RISK ANALYSIS ON MOBILE HYDROGEN REFUELING STATIONS IN THE WORLD EXPO SHANGHAI

Li Zhiyong[1], Pan Xiangmin[2, 3], Ma Jianxin[2, 3*]
1. Institute for energy Conservation, Jiaxing University, Jiaxing, 314001, PR China
lizhiyong000000@163.com
2. Clean Energy Automotive Engineering Center, Tongji University, Shanghai 201804, China
panxiangmin@tongji.edu.cn
3. School of Automotive Studies, Tongji University, Shanghai 201804, China
jxma@tongji.edu.cn

ABSTRACT

During the World Expo Shanghai, there were one hundred fuel-cell sight-seeing cars in operation at the Expo Site. The sight-seeing cars were not allowed to drive out of the Expo Site, and the stationary hydrogen refueling station was not permitted to build at the Expo Site for the sake of safety. A flexible solution to refuel the cars was the application of mobile hydrogen refueling stations. To better understand the hazards and risks associated with the mobile hydrogen refueling stations, a risk analysis was preformed to improve the safety of the operations. The risks to the station personnel and to the public were discussed separately. Results show that the stationary risks of the mobile stations to the personnel and refueling customers are lower than the risk acceptance criteria over an order of magnitude, so occupational risks and risks to customers are completely acceptable. The third party risks can be acceptable as long as the appropriate mitigation measures are implemented, especially well designed parking area and operation time. Leak from boosters is the main risk contributor to the stationary risks because of its highest failure rates according to the generic data and its worst harm effects based on the consequence evaluations. As for the road risks of the mobile stations, they can be acceptable as long as the appropriate mitigation measures are implemented, especially well-designed moving path and transportation time.

1. INTRODUCTION

In the past ten years, a number of fuel cell vehicle (FCV) demonstration programs have been conducted in China. In 2003, a fuel cell bus demonstration was launched by the Chinese government in collaboration with the Global Environmental Facility and the United Nations Development Program. In 2008, a fuel cell car & bus demonstration was carried out during Beijing Olympics. In 2009, a demonstration project supported by the Chinese government began to promote new energy vehicles in thirteen cities throughout China, targeting at public transportation such as taxis and buses. In 2010, a multi-category FCV demonstration was conducted during the World Expo Shanghai, with a range of fuel cell vehicles from larger size such as bus, to small size such as sight-seeing cars. After the world Expo, FCV demonstrations were accelerated and several FCV demo projects were performed in different cities such as in Guangzhou during the Asian Games and in Shenzhen during the World University Games, etc.

Among the demonstrations, the FCV program during the World Expo Shanghai is considered as the most successful demonstration, not only because of its coincidence with high-profile public events and attracts millions of people's interest towards hydrogen-powered vehicles, but also because of the safety and successful operation of a hydrogen supply network, which includes one by-product hydrogen purification plant, several hydrogen tube trailers, two stationary hydrogen refueling stations(stationary HRS), and two mobile hydrogen refueling stations(mobile HRS). The network served 196 fuel-cell vehicles during the Expo, including 6 fuel-cell buses, 90 fuel-cell cars and 100 fuel-cell sight-seeing cars. A diagram of the hydrogen supply network is shown in figure 1 [1]. In the hydrogen supply network, the two stationary HRS can fill fuel cell cars and buses directly. However they can not reach the fuel cell sight-seeing cars that were not allowed to drive out of the Expo Site. A flexible solution to refuel the sight-seeing cars was the application of mobile HRS. The mobile HRS can move into the Expo Site to refuel the sight-seeing cars and then leave for Expo HRS to replenish hydrogen.

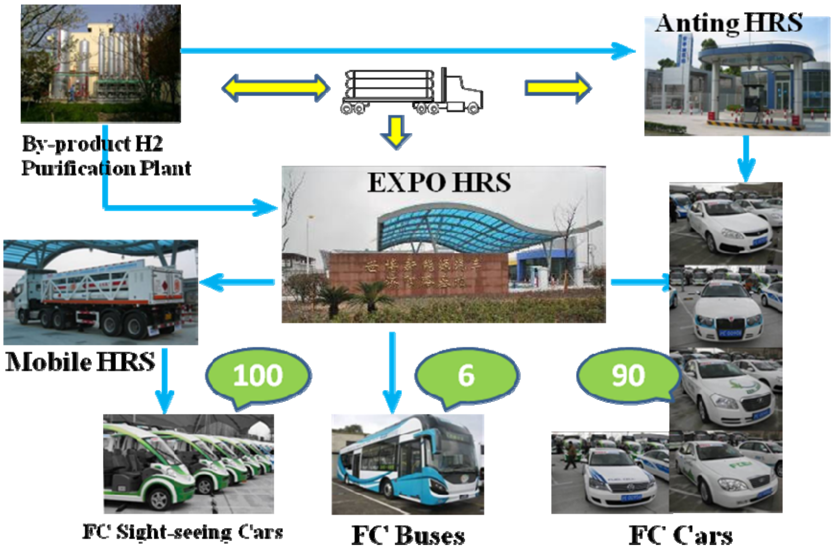

Figure 1 Hydrogen supply network during the World Expo [1]

There were two mobile stations in operation to refuel the sight-seeing cars during the World Expo. The designed maximum pressure of the mobile HRS can be 43.8MPa, which is a very high pressure that requires special safety approval. One critical concern is the mobile risks associated with the moving path and its vicinity, the other public concern is the stationary risks in refueling operation at the Expo Site. To better understand the hazards and risks associated with the mobile HRS, a risk analysis is preformed to facilitate communications with the government authorities and to improve the public awareness in the safety of the stations.

In risk assessment studies there are generally three main types of risks considered: (1) Occupational risks; (2) Community risks; and (3) Economic risks. Each category has its own risk acceptance criteria. The economic risks are usually covered by insurance and not our concern. The main concern to the introduction of a mobile HRS to public is its risks to people, including occupational risks and especially community risks. For mobile HRS there are two kinds of community: the refueling customers inside the filling area and the people in the vicinity of the parking site and moving path of the station. If the occupational risks are defined as the first party risks, then the risks to the refueling customers can be defined as the second party risks, and the risks to people in the vicinity of the parking site and moving path of the station can be perceived as the third party risks. The risks to these three parties will be studied in this paper.

2. DESCRIPTIONS AND OPERATIONS OF MOBILE HYDROGEN REFUELING STATIONS

The two mobile HRS operated during the Expo are the third generation of transportable hydrogen facilities developed by Tongji University and Shanghai Sunwise Energy System Company. The first and second generations were developed in 2004 and 2007, respectively, to support the research and development of FCV in Shanghai from 2004 to 2009. The mobile HRS was originally designed to help support early hydrogen FCV initiatives, and later turned to help establish hydrogen refueling network in Shanghai. With the support of the National High Technology R&D Program, the third generation of mobile HRS has been greatly improved in terms of filling efficiencies, safety barriers, operation protocols, and other key performances such as compression capabilities.

2.1 General descriptions of the mobile hydrogen refueling stations

A snapshot of the mobile HRS is shown in figure 2. It is a truck-like vehicle that consists of several subsystems, including hydrogen storage system, compression system, dispensing system and safety systems. Details can be seen in figure 3. The mobile HRS storage consists of 6 cigar-like pressure vessel tubes with a volume of approximate 520 liter each and contains compressed hydrogen pressure no more than 43.8MPa. The estimated hydrogen storage capacity is approximately 90 kilograms. The tubes are interconnected by a group of valves and pipes, which are connected to dispensing system to fill hydrogen at 35MPa. In filling operation, the tubes can be divided into three categories: one high-pressure tube, two medium-pressure tubes and three low-pressure tubes. This kind of three-division operation will help reduce the amount of residential gas in the hydrogen tubes and improve the filling capacity of the mobile HRS.

Figure 2 A glance of the mobile HRS

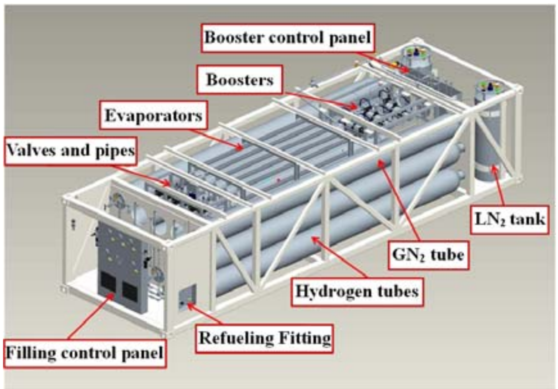

Figure 3 Components of the mobile HRS

For the compression system, the boosters, functioning as a compressor, not only can increase hydrogen pressure in the hydrogen tubes to meet the filling pressure requirement, but also can draw hydrogen from the tubes and immediately fill the cars through dispensers. Unlike compressors used in stationary refueling station, the boosters are not powered by electricity but by the nitrogen powered pneumatic tools, in which risks from electrical devices are completely removed. The nitrogen system, including one high pressure vessel tube, two liquefied nitrogen tanks, a group of vaporizers, and other assistant accessories has multiple functions. It drives the boosters to increase pressure in hydrogen tubes, blows residual hydrogen in maintenance operations, and dilutes hydrogen concentration in accidental hydrogen releases.

The dispensing system mainly contains two dispensers, several different valves, a few of indicators such as flow meters, pressure and temperature sensors, a control panel and other connecting components. The designed continuous filling capacity is more than 40kg without overheating above 85°C. When refueling, hydrogen will be drawn from the hydrogen tubes through hydrogen pipes to the dispenser, and fill cars to a maximum pressure of 35MPa. The estimated filling time for a sight-seeing car is less than 3 minutes.

As for the safety system, it is not a separate system that can be seen clearly like other systems. The safety system is embedded throughout the mobile HRS. All the relief valves, safety valves, rupture discs, breakaway couplings, pressure and temperature indicators, hydrogen detectors and emergency shut down devices and all other safety-related accessories work together as a barrier system to safeguard the mobile HRS. Besides the hardware, the software including operation protocols and safety management actually plays a vital role to achieve a safety operation. The operation protocols, written in the filling codes, control the filling process in a safety condition. As for the safety management, there are a lot of details. For example, both the filling operators and vehicle drivers are specially well-trained with safety licenses, and in the station parking area ordinary people can not access to the station unless with special permission, and caution signs “No Smoking or Open Flame” must be installed to warn against unsafe practices, etc. All of these software can be considered as part of the safety system.

2.2 Moving path and parking sites of the mobile hydrogen refueling stations

Figure 4 highlights the moving path and parking locations of the two HRS during the World Expo. The vulnerable targets along their moving path should be the road vehicles，side walkers and other populated area in the vicinity of the moving path such as residential areas. It was difficult for the mobile HRS to get an ordinary approval to be on road because the designed maximum storage pressure was 43.8MPa, much higher than 20MPa, the upper limit on road restricted by the transportation law in China. Therefore, a special permission for the mobile HRS was issued under a few terms and conditions, including the well-designed moving path and time of the mobile HRS, two given safety parking sites, and several sound emergency response plans, etc. The moving path should pass by the smallest population density area, and the moving time must be at midnight with less road traffic and few people activity. There were two parking sites, one located at the Expo stationary hydrogen station, the other located at the parking area of the sight-seeing cars inside the Expo Site. Both sites were specifically approved by the authorities, and the siting requirements accorded with the Shanghai provincial regulation DGJ08-2055-2009[2] and China national code GB 50177-2005[3]. They also met the new national code GB50516-2010[4], which was issued a year later after the sitting work.

Figure 4 Moving path and parking sites of the mobile HRS

2.3 Routine operations of the mobile hydrogen refueling stations

The task of the two mobile HRS was to refuel 100 fuel cell sight-seeing cars during the World Expo, so the routine operations were to replenish hydrogen in the Expo stationary hydrogen station outside the Expo Site, and then moved into the Expo Site to refuel the sight-seeing cars, and then left for Expo stationary hydrogen station to replenish hydrogen again. During the Expo days from May 1st to October 31st, the routine operation of the HRS followed almost the same schedule. Every midnight at about 23:30, the two hydrogen HRS, with storage pressure around 42MPa, moved out of the Expo stationary hydrogen station and followed the exact designed moving path to the Expo Site. A half hour later, they entered into the Expo Site and stayed at their given parking place. From midnight to about 5:00 next morning, each mobile HRS filled 50 fuel cell sight-seeing cars to a maximum pressure of 35MPa. Almost five hours of parking were sufficient for the mobile HRS to finish their filling task. As the estimated filling time per car was less than 3 minutes, the total filling duration for all of the sight-seeing cars would be less than 75minutes. Later, at about 5:00 in the morning, the two mobile HRS moved out of the Expo Site and left for the Expo stationary hydrogen station to replenish hydrogen again. The replenish operation should be done before noon. In the whole afternoon, both mobile HRS parked inside the northeast corner of the Expo stationary hydrogen station until 23:30 to start next routine operation. Figure 5 shows two typical routine operation of the mobile HRS including both replenishing and filling operations. During the 184 days of the Expo, statistics show there were totally more than 7600kg of hydrogen filled to the sight-seeing cars in overall 15251 times of filling. This relatively heavy duty work might increase risks of equipment failures and unintentional releases, so regular daily check and maintenance work was implemented for the mobile HRS every afternoon. During the Expo days, no major accidents were recorded except for a few minor leakage incidents, causing no harm to people and no damage to equipment.

Replenishing hydrogen in Expo stationary station

Filling sight-seeing cars inside the Expo Site

Figure 5 Typical routine operation of the mobile HRS including both replenishing and filling

3. MODELING ASSUMPTIONS AND INPUT DATA

3.1 Possible consequences of hydrogen releases

Releases of hydrogen can be either instantaneous or continuous. The "instantaneous release" is a sudden violent burst high pressurized hydrogen storage vessel. The result is a rapid depressurization of the hydrogen and subsequent dispersion of the hydrogen cloud. Ignition of the hydrogen cloud will result in a flash fire. In the case of a catastrophic rupture of a cylinder, the contents of only one cylinder will be instantly released. It is not expected that several cylinders will rupture simultaneously. The rupture of a cylinder can cause a domino effect. As the peak overpressures are not likely to coincide, the effects of the domino event will not be considerably larger than the effects of a single event [5]. The “continuous release” is leakage event from the high pressure hydrogen equipment. The result is a hydrogen jet and subsequent dispersion of the hydrogen jet. The consequences of a hydrogen jet will depend on the time of ignition. Direct ignition results in a jet fire, while delayed ignition results in a flash fire.

The vapor cloud explosion is not considered in modeling because no confined area or semi-confined spaces is expected in the vicinity of both the parking sites and moving path. Both parking sites are open-space design and the moving path of mobile HRS are specifically planned. On the other hands, even though there are chances to have vapor cloud explosions, the likelihood will be very small, according to event tree probability analysis. Ignoring the small probability event will not lead to underestimate the overall risks of mobile HRS. Besides, it is noticed that both the ISO [6] and NFPA [7] adopt flash fires and jet fires as the representative consequences in their determination of safety distances or separation distances for hydrogen equipment.

3.2 Scenarios and input data

The scenarios and input data showed in Table 1 are used for the risk calculations for the mobile HRS. The scenarios are chosen based on previous HAZOP studies. The two stations are assumed to do their duty work every day during the 184 day of the Expo. Each duty is assumed to be at full capacity, which means to fill 100 sight-seeing cars from empty to full every day, though in reality some sight-seeing cars are filled from half-empty to full. The initial frequencies of failure are taken from the Purple Book [8]. It is difficult to find failure frequencies of the booster. Instead, the failure rates of reciprocating compressors are adopted. In UK data base [9], the highest failure rates of reciprocating compressors are at 6.50×10^{-2} per year. Catastrophic failure of the booster is assumed to take up 1/10 of the total failure rates and others are attributed to leak scenarios.

For the scenarios of catastrophic rupture, it is not likely two or more tubes will burst simultaneously, so the maximum hydrogen released instantly can be approximately assumed to be the inventory of one tube. In case of domino effects, the most possible scenarios would be the leakages from tubes in the vicinity of the burst vessel. The likelihood of another catastrophic rupture is very small. For the scenarios of leakages, the worst case should be that hydrogen is released continuously till the whole inventory of all tubes is emptied because of the interconnected design.

The ignition probabilities are also based on the Purple book suggestions. The direct ignition probability of an instantaneous and a continuous release is assumed to be 0.4 and 0.1, respectively. The delayed probability for any gaseous flammable release is assumed to be 0.2. For a delayed ignition, the probability of a flash is 100% and no vapour cloud explosions are considered.

3.3 Harm criteria and risk acceptance criteria

Exposures to hydrogen flames or heat radiation can results in burn injury or lethality. For flash fire, it is assumed that 100% lethality in the flame envelope and 0% lethality outside the envelope. For heat radiation, it is assumed that 100% lethality for 35Kw/m^2 and f(Q,t) lethality for lower radiation levels.

$$\mathrm{f}(Q,t) = 0.07\times[1+\mathrm{e}rf\left(\frac{-41.38+2.56\times\ln\left(\mathrm{Q}^{4/3}\times\mathrm{t}\right)}{\sqrt{2}}\right)],\ \text{where: } erf(x)=\frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt$$

Q-heat radiation, t-exposure time

Risk acceptance criteria are taken from EIHP2 document of Risk Acceptance Criteria for Hydrogen Refueling Stations [10]. For the first party risks, the individual probability of fatality caused by the hydrogen-process related events on the refueling station should not exceed 10^{-4} per year. For the second party risks, the probability of a major accident causing one or more fatalities among customers shall not exceed 10^{-4} per year. For the third party risks, no residential area, third party working premises or public assembly area outside the station shall be exposed to fatal exposure levels caused by major accidents at the station of probability greater than 10^{-6} per year. The unacceptable and acceptable societal risk criteria are 10^{-3}∗(Number of fatalities)$^{-2}$ per year and 10^{-5}∗(Number of fatalities)$^{-2}$ per year, respectively. Risks between the two criteria are the ALARP (As Low As Reasonably Practicable) region.

Table 1 Model input data and assumptions

Item	Scenario number and description	Release pressure (bar)	Release hole size (mm)	Max. quality released (kg)	Initial failure frequency
Six high pressure vessel tubes	1 Catastrophic failure of tube	43.8	N/A	15	1×10^{-6} per year per tube
	2 Leak from tube trailer fittings	43.8	8	90	1×10^{-5} per year per fitting
Group of Pipes and valves	3 Full bore rupture of pipes	43.8	8	90	1×10^{-6} per year per meter
Boosters	4 Catastrophic failure of booster	43.8	N/A	1	6.5×10^{-3} per year per booster
	5 Leak from booster	43.8	8	90	5.85×10^{-2} per year per booster
Two dispensers	6 Catastrophic failure of dispenser	35	N/A	0.5	1×10^{-5} per year per dispenser
	7 Full bore rupture of flexible hose between dispenser and vehicle	35	6	90	4×10^{-6} per hour of filling
Fuel cell sight-seeing cars	8 Catastrophic failure of hydrogen storage vessel	35	N/A	0.8	1×10^{-6} per year per cylinder
	9 Leak from vehicle fittings	35	3	0.8	1×10^{-5} per year per fitting

4. RESULTS AND DISCUSSIONS

Consequence calculations are carried out with Process Hazard Analysis Software Tool (PHAST) from Det Norske Veritas. The calculations are done in three steps including discharge calculations, dispersion calculations and flammable effects calculations. Then sequence frequency evaluations are performed to achieve the probabilistic outcome of each consequence. Finally, the outcomes from consequence modelling and sequence frequency evaluation are combined together to form risk values, which will be compared with the risk acceptance criteria to draw conclusions.

4.1 Stationary risks in the parking site

Figure 6 shows the risk contour of the two HRS in the Expo Site. There are no 10^{-4} risk contours in the map, showing station personnel near the station shall not be exposed to fatal exposure levels greater than 10^{-4} per year. A risk transect from the west to the east across the centerline between two HRS shows the maximum risk level is no more than 8×10^{-6} per year, as shown in figure 7. Risk to station personnel is acceptable, compared with the occupational risk acceptance criteria of 10^{-4} per year.

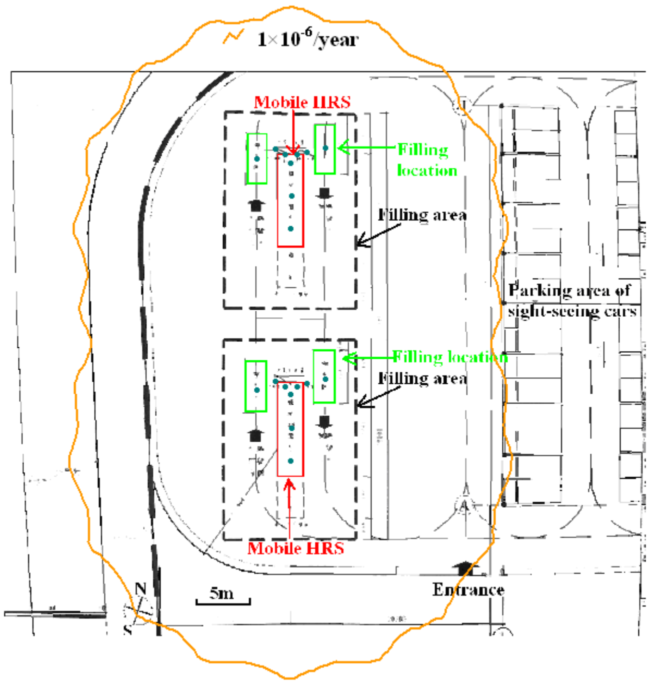

Figure 6 Risk contours of the two HRS in the Expo Site

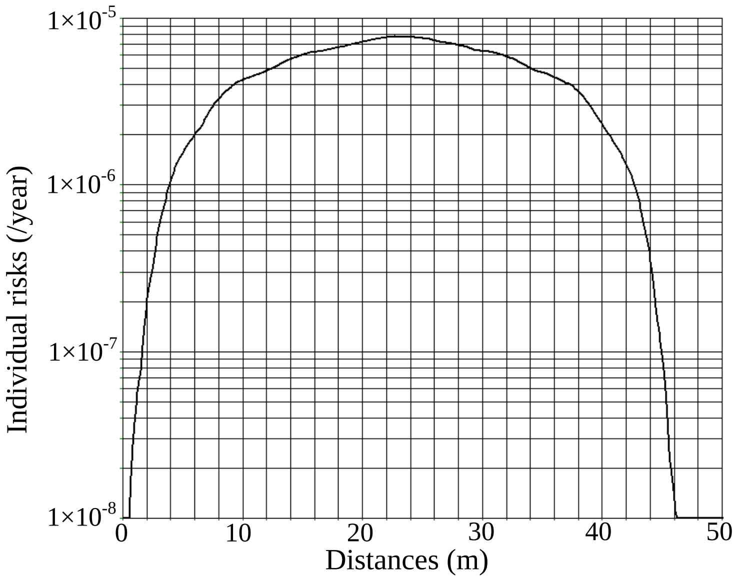

Figure 7 Risk transect from the west to the east across the centreline between two HRS

Further risk contribution results are listed in table 2. It can be seen that leak from boosters contributes the most to the overall risks, almost 69%. Leak from tubes contributes the second to the overall risks, approximately 27%. Full bore rupture of pipes ranks the third place, less than 4%. Failure of the boosters is the most critical accident of all. It is understandable that the leak from the boosters dominate the risks due to the highest failure rates of the boosters as shown in table 1. Additionally, a summary of consequence evaluation, expressed as the lethal distances in figure 8, shows that leak events from tubes, pipes and boosters lead to the longest lethal distances of 25.5m and 20.5m for flash fire and jet fire, respectively. These three scenarios are just the three main risk contributors listed in table 2.

Table 2 Individual risk contributions to the center of filling area

	Risks(/year)	Percentage (%)
Leak from boosters	5.26×10^{-6}	68.8
Leak from tubes	2.05×10^{-6}	26.8
Full bore rupture of pipes	0.27×10^{-6}	3.5
Others	0.07×10^{-6}	0.9
Total	7.65×10^{-6}	100

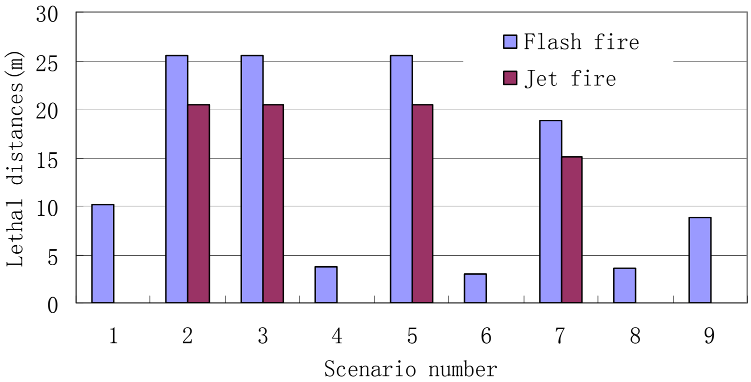

Figure 8 Summary of consequence evaluation

As for the refueling customers, table 3 lists the probability of a major accident causing one or more fatalities among customers. It is assumed that there are four car drivers located in the filling area at the same time. The probability of a major accident causing one or more fatalities among refueling customers is no more than 9×10^{-6}/year, which is caused by leak from boosters, the dominant event that contributes to more than 55% societal risks of all. Therefore, risks to the refueling customers are acceptable. It is also noticed that even the total probability of major accidents causing one or more fatalities among drivers is no more than 1.63×10^{-5}/year, lower than the risk acceptance criteria of 10^{-4}/year. The refueling sites are adequately safe for the refueling customers.

Table 3 Probability of a major accident causing one or more fatalities among customers

	Risks(/year)	Percentage (%)
Leak from boosters	8.99×10^{-6}	55.2
Leak from tubes	3.24×10^{-6}	19.9
Catastrophic failure of boosters	2.96×10^{-6}	18.2
Full bore rupture of pipes	0.43×10^{-6}	2.6
Catastrophic failure of dispensers	0.41×10^{-6}	2.5
Leak from vehicle fittings	0.20×10^{-6}	1.2
Others	0.07×10^{-6}	0.4
Total	1.63×10^{-5}	100

As for the third party risks, the risk contour of 10^{-6}/year is shown in figure 6. It is noticed that the risk contour covers a little bit north and south road, in which the Expo visitors may pass by in the daytime. However, the filling facilities are only parked at night, approximately from midnight to five o'clock next morning. During this period, there are absolutely no tourists at all. Thus, risks to the third party are acceptable because there is no third party inside the risk contour of 10^{-6}/year.

4.2 Road risks

In the transportation, the boosters do not work and thus are not likely to fail. The most possible failures should come from high pressure tubes and related parts connected to them. On the basis of this assumption, the individual risk contours of the two mobile HRS are shown in figure 9. There are no visible contours of 10^{-6}/year from the HRS in the map, showing that the risk caused by the two mobile HRS increases the background risks by no more than 10^{-6}/year. Risks on the road can be acceptable along the moving path of the mobile HRS. The risk transect across the moving path shows the maximum IR risk is no more than 2×10^{-8}/year, much lower than the risk acceptance criteria of 10^{-6}/year, showing that the influence of the mobile HRS on the background risks of the road is very small. Even if during the daytime when the heavy traffic is conservatively assumed to increase the failure rate by ten times, the decuple individual risk would be still less than the risk acceptance criteria. However, the societal risks may not be the case because of the increased population density for the daytime.

Figure 9 Risk contours along the moving path of the mobile HRS

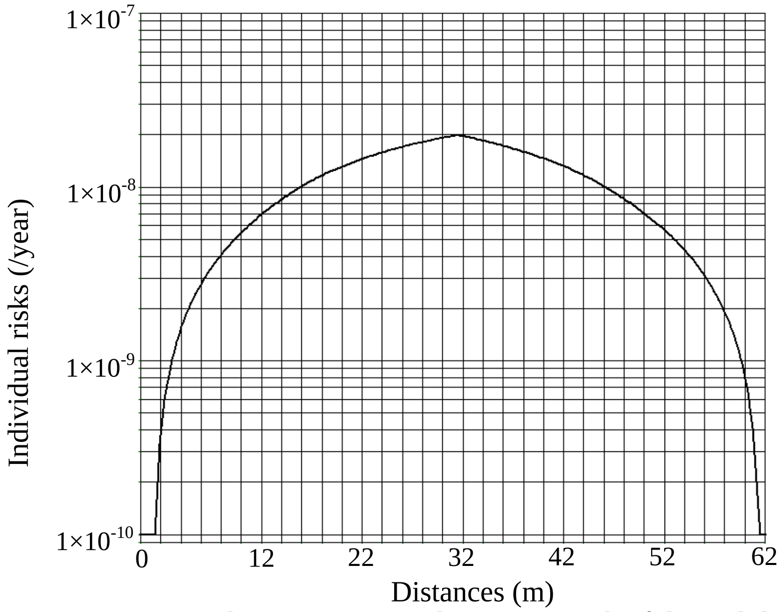

Figure 10 Risk transect across the moving path of the mobile HRS

On the basis of the conservative assumption of 100 people per 100 meters along the road at midnight and 1000 people per 100 meters along the road in the daytime, it is supposed the population density in the vicinity of the moving path is 0.001person /m^2 and 0.01person/m^2 for midnight and daytime, respectively. The F-N curves are shown in figure 11. It can be seen that at midnight, the societal risks for the road transportation are lower than the acceptable risk criterion, while in the daytime, the risks are located in the ALARP region, indicating that further cost-benefit analysis is necessary to judge if additional safety measures are needed. In engineering practice, it would be wise to directly choose the night operation to ensure safe transportation, rather than do further investigations for daytime operation.

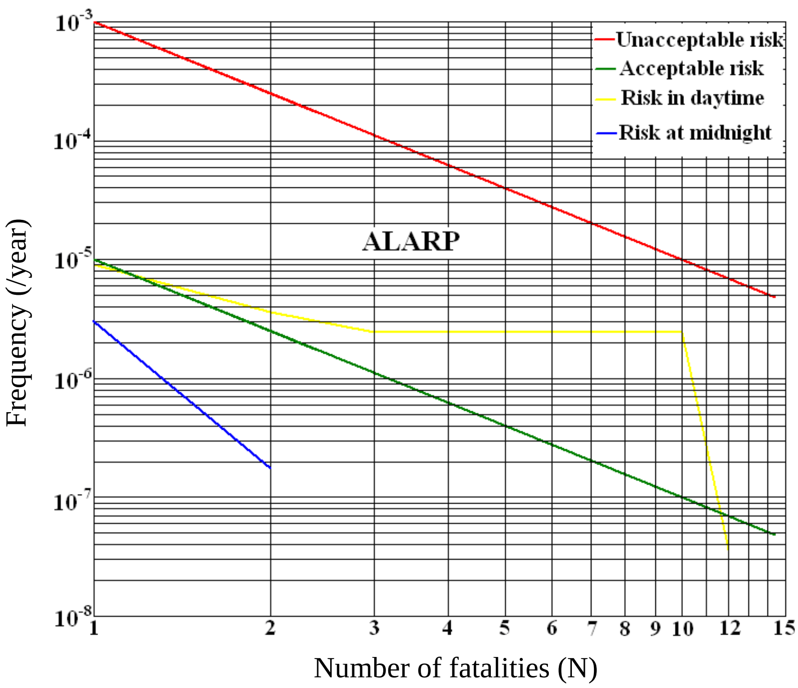

Figure 11 Societal risks for different operation time

For the same reason, it would also be vitally important to specify a moving path in the area with low population density. In our case, the population density in the vicinity of the moving path is much less than 0.001person /m^2 at midnight and the societal risks are completely acceptable.

5. SUMMARY

This paper introduces the operations of mobile hydrogen refueling facilities during the Expo and presents a risk assessment on them. The main results can be summarized as follows.

(1) Stationary risks of the mobile stations to the personnel and refueling customers are lower than the risk acceptance criteria over an order of magnitude, so occupational risks and risks to customers are completely acceptable. The third party risks can be acceptable as long as the appropriate mitigation measures are implemented, especially well designed parking area and operation time.

(2) Leak from boosters is the main risk contributor to the stationary risks because of its highest failure rates according to the generic data and its worst harm effects based on the consequence evaluations.

(3) Road risks of the mobile stations can be acceptable as long as the appropriate mitigation measures are implemented, especially well-designed moving path and transportation time.

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