, 200135, P.R.China, Xie.Bin@gexcon.com

ABSTRACT

The number of hydrogen refueling stations worldwide is growing rapidly in recent years. The first large capacity hydrogen refueling station in China is under construction. A 3D quantitative risk assessment （QRA） is conducted for this station. Hazards associated with hydrogen systems are identified. Leakage frequency of hydrogen equipment are analyzed. Jet flame,explosion scenarios and corresponding accident consequences are simulated. Risk acceptance criteria for hydrogen refueling stations are discussed. The results show that the risk of this refueling station is acceptable. And the maximum lethality frequency is $6.3*10^{-6}$. The area around compressors has the greatest risk. People should be avoided as far as possible from the compressor when the compressor does not need to be maintained. With 3D QRA, the visualization of the evaluation results will help stakeholders to observe the hazardous areas of the hydrogen refueling station at a glance.

1.0 INTRODUCTION

As the future development direction of the automotive industry, fuel cell vehicles are receiving more and more attention. In addition to factors such as technology, durability and cost, the construction of hydrogen refueling stations network has become a key factor in the commercialization of fuel cell vehicles. The growth rate of hydrogen refueling station construction is obvious in recent years. A total of 64 stations were put into operation worldwide in the past year [1].

The Chinese government has listed the development of hydrogen energy and fuel cell technology as a key task, and lists fuel cell vehicles as a key support area. It is clearly stated that in 2020, the scale of 5,000 fuel cell vehicles will be demonstrated in the public service vehicles sector in specific regions, and 100 hydrogen refueling stations will be built; in 2020, 50,000 vehicles will be used and 300 hydrogen refueling stations will be built; In 2030, the commercial application of millions of fuel cell vehicles will be realized, and 1,000 hydrogen refueling stations will be built. As a pioneer in the development of the fuel cell vehicle industry, Shanghai released a fuel cell vehicle development plan in 2017. According to the plan, Shanghai will build 5-10 hydrogen refueling stations by 2020. And the Shanghai Chemical Industry Park hydrogen refueling station will be built soon. The hydrogen of this station is derived from pipeline transportation. As a parent station, it will be the main gas source for Shanghai fuel cell vehicle hydrogen refueling stations for a long time.

The safety issues of hydrogen are always a critical concern to the implementation of hydrogen facilities. Hydrogen has the characteristics of flammability, low ignition energy, easy leakage and diffusion, and fast flame propagation. So the safety has been a major concern in hydrogen applications. Some characteristics of hydrogen can reduce risk, while others may increase risk. Once hydrogen continuously leaks, a jet flame can be formed in case of immediate ignition; if the jet flow encounters obstacles or agglomerates within a confined space, a flammable gas cloud (hydrogen volume fraction between 4% and 75%) can be formed. If an ignition source exists in the flammable gas, the explosion can occur in certain cases, and the overpressure can do harm to the equipment and people in the hydrogen refueling stations[2]. In confined spaces, hydrogen can be detonable due to the wide explosion limit. In open spaces, the probability of hydrogen explosion is greatly reduced due to the rapid diffusion and rising upwards resulted from lower density than air. In addition, hydrogen is usually stored in hydrogen refueling stations at very high pressure, which has the potential to physical explosion.

There has been numerous studies that focused on risk assessments and safety studies on different types of hydrogen stations. For example, risk assessments have been carried out with quantitative methods[3][4][5][6][7],qualitative techniques[8][9][10][11], integrated methods [12][13][14],and the safety distance of hydrogen refueling station have been analyzed [15][16][17]. Additionally, some literatures focus on the hydrogen accident simulation by using computational fluid dynamics (CFD) codes [18][19][20].Research on quantitative risk assessment of hydrogen refueling station combines the leakage probability of equipment, ignition probability and human hazard criteria to calculate the personal mortality rate of hydrogenation stations [4][5][6][8]. Japanese researchers utilize qualitative risk assessment methods to analyze the safety of different types of hydrogen refueling stations [9][10][11]. Risk matrix is usually used as risk acceptability criterion in qualitative analysis. Korean researchers use CFD software to simulate hydrogen accidents and lay the foundation for hydrogen station standards[. The simulation in this paper based on real hydrogen refueling station that is being operated. The most serious consequences of the hydrogen accident are considered in the simulation. In addition, the effects of wind speed, leakage direction and wind direction on the consequences of the accident are analyzed.

In the past research on the quantitative risk assessment (QRA) of hydrogen refueling stations, the quantification of the consequences is always based on two-dimensional CFD simulation. However, 2D simulation cannot consider the impact of obstacles and other factors on the consequences. This paper attempts to conduct a 3D fire quantitative risk assessment of the Shanghai Chemical Industry Park hydrogen refueling station. And the results of the evaluation are visualized.

2.0 DESCRIPTION OF THE HYDROGEN REFUELING STATION

The Shanghai Chemical Industry Park station is a comprehensive energy station, which is equipped with hydrogen refueling and charging facilities. And the station is designed to fill fuel cell vehicles to either 35 MPa or 70 MPa. This station not only performs hydrogen filling for 100 fuel cell buses, but also fills tube trailers for gaseous hydrogen. The daily hydrogen supply capacity of the hydrogen refueling station is about 1800kg: the fixed hydrogen storage capacity in the station is about 860kg, and the storage pressure is 20MPa, 45MPa, 90Mpa, respectively; three tube trailers are parked, which's storage pressure is 20 MPa, and the total hydrogen storage capacity is 840kg (each 280kg). The charging station has one set of 131.22kW photovoltaic power generation device and one set of 400kWh energy storage device. There are six double gun charging piles, twelve charging parking spaces and seven ordinary bus parking spaces. There is also a vehicle detection workshop and a switch station.

Fig. 1 shows the station layout. The hydrogen refueling station is mainly composed of the following five parts:

- Hydrogen metering area, located in the southeast of the station, comprising a hydrogen metering device;
- Trailer filling area, located in the middle of the east side of the station, includes three tube trailer spaces and two filling columns;
- Gas storage area, located on the west side of the trailer filling area, including 20MPa cylinder assemblies storage for gaseous hydrogen, two fixed 45MPa vessels for gaseous hydrogen storage, and two fixed 90MPa vessels for gaseous hydrogen storage.
- Compression area, located in the middle of the east side of the station, adjacent to the east side wall, including a 20MPa hydrogen compressor, a 45MPa hydrogen compressor and a 45MPa/90MPa hydrogen compressor;

- Hydrogenation area, located in the southeast of the station, consisting of three hydrogen fueling islands, equipped with two 35MPa hydrogen dispenser, one 70MPa hydrogen dispenser and one pre-cooler serving 70MPa hydrogen dispenser. A tent is provided in the hydrogenation area.

The charging station is mainly composed of the following two parts:

- Parking area, located on the west side of the station, including twelve charging parking spaces, seven ordinary bus parking spaces, and a photovoltaic panel is arranged on the tent of the charging parking space adjacent to the west side wall;

- Vehicle detection room, located on the north side of the station. The main function is to diagnose the hydrogen fuel cell vehicle through the diagnostic instrument, and to troubleshoot the vehicle when the hydrogen in the vehicle has been drained (hydrogen evacuation is not carried out in this station, and no discharge occurs during troubleshooting). Specifically, the function of vehicle detection room is refined by the operation unit.

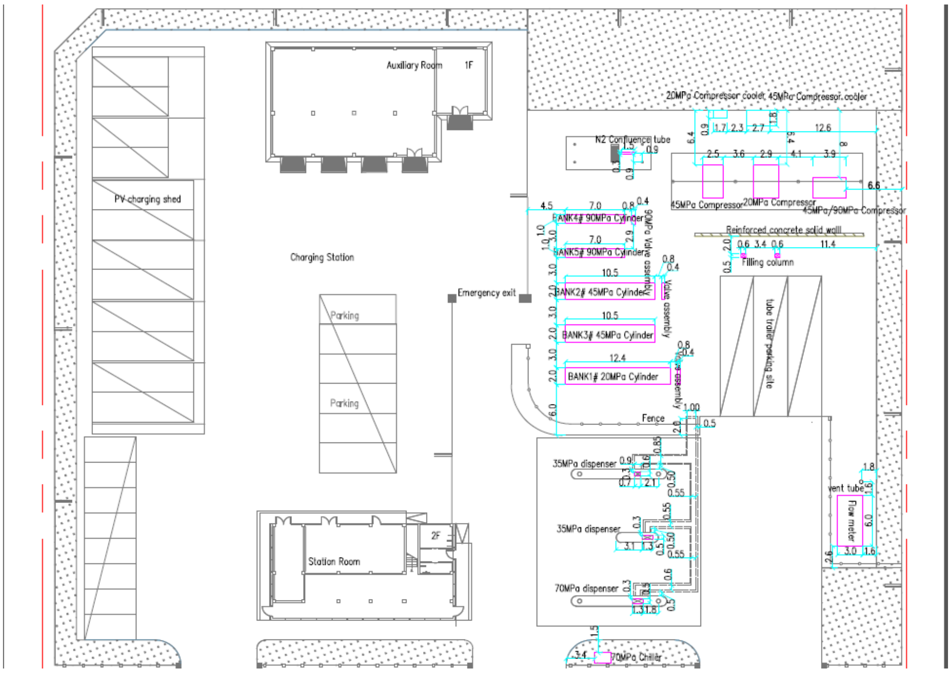

Figure 1. The layout plan of the station

The flowchart of the station is shown in Fig. 2. The entire fixed hydrogen refueling station mainly consists of hydrogen metering system, filling system (tube trailers for gaseous hydrogen), compression system (hydrogen compressor), gas storage system (cylinder assemblies storage for high-pressure gaseous hydrogen), gas sales system (hydrogen dispenser), control system, technical defense system (including infrared perimeter alarm, video monitoring, hydrogen leak alarm, flame detection alarm, lightning protection, static protection, water spray cooling, fire protection system, etc.), auxiliary system (instrument drive, purge, empty system, etc.).The gaseous hydrogen source outside the station is transported into the station through the pipeline. The pressure of the gas source is 1.5~2.0MPa, and the purity of hydrogen is 99.99%, which can meet the filling purity requirements of hydrogen fuel cell vehicles. After the hydrogen is metered, it is sent to the compressor through the hydrogen pipe in the station for pressurization.

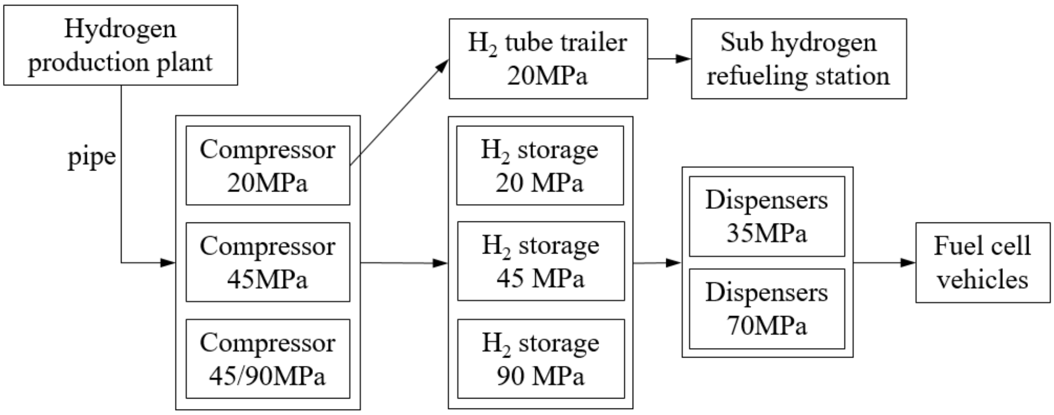

Figure 2. The flowchart of the station

The 20MPa compressor can pressurize hydrogen to 20MPa, and the 45MPa/90MPa compressor can pressurize hydrogen to two pressure levels of 45MPa and 90MPa, respectively. A part of the 20MPa hydrogen output from the 20MPa compressor can be filled with hydrogen tube trailers through hydrogen charging columns, a part of which is supplied to 45MPa compressor for recompression, and another part can be stored in 20MPa cylinder assemblies storage for gaseous hydrogen in the station. The 45MPa and 90MPa hydrogen output from the 45MPa/90MPa compressor are separately stored in the 45MPa vessels for gaseous hydrogen storage and the 90MPa vessels for gaseous hydrogen storage. The fixed hydrogen refueling station adopts a method of multi-stage gas extraction and hydrogenation, and according to the set internal pressure of each vessels, the fuel cell vehicle is filled in the order of low pressure to high pressure. A Piping & Instrument Diagram of the station is shown in Fig. 3. And three dimensional model of this station is shown in Fig.4

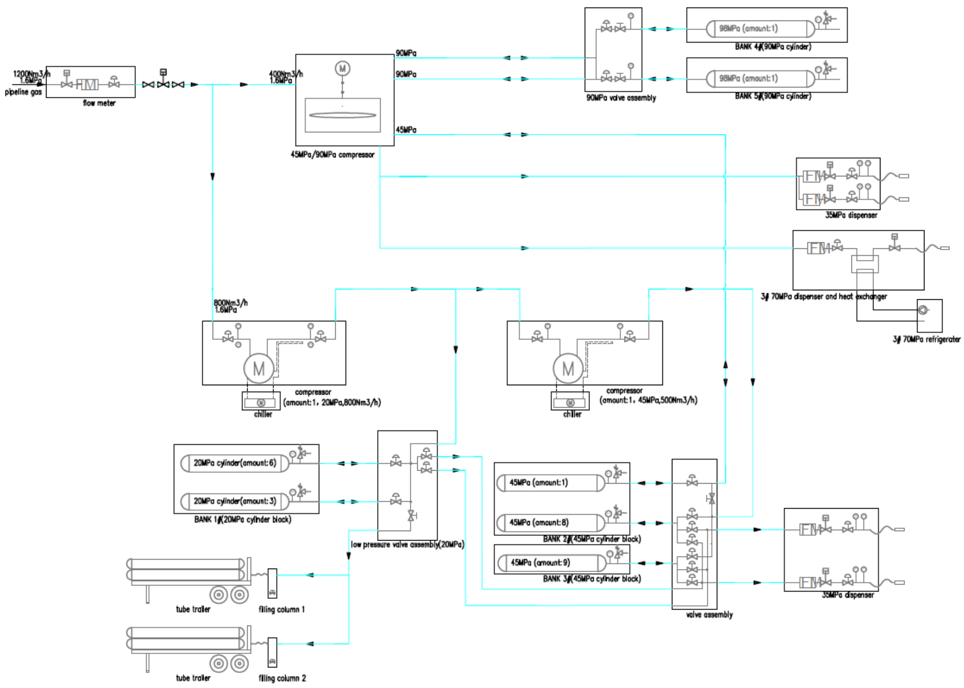

Figure 3. The P&ID of the station

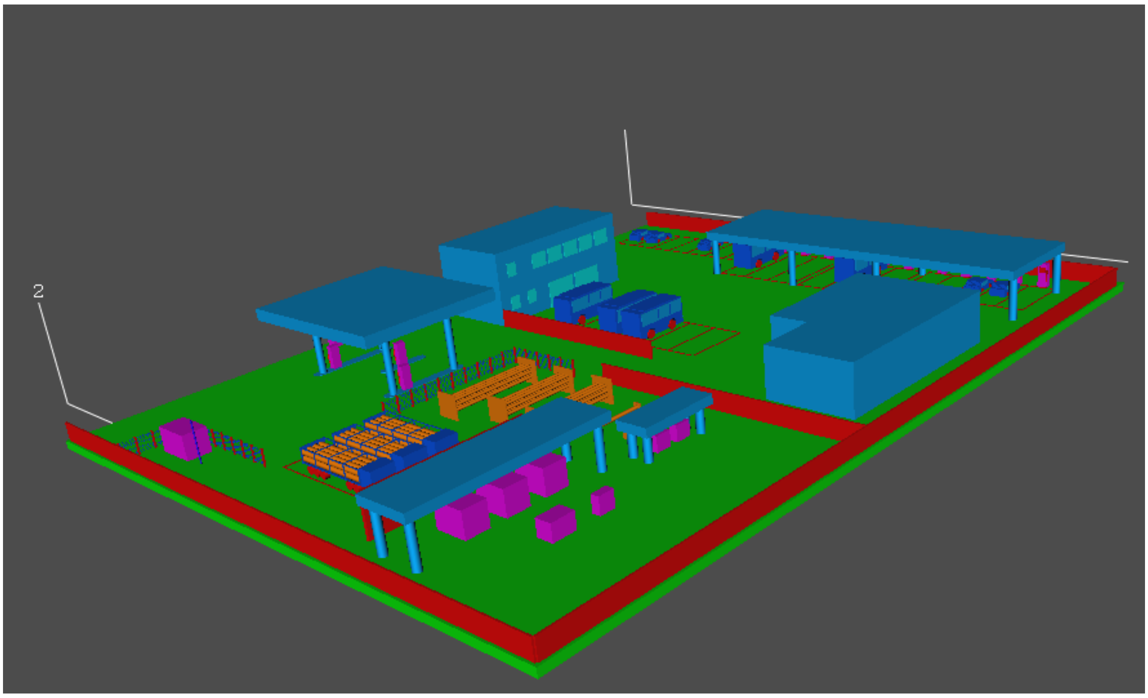

Figure 4. Three dimensional model of the station

4.0 RISK IDENTIFICATION AND PROBABILITY ANALYSIS

The hazard of the Shanghai Chemical Industry Park station is mainly from the compressed hydrogen. This is because hydrogen has flammable and explosive properties. Once the hydrogen equipment fails, a hydrogen leak accident occurs. The consequence of the accident depend on whether it is ignited and the time of ignition. Hydrogen will diffuse rapidly in the air if there is no ignition source. In the case of immediate ignition, a jet flame will occur. It would be lethal or harmful to people if they directly contact with the hydrogen flame, or are exposed to the high temperature and heat radiation with oxygen-depleted atmosphere. In the case of delayed ignition, the ignition may result in a strong vapour cloud explosion if the hydrogen is in a confined or congested area. And the overpressure generated can harm people or damage equipment. The QRA flow chart is shown in Fig.5. The hazards caused by thermal radiation and overpressure are considered.

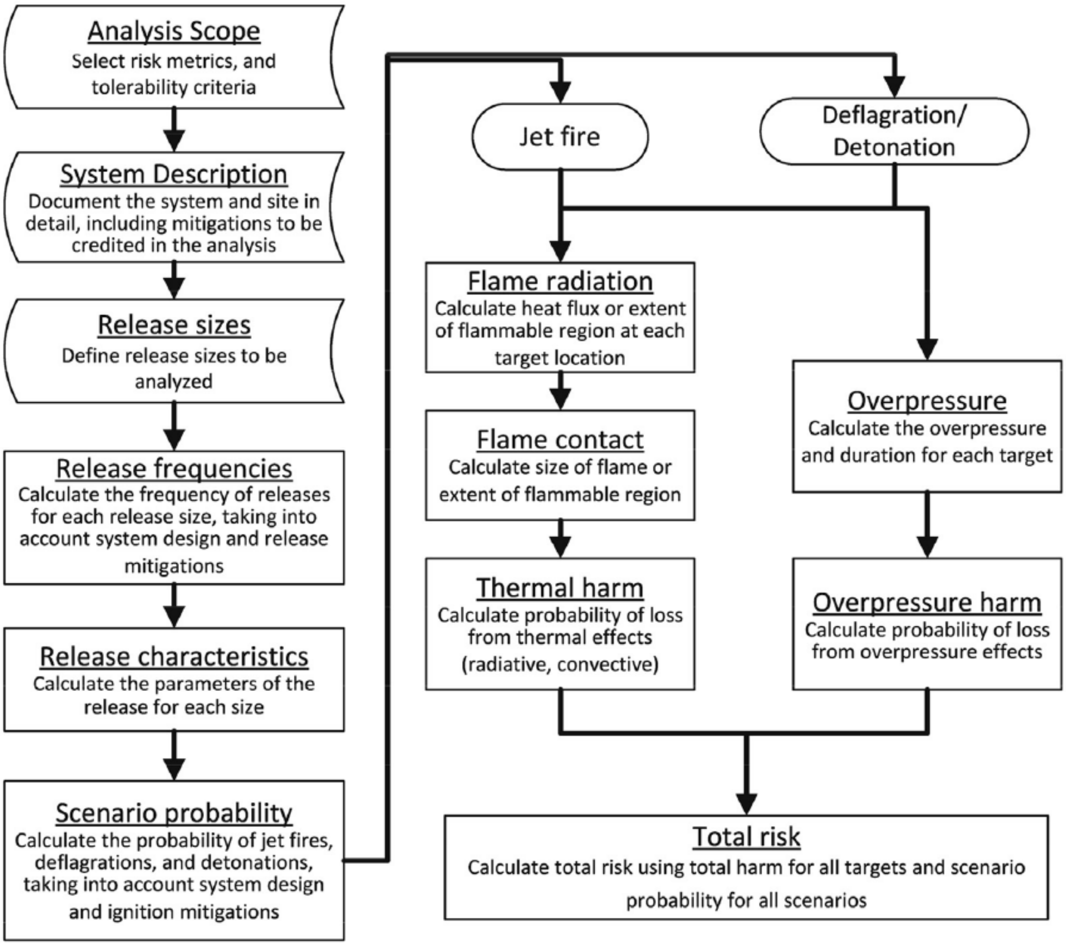

Figure 5. The QRA flow chart

All operating hydrogen equipment has the possibility of leakage. Therefore, the leakage location considered in this paper involves compressors, hydrogen dispenser, hydrogen storage tanks, tube trailers, hydrogen metering device and hydrogen pipeline. And leakage accidents are most likely to occur at equipment interfaces and valves, which are taken as hydrogen leakage locations when considering equipment leakage. Two ends and intermediate points of hydrogen pipeline are taken as hydrogen leakage locations. The release hole size is set to 1%, 10% and 100%, respectively of the pipeline area.

The European Industrial Gas Association (EIGA) directly uses general leakage statistics when selecting the failure frequency [21]. These data are mostly derived from the failure and accident statistics in the oil and gas industry. The direct use of these data for hydrogen leakage has certain problems. Because hydrogen has a smaller molecular volume than gas such as natural gas, it is more prone to leakage. The International Organization for Standardization (ISO) also adopts general leakage frequency data. However, unlike the EIGA, the general leakage statistics are not directly used. Instead, the relationship between the leakage frequency and the leakage aperture is linearly processed with logarithmic coordinates. The hydrogen leak frequency of American Fire Protection Association （NFPA） is developed from a Bayesian updating process using generic leak probabilities and available hydrogen data [22]. One of the great benefits of Bayesian analysis is that it can absorb the existing limited hydrogen energy equipment leakage data into the general leakage data, so that the analysis results are closer to the actual situation of the hydrogen energy infrastructure. Therefore, this paper adopts the leak frequency of the NFPA. All possible scenarios and corresponding parameters are listed in Table 1.

Table 1. Failure scenarios and related parameters

Equipment	Leakage location	Release pressure (MPa)	Release hole size	Failure frequency (/year)	Leakage direction
1. Metering device	Joints	2	2” pipe, 1%, 10% and 100% of the pipe	7.8×10^{-6} 6.96×10^{-6} 6.21×10^{-6}	4
2. Pipe work-1 (from metering device to compressors)	Both ends and intermediate points of the pipe.	2	1” pipe, 1%, 10% and 100% of the pipe	1.8×10^{-6} 9.12×10^{-7} 6.43×10^{-7}	2
3. Compressor (20 MPa)	Gas outlet	20	1” pipe, 1%, 10% and 100% of the pipe	8.01×10^{-3} 2.06×10^{-4} 3.04×10^{-5}	4
4. Compressor (45 MPa)	Gas outlet	45	3/4” pipe, 1%, 10% and 100% of the pipe	8.01×10^{-3} 2.06×10^{-4} 3.04×10^{-5}	4
5. Compressor (90 MPa)	Gas outlet	90	9/16” pipe, 1%, 10% and 100% of the pipe	8.01×10^{-3} 2.06×10^{-4} 3.04×10^{-5}	4
6. Tube trailer	Hydrogen filling port	20	1” pipe, 1%, 10% and 100% of the pipe	7.8×10^{-6} 6.96×10^{-6} 6.21×10^{-6}	4
7. Hydrogen storages tanks (20 MPa)	Joints or Valves	20	1” pipe, 1%, 10% and 100% of the pipe	6.98×10^{-7} 3.9×10^{-7} 2.09×10^{-7}	4
8. Hydrogen storages tanks (45 MPa)	Joints or Valves	45	3/4” pipe, 1%, 10% and 100% of the pipe	6.98×10^{-7} 3.9×10^{-7} 2.09×10^{-7}	4
9. Hydrogen storages tanks (90 MPa)	Joints or Valves	90	9/16” pipe, 1%, 10% and 100% of the pipe	6.98×10^{-7} 3.9×10^{-7}	4

				2.09×10^{-7}	
10. Pipe work-2 (from compressor to storages tank)	Both ends and intermediate points of the pipe.	20 or 45 or 90	1” or 3/4” or 9/16” pipe, 1%, 10% and 100% of the pipe	1.8×10^{-6} 9.12×10^{-7} 6.43×10^{-7}	2
11. Dispenser (35 MPa)	Hoses	35	9/16” pipe, 1%, 10% and 100% of the pipe	1.79×10^{-4} 1.6×10^{-4} 7.47×10^{-4}	4
12. Dispenser (70 MPa)	Hoses	70	9/16” pipe, 1%, 10% and 100% of the pipe	1.79×10^{-4} 1.6×10^{-4} 7.47×10^{-4}	4

The direct and delayed ignition probabilities of hydrogen using NFPA findings [23], which are shown in table 2. The equipment at the charging station may increase the ignition probabilities of hydrogen. But the charging facility and the hydrogen filling facility are separated by enclosure in this station. Therefore, the ignition probability of hydrogen does not increase.

Table 2. Hydrogen ignition probabilities adopted in NFPA risk analysis.

Hydrogen release rate (kg/s)	**Immediate ignition probability**	**Delayed ignition probability**
<0.125	0.8%	0.4%
0.125–6.25	5.3%	2.7%
>6.25	23%	12%

5.0 RESULTS AND DISCUSSION

Considering wind speed and direction, more than 200 hydrogen accident scenarios are simulated. The jet fire caused by 90MPa storage tanks leaking is shown in Fig. 6. The thermal radiation produced by jet fire will do harm to people.

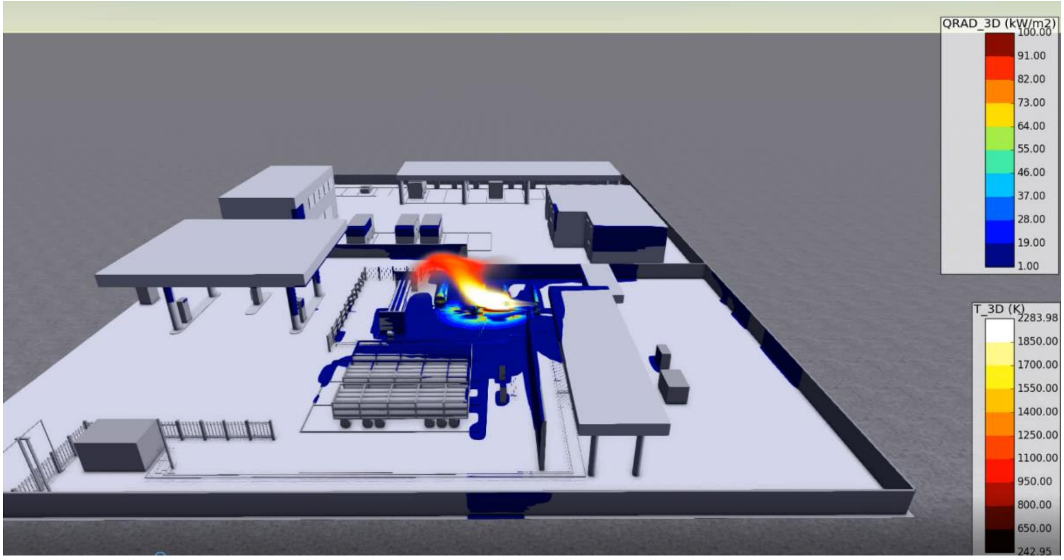

Figure 6. Jet fire and radiation contours near 90MPa storage tanks

Fig. 7 illustrates the radiation contours when all jet fire scenarios occur simultaneously. Obviously, this situation is basically not going to happen. But this figure can show the area where the hydrogen refueling station is at risk of thermal radiation. Heat radiation contours with frequency exceeding 10^{-6} /yr is shown in Fig. 8. As can be seen from Figure 6, the high probability scenario occurs essentially around the compressors and the dispensers. The blast-wall prevents damage from the tube trailer by the jet flame around the compressor. When considering the probability of occurrence, there is basically no jet flame around the hydrogen storage tank.

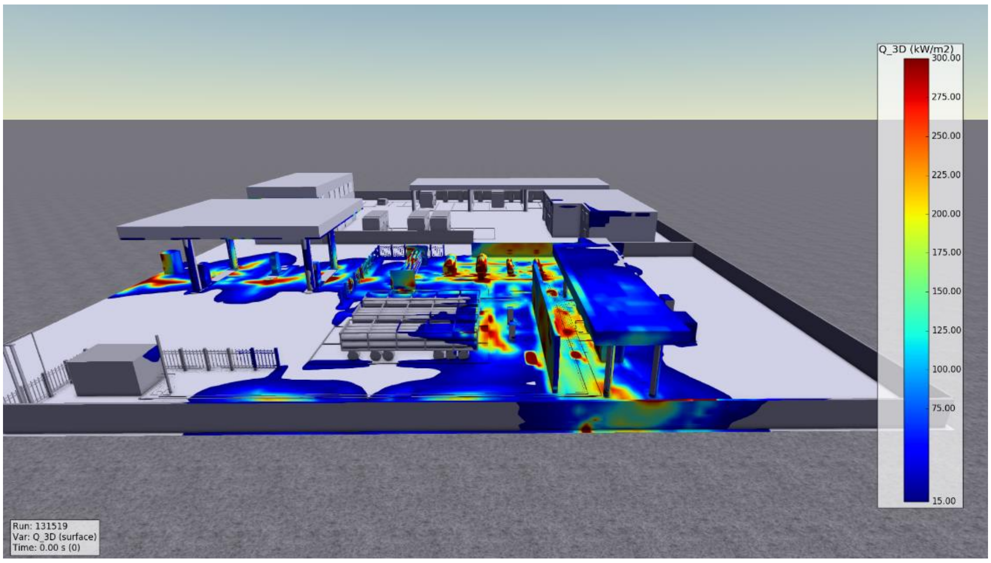

Figure 7. Radiation contours caused by jet fire

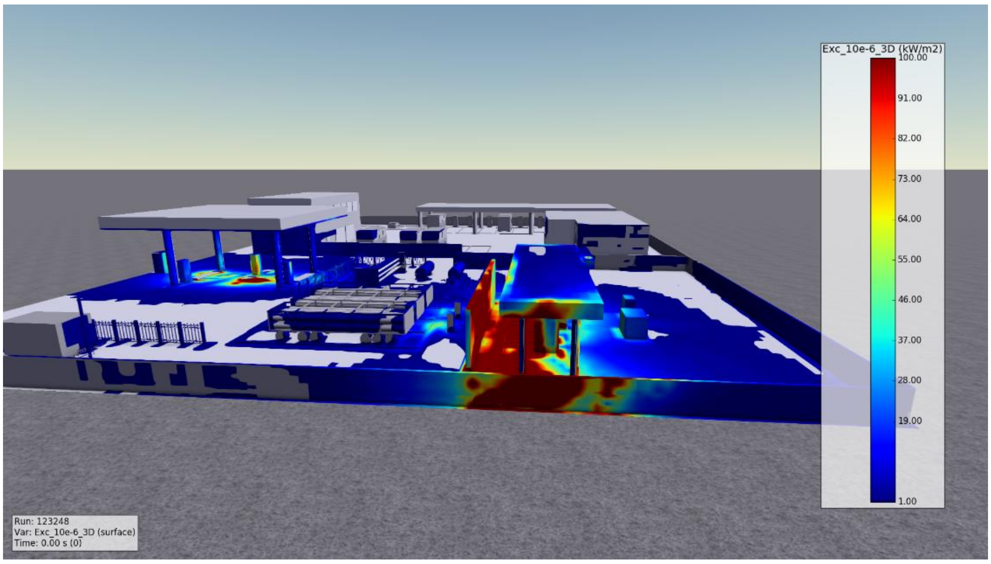

Figure 8. Heat radiation contours with frequency exceeding 1 *10^{-6} /yr

Harm criteria and human vulnerability model

To evaluate these hazards, corresponding lethal and harm criteria are required. The Sandia National Laboratories have tried to development of uniform harm criteria for use in quantitative risk analysis of the hydrogen infrastructure [24]. They present a survey of harm criteria that can be utilized in QRAs and makes recommendations on the criteria that should be utilized for hydrogen-related hazards. The risk of death is calculated based on the following formula [25]:

$$\text{Probit} = 38.48 + 2.56\, ln\, (t\, q^{4/3}) \qquad (1)$$

where t –exposure time, s; q –W m^{-2}.

T is assumed to be 20 s, q can be estimated from the CFD simulations. the frequency of fatality for a given scenario is the product of the event frequency and the probability of fatality. Fig. 9 shows the annual location-based fatality risk contours calculated from all the fire scenarios.

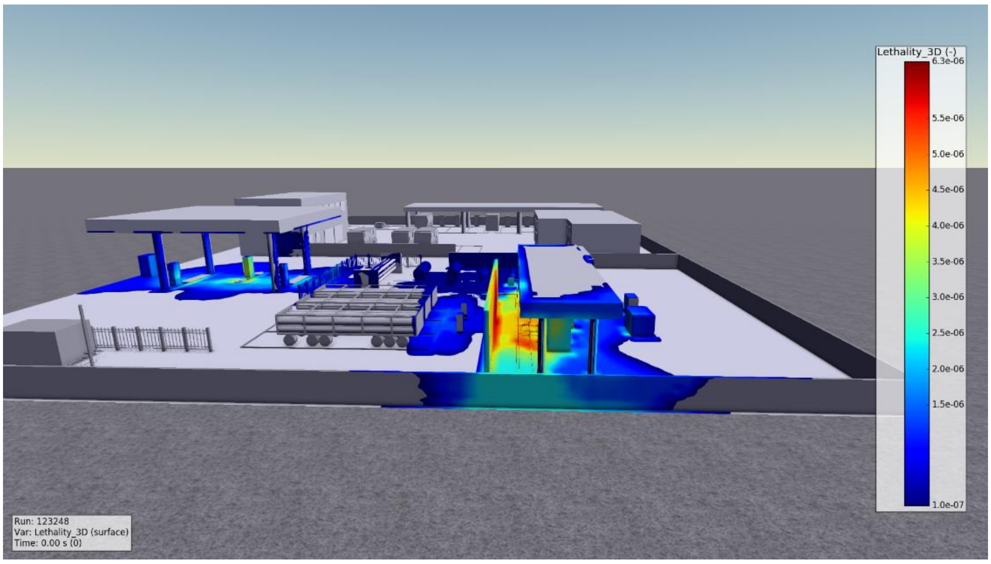

Figure 9. Fire radiation location based lethality frequencies

The corresponding accident consequence of direct ignition is jet flame. In the presence of a flammable cloud, delayed ignition may cause an explosion. The overpressure and thermal radiation produced by explosion will do harm to human body. The overpressure contours caused by explosion accidents with a probability greater than 1 $*10^{-6}$/year is shown in Fig. 10.

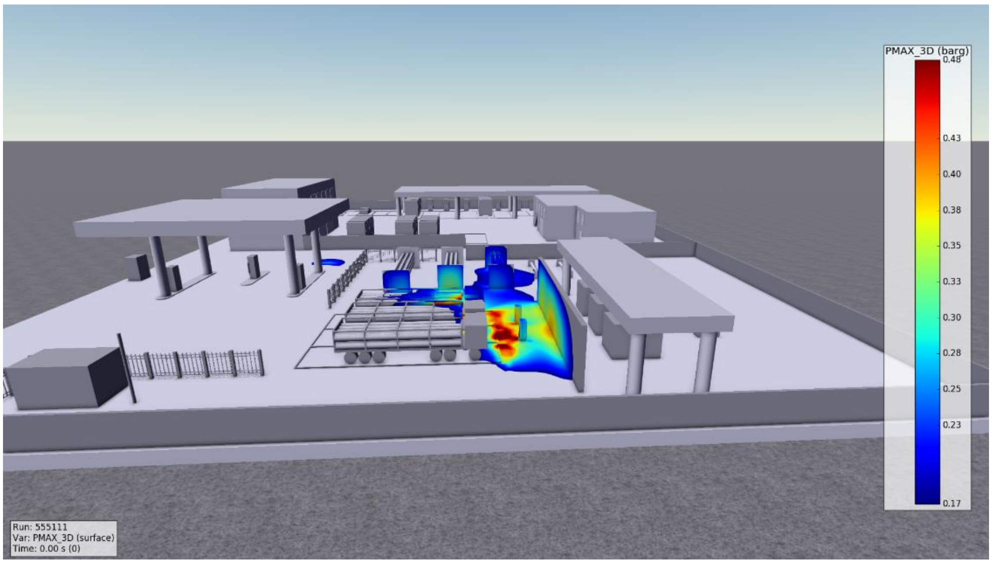

Figure 10. Overpressure contours with frequency exceeding 1 $*10^{-6}$/year

It can be seen from Fig. 10 that the hazard area caused by the explosion accidents is significantly smaller than which are caused by the jet fire accidents. This is because that the chances of vapour cloud explosions in the hydrogen refueling station are very small as the station is located in an open atmosphere with good ventilation. Only a single hydrogen leakage accident which is shown in Table 1 will eventually form an explosion.

We adopt two levels of criteria in the analysis. One is lethal criteria that represent for 100% fatality. The other is harm criteria that is defined as 1% probability of fatality. As for the overpressure effects, 48.3 kPa is conservatively assumed to result in lethality. 48.3 kPa is actually the threshold of internal injuries by blast and the lower threshold for 100% probability of fatality from missile wounds. As for the harm criterion for 1% fatality, an overpressure of 17 kPa is adopted, according to the Health and Safety Executive document. Based on the harm criteria and lethal criteria, the lethality frequencies caused by the explosion is shown in the fig. 11. And the maximum lethality frequency is $1*10^{-8}$. As can be seen from the figure, hydrogen is not easy to accumulate due to the open design. Therefore, the lethality frequencies caused by overpressure is very low.

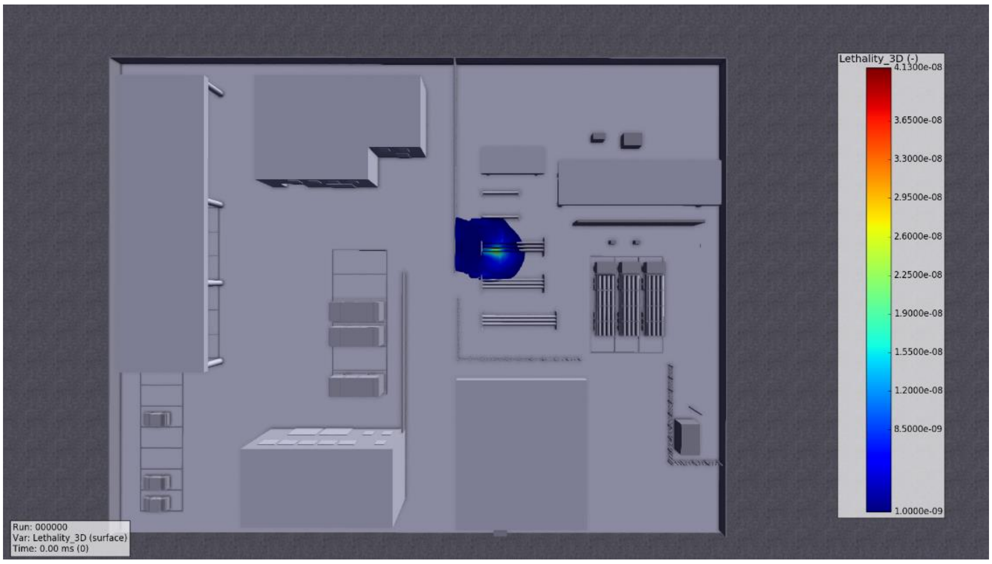

Figure 9. Overpressure location based lethality frequencies

Risk acceptance criteria

Countries and research institutions have been controversial about the acceptance criteria for individual risks, and the results of the evaluation will vary depending on the differences in risk acceptance criteria. Individual acceptable risk criteria of the International Energy Agency (IEA) have a value of 1 $*10^{-4}$/year and 1 $*10^{-5}$/year for staff and public at the station, respectively [26]. The source of this risk standard is actually based on the document [27] of the former Norwegian National Petroleum Corporation in 1995, mainly on the risk statistics of the former Norwegian National Petroleum Corporation in the field of oil and gas for many years. This value has also been adopted by ISO and Sandia National Laboratory [28]. The individual acceptable risk criterion of the EIGA is based on the average unexpected mortality rate in European society, which is 3.5 $*10^{-5}$/year [29], while the NFPA takes 2 $*10^{-5}$/year according to accident statistics of gas stations in the United States [30]. The European Hydrogen Integration Plan (EIHP2) laied down individual acceptable risk criteria for hydrogen refueling stations, which, like IEA, distinguishes employees from the general public, with values of 10^{-4}/year and 10^{-6}/year, respectively. Unlike other countries and organizations, Japan compares the consequences and probabilities with the risk matrix when performing risk assessment on hydrogen refueling stations. China's national standards also specify acceptable risks for individuals. The value is 10^{-5}/year for new installations.

The maximum lethality frequency is $6.3*10^{-6}$ in this station, which is less than all of the values mentioned above. That is to say, no matter what individual acceptable risk criteria is adopted, the risk of this station is acceptable.

As can be seen from Figure 9, the areas with higher lethality frequencies are located around compressors and dispensers. In particular, the risk of death in the compressor area is greatest. Compressor is major risk contributor to this station. Therefore, when the compressor does not need to be maintained, people should be avoided as far as possible from the compressor.

3D quantitative risk assessment considers the impact of obstacles on the consequences. The risk at the blast-wall (between compressor and tube trailer) may be miscalculated if performing a 2D quantitative risk assessment. In addition, the visualization of the evaluation results will help stakeholders to observe the hazardous areas of the hydrogen refueling station at a glance. This also facilitates the deployment of risk mitigation measures.

6.0 CONCLUSIONS

In this paper, a 3D quantitative risk assessment is performed on the Shanghai Chemical Industry Park hydrogen refueling station. The leakage frequency of hydrogen equipment and risk acceptance criteria for hydrogen refueling stations are discussed. The main conclusions are summarized below:

- No matter what individual acceptable risk criteria is adopted, the risk of Shanghai Chemical Industry Park hydrogen refueling station is acceptable. And the maximum lethality frequency is $6.3*10^{-6}$ in this station.

- The area around compressors has the greatest risk. Compressors are the major risk contributor due to highest leakage frequency in this station. People should be avoided as far as possible from the compressor.
- 3D quantitative risk assessment can consider the impact of obstacles on the consequences, which is not possible with 2D quantitative risk assessment.
- The lethality frequencies caused by overpressure is very low. More attention should be paid to the hazards caused by hydrogen fire accidents in daily operation.

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