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Risk Assessment of Vapor Cloud Explosions in a Hydrogen Production Facility with Consequence Modeling

Esmaeil Zarei (MSc)[a], Mohammad Javad Jafari (PhD)[b*], Naser Badri (PhD)[c]

[a] Neyshabur Student Research Committee, Neyshabur University of Medical Sciences, Neyshabur, Iran

[b] Department of Occupational Health Engineering, School of Health, Shahid Beheshti University of Medical Sciences, Tehran, Iran

[c] Department of Chemical and Petroleum Engineering, Sharif University of Technology, Tehran, Iran

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**** Correspondence***
Mohammad Javad Jafari (PhD)
Tel:*+98 2122432040*
Fax:*+982122432037*
E-mail:*Jafari1952@yahoo.com*

ABSTRACT

Background: New technologies using hazardous materials usually have certain risks. It is more serious when the technology is supposed to be applied in a large scale and become widely used by many people. The objective of this paper was to evaluate the risk of vapor cloud explosion in a hydrogen production process.

Methods: Potential hazards were identified using the conventional hazard identification method (HAZID). The frequency of the proposed scenarios was estimated from statistical data and existing records. The PHAST professional software was applied for consequence modeling. Both individual and societal risks were evaluated. This cross-sectional study was conducted from June 2010 to December 2011 in a Hydrogen Production Plant in Tehran.

Results: The full bore rupture in heat exchanger had the highest harm effect distance. The full bore rupture in desulphurization reactor had the highest (57% of total) individual risk. Full bore rupture in heat exchanger was the highest contributor to social risk. It carried 64% & 66.7% of total risk in day and night respectively.

Conclusions: For the sake of safety, mitigation measures should be implemented on heat exchanger, reformer and hydrogen purification absorbers. The main proposed risk reductive measures included; the increasing of installed equipment elevation, the application of smaller vessels and pipes.

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Introduction

Rapid development of hydrogen technology and its large scale application is expected to end up with many more hydrogen production plants[1]. Although the current annual production of hydrogen in the world is around 50 million tons, higher amounts are expected to be produced in the near future[2]. Currently, hydrogen generation in the world is mostly based on fossil fuels and about 50% of it is generated through natural gasreforming[3]. About 99% of hydrogen consumed in industries is generated through natural gas reforming process[2,3]. Hydrogen generation lines are usually integrated with production lines therefore the exact number of hydrogen generation plants is not available in Iran.

Large scale production of hydrogen through steam methane reforming (SMR) deals with highly explosive and flammable gases such as methane and hydrogen in high concentration which could lead to large scale incidents if not properly dealt with[2].

US department of energy, have recorded 208 incidents in hydrogen production plants from 1995 to May 3, 2013, these incidents contributed by a variety of global sources, including industrial, government and academic facilities[4]. Typical examples of hydrogen accidents in previous decades involve massive and destructive hydrogen vapor cloud explosion with 110 injuries and 22 deaths (Pasadena, USA, 1989), the ignition of hydrogen proceeded rapidly to fire and explosion with 36 deaths (Hindenburg disaster, USA, 1937) and etc. Details of these accidents may be found in relevant literature and databases[5,6,7]. Unfortunately there is no specific organization in Iran for documentation of incidents, thus the exact number of hydrogen incidents occurred in Iran are not available.

There are numerous papers addressing various aspects of hydrogen risk assessment but there have been few attempts at quantitative risk assessments of explosion in relation to hydrogen production. Reports on risk assessment methods (e.g. DNV Research & Innovation, 2008)[8], and risk studies on refueling stations e.g. IEA [9], hydrogen refueling station[1], harm effect distances evaluation of severe accidents for gaseous hydrogen refueling station[10], the quantitative risk assessment of a hydrogen generation unit[3] as well as other facilities e.g[11] are certainly good steps but not matured.

The Quantitative risk assessment (QRA) methodology is often used to quantify the risk around industrial facilities and is considered as a valuable tool to support the communication with authorities and other stakeholders during the permitting process[1]. This paper is a case study on a hydrogen production plant in an industrial complex using QRA methodology to assess the risk of vapor cloud explosion.

Methods

This cross-sectional study was conducted from June 2010 to December 2011 in a Hydrogen Production Plant in Tehran. The systematic quantitative risk assessment procedure shown in Figure1 was followed to assess the risk imposed on the neighborhood from a vapor cloud explosion caused by the studied plant. For this purpose, the related documentation of CCPS (Center for Chemical Process Safety)[12] and DNV (Det Norske Veritas) Co[13] were used. The study consisted of two major parts including hazard identification and risk assessment. A brief description of each part is given in the following.

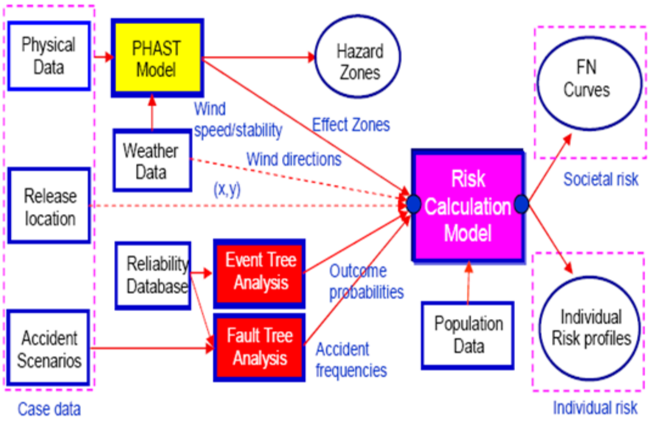

Figure 1: Flow diagram of the procedures used for quantitative risk assessment[12,13]

Hazard identification

The HAZID (hazard identification) technique was applied to identify the hazards and select the scenarios to be studied. After screening all scenarios considering their frequency and consequence, the most credible scenarios with considerable frequency and consequence were selected. The pipe sizes of the studied plant ranged from 6 to 12 inches. On this basis, leakage scenarios were modeled in three sizes including small leaks (5mm hole size), medium leaks (30mm hole size) and large leaks (300mm hole size or full bore rupture). For the quantitative risk assessment of vapor cloud explosion in studied hydrogen generation unit, 15 scenarios were selected. More details of selected scenarios are shown in Table 1.

Table 1: Credible scenarios, frequency estimates and Consequence modeling input data

Item	Scenario No.	Hole size (mm)	Frequency (event/year)	Mass (kg)	Material Composition (Molar %)	Process Condition	
						P(bar)	T(°C)
Desulphurization reactor	S-1	5	1.1×10^{-4}	42	Natural Gas(95%)	25	200
	S-2	30	9.4×10^{-6}	1517	H_2(5%)		
	S-3	300	4.1×10^{-4}	151746			
Heat exchanger	S-4	5	5.7×10^{-6}	42	Natural Gas (52%)	27	530
	S-5	30	6.8×10^{-7}	475	H_2(2%)		
	S-6	300	1.1×10^{-5}	47459	H_2O(46%)		
Reformer (Furnace)	S-7	5	7.5×10^{-5}	41	Natural Gas (5%)	35	300
	S-8	30	8.7×10^{-5}	1520	H_2(60%)		
	S-9	300	2.4×10^{-4}	152002	H_2O(25%)		
					CO_2(8%)		
					CO(2%)		
Hydrogen purification absorbers	S-10	5	5.2×10^{-5}	11	H_2 (100%)	15	40
	S-11	30	4.3×10^{-6}	383			
	S-12	300	5.8×10^{-5}	38287			
Purge Gas Buffer	S-13	5	8.6×10^{-6}	36	Natural Gas (12%)	4	35
	S-14	30	7.7×10^{-7}	1304	H_2 (34%)		
					CO_2 (40%)		
	S-15	300	8.6×10^{-6}	130427	CO (13%)		

Consequence modeling

The TNT equivalent model was used to assess vapor cloud explosions. In this model, the explosion is taken to be equivalent to that of a TNT explosion. Accordingly, the mass flow discharge is calculated using the following equation[12]:

$$\dot{m}_{chocked} = C_D.A.P_1\sqrt{\frac{k.g_c}{R_g}.\frac{M}{T_1}.\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \quad (1)$$

Where, $\dot{m}_{chocked}$ is mass flow discharge (Kg/s), T_1 is temperature (${}^{O}K$), A is the hole area (m^2), R_g is ideal gas constant (8314 $Pa.m^3/mole.{}^{O}K$), g_c is gravitational constant ($N.s^2/kg.m$), M is molecular weight (kg/mole), K is the ratio of specific heat capacity at constant pressure to constant volume). The following equation is used to calculate the mass presented in vapor cloud explosion.

$$M = \dot{m}_{chocked} \times T \quad (Time\ required\ to\ control\ leakage = 10\ \text{min}) \quad (2)$$

The release of substances in all scenarios was considered to be continues. The consequence modeling input data and assumptions shown in Table 1 were used to calculate the risk of explosions at the studied hydrogen production process.

All of the steps described in PHAST 6.5 software package developed by DNV[14] were applied in modeling process. This software was validated specifically for the release of hydrogen in 2008[15]. The influences of explosion on humans (inside and outside the building) and property (equipment and building) were studied.

Persons Outdoors

One of the most commonly used Probit's models which determines the fatalities of outdoor persons from blast overpressure is the Hurst, Nussey and Pape (1989) Probitmodel[16,17]. The relationship of this Probit is generally quoted as:

$$\text{Probit} = 1.47 + 1.35\text{Ln(P)} \quad (3)$$

Where: P is the pressure (psi).The probability is then calculated from the following equation using the calculated Probit.

$$P = 0.5\left[1 + \frac{p-5}{|p-5|} erf\left(\frac{|p-5|}{\sqrt{2}}\right)\right] \quad (4)$$

The combination of this equation and distribution of the population will give the number of fatalities in all incident outcomes by the following equation [12].

$$d = D_p A V_c \quad (5)$$

D_p is the population density in the geographical area where the process is located; A is the area involved in the accidental event (e.g. the area with a determined overpressure level (0.83bar);V_C is a vulnerability coefficient (equal to 50%); it means that the percentage of the people who will die because of the accidental event.

Persons Indoors

The purpose of this model is to determine the fatality probability of the occupants of buildings subjected to blast loading. This is dependent on the level of blast loading and the type and construction of the building. The CCPS has published relationships between the probability of fatality for occupants and the level of blast overpressure for 5 different types of buildings[17,18].In this study only primary injury due to direct blast wave overpressure was analyzed.

Property Damage

This will enable authorities to consider the economic risks to properties, structures and businesses as part of any land use planning decision. In present study explosion overpressure levels are 0.01, 0.17, 0.34 and 0.83 bars. Overpressure effect of these criteria on structures including safety distance (0.01bar), moderate damage (0.17 bars), severe damage (0.34 bars) and total destruction (0.83 bars). An overpressure of 0.34 bar is expected to cause 15% outdoor fatality and 50% indoor fatality while the overpressure of 0.83 bar is likely to cause 50% outdoor fatality and 100% indoor people fatality.

In general, consequence modeling requires the dispersion modeling of flammable clouds for several realistic scenarios in a range of representative atmospheric conditions. Atmospheric conditions in present study including wind velocity, atmospheric stability class, ambient temperature and relative humidity. These parameters were equal to 5 m/s, class D, 28.33 °C and 19.35% respectively during the day and 2 m/s, class F, 2.77 °C and 67.27% at nights. All of the selected scenarios were investigated in two different atmospheric conditions corresponding to day (spring – summer) and night (fall – winter).

Frequency estimation

Generic values were applied to estimate scenario frequencies[19] (Table 1). Frequencies were calculated for the main scenarios concerning leakages and ruptures. To continue the study, the frequency of all incident outcomes is required which can be calculated using Event Tree Analysis (ETA).

Risk estimation

Experimental results have shown that in order to have a balanced perspective of the risks associated with the processing plant the risk must be evaluated from two perspectives; (1) Individual risk and (2) Societal risk. The individual risk is defined as the probability of death at any particular location due to all undesired events. It can be expressed as the probability of a person becoming a casualty in a specific location within a year in the analyzed area[12]. Social risk is normally used for evaluating the exposed risk on a group of people. It is the relationship between the frequency and the number of people suffering from a specified level of harm in a given population due to specified hazards [12].Thus, the total individual risk at each point is equal to the sum of the individual risk of all scenario effects at that point.

$$IR(x, y) = \sum_{i=1}^{n} IR_i(x, y) \quad (6)$$

Where, *IR(x,y)* is the total individual risk of fatality at the geographical location of (x, y) and $IR_{,i}(x, y)$is the individual risk of fatality at the geographical location of (x, y) from scenario *i* as the following equation:

$$IR_i(x,y) = F_i P_i(x,y) \qquad (7)$$

Risk acceptance criteria

The following individual and social risk criteria were adopted from the British Health and Safety Executive and EIHP2 measures specifically considered for Hydrogen[20]. Individual risk criteria is defined at three risk levels of acceptable, ALARP and unacceptable. Acceptable individual risk is 10^{-6} per year; ALARP is 10^{-5} per year and unacceptableis10^{-4} per year. The acceptable individual risk criteria of 10^{-6}means that distances outside the risk contour are acceptable and distance of 10^{-6} contour from boundary limit can be perceived as a safe distance. The results of social risk were also compared with social acceptability boundaries of the UK, Hong Kong and the Netherlands.

Study setting

The subject was a hydrogen production facility located in Behshar Industrial Complex, Tehran, Iran with an area of 176400 m^2 and 1200 employees (800 day shifts & 400 night shifts). Average occupancy was 0.005 person/m^2 and 0.002 person/m^2 during the day and night respectively. The produced hydrogen was applied to hydrogenize vegetable oils.

Hydrogen was generated at a purity level of 99.99% by volume and at15 bar pressure at 40 °C. More details of the operating process may be found in Quantitative Risk Assessment of a Hydrogen Plant in Tehran[21]. The system is fully automated and monitored from the control room.

Results

The major explosion hazards are related to the desulphurization reactor. Maximum effect distance is in case of a full bore rupture at the desulphurization reactor. The safe distance for this scenario is 1130 m and 1233 m in the day and at night respectively.

The overpressure radius of the vapor cloud explosion when the leading edge reaches a given distance downwind and a comparative analysis between the distance effects of different scenarios is given in Figure 2. This figure shows that a full bore rupture at desulphurization reactor will lead to the longest safe distance (810 m) at 0.01bar overpressure (Threshold for glass breakage). The next longest safe distance (760 m) is that of the hydrogen purification absorbers. Larger release size leaks have longer effect distances mainly because of more mass flammable material release which contribute to the related cloud. Smaller release diameters could remarkably reduce harm effect distances. A 30 mm pipe rupture's (S-3and S-2) harm effect distance is reduced by 94% to 76m compared with a 300 mm pipe rupture (Figure 2).

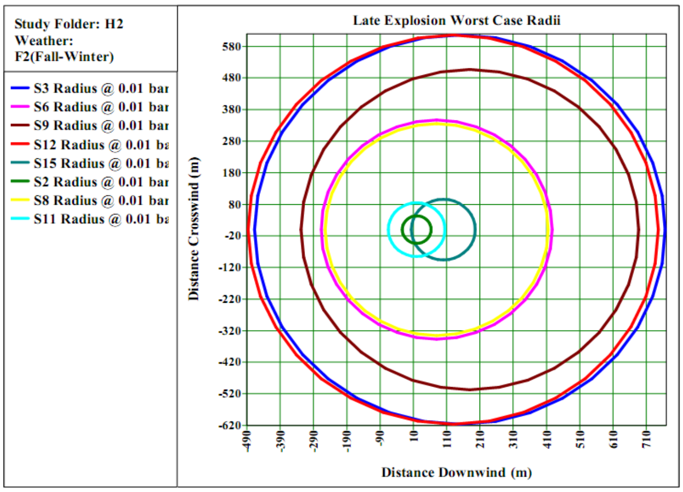

Figure 2: Safe distance of 0.01 bar overpressure (downwind and crosswind)

The overpressure resulting from a full bore rupture is increased to the maximum peak and then it is decreased with the increase of distance. The maximum overpressure of 1 bar caused by S-3 and S-12 will cover the longest distances. This overpressure is high enough to fully destroy the structures and equipment located at these distances.

A further individual risk contribution analysis (Table 2) based on the maximum overpressure reaching from each scenario to the control room shows that the desulphurization reactor leak has the most contribution to the individual risk of the control room. The control room is the place where it is most frequently occupied by workers. Desulphurization reactor and reformer leaks contribute 57% and 34% to the total individual risk of the control room respectively (Table 2). Individual risk was calculated on the basis of maximum overpressure that reaches from each scenario to the control room.

Further social risk contribution analysis (Table 3) shows that S-3 (full bore rupture of desulphurization reactor) contributes the most to the social risk of the hydrogen production process. This scenario contributes 64% in day and 67% at night. S-9 (full bore rupture of reformer) contributes 26% in day and 26 % at night to the total social risk of the hydrogen production process holding second place.

The social risk of all studied scenarios was evaluated by social risk measures accepted in the UK, Hong Kong and the Netherlands (Figure 3)[22,23]. The social risk of S-2, S-8, S-11 and S-15 fall in the social acceptability boundaries, whereas the social risk of S-3 falls nearly in ALARP zone in the UK and unacceptable zone in Hong Kong and the Netherlands measures (Figure 3).

Table 2: Individual risk contribution for the control room

Scenario	Max Overpressure (bar)	Fatality Probability	Frequency (event/year)	Individual Risk (fatalities/year)
Desulphurization reactor	0.83	1.00	4.19×10^{-4}	4.19×10^{-4} (57.00%)
Heat exchanger	0.34	0.90	1.17×10^{-5}	1.05×10^{-5} (1.00%)
Reformer	0.83	1.00	2.49×10^{-4}	2.49×10^{-4} (34.00%)
Hydrogen purification absorbers	0.83	1.00	6.23×10^{-5}	6.23×10^{-5} (8.00%)
Purge Gas Buffer	0.01	0.50	8.60×10^{-6}	4.30×10^{-6} (0.58%)
Total				7.43×10^{-4} (100%)

Table 3: Social risk values of vapor cloud explosion of hydrogen production process

Scenario No	Dp (persons/m^2)		A (m^2)			D (fatalities/event)		Frequency (event/year)	SR (fatalities/year)	
	Day	Night	Day	Night	Vc	Day	Night		Day	Night
S-3	0.005	0.002	13	13	0.500	0.030	0.010	9.4×10^{-6}	3.0×10^{-7}	1.2×10^{-7}
S-6	0.005	0.002	2374	2826	0.500	6.000	3.000	4.1×10^{-4}	2.5×10^{-3}	1.2×10^{-3}
S-8	0.005	0.002	0	0	0.500	2.000	1.000	1.1×10^{-5}	1.9×10^{-5}	9.4×10^{-6}
S-9	0.005	0.002	0	0.785	0.500	0.020	0.010	8.7×10^{-6}	1.5×10^{-7}	6.2×10^{-8}
S-11	0.005	0.002	707	855	0.500	4.000	2.000	2.4×10^{-4}	1.0×10^{-3}	4.8×10^{-4}
S-12	0.005	0.002	0	0	0.500	0.100	0.050	4.3×10^{-6}	4.2×10^{-7}	2.2×10^{-7}
S-15	0.005	0.002	7	7	0.500	7.000	3.000	5.8×10^{-5}	3.8×10^{-4}	1.6×10^{-4}
Total						**19.000**	**9.000**	-	**3.9×10^{-3}**	**1.8×10^{-3}**

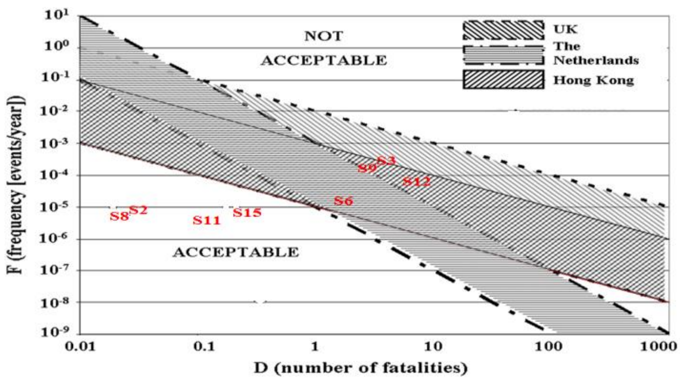

Figure 3: Comparison of risk assessment with social acceptability limits of the UK, Hong Kong and the Netherlands[23,24]

Discussion

The clouds caused by small leaks (5 mm) in all scenarios and medium leaks (30 mm) in the heat exchanger and purge gas buffer would not lead to an explosion mostly because of low concentration of released material.

The overpressure of vapor cloud explosion caused by a full bore rupture at desulphurization reactor (S-3) at a distance of 55 m in day and 60 m at night will be high enough (0.83 bar) for complete destruction of all buildings and equipment located in this distance. This overpressure is likely to kill everyone inside and 50% of persons outdoor. High methane concentration (83%) and high pressure of the process (25 bar) in desulphurization reactor are the main reasons for the high risk in this scenario.

After S-3, a full bore rupture at purification hydrogen absorbers (S-12) has the highest distance effect (1120 m, 1230 m in the day and at night respectively). This is because of high purity level of hydrogen in these absorbers (99.99%). A harm effect distance evaluation conducted by Zhiyong et al. in a gaseous hydrogen refueling station in 2010[10] showed that the longest vapor cloud explosion's harm effect distance to persons is 55 m which is far lower than our results. This is because of good ventilation design, smaller release holes diameter, new installations, slight temperature drift and no chemical reaction in the gaseous station which can lead to a lower harm effect distances compared to the hydrogen generation plant. A study conducted by Rosyid in 2006 at a solar hydrogen plant showed that worst case scenario set by a tank rupture had a harm effect distance of 110 m at 0.01 bar overpressure[2] which is lower than our results. This is due to the use of solar energy instead of natural gas reforming for hydrogen generation. Less severe process conditions and a lack of flammable substances in solar hydrogen plants compared to natural gas reforming (the present study) has probably led to a lower harm effect distance in Rosyid's study.

Another study by Moonis & Wilday in 2010 showed that a catastrophic rupture of distribution storage had an effected distance of 30900 m[24] which is much higher than the results of the present study. This is due to the presence of liquid hydrogen and high inventory (200 ton) of hydrogen gas compared to the present study.

According to the results, harm effect distance at night is longer than daytime. It is generally accepted that higher wind speeds during the day will help the dispersion of hydrogen and consequently reducing the harm effect distances. Lower ambient temperature, higher relative humidity and stable atmospheric condition at night help the hydrogen cloud to stay at ground level before it rises. Therefore, at night the hydrogen cloud will have larger harm effect distance. Harm exposure threshold value to people and equipment are at peak overpressures of 0.07 and 0.2 bars respectively and should be adopted and recommended according to IGC Doc 75/07/E/rev[25]. The peak overpressure of vapor cloud explosion caused by a full bore rupture in all studied units (e.g. S-3, S-6, S-9, S-12 & S-15) were much higher than these criteria.

Individual risks of desulphurization reactor and reformer for the control room operators are unacceptable. Individual risks of heat exchanger and hydrogen purification absorbers are in ALARP, whereas only Individual risk of purge gas buffer is acceptable. Both desulphurization reactor and reformer leaks are the main contributors to the total risks and therefore risk-reducing measures should be implemented primarily on desulphurization reactor and reformer. In this study individual risk in the control room was determined based on the American Petroleum Institute[18]. The recommended practice was 752 and building type of control room was B4. A quantitative risk assessment conducted by Rosyid in 2006 showed that individual risk is unacceptable in all stages of the hydrogen generation cycle which is consistent with the present study[2].

S-3 has the highest fatality rate of 2.5×10^{-3} case per year in day and 1.2×10^{-3}case per year at night. Overpressure effect distance at night is greater than it in daytime but because of high population density, the fatality and consequent social risk in day is greater than it at night.

The results of the present risk analysis, which might be of interest for those in charge of considering the introduction of new energy sectors in an urban area or in a region, have been presented in correlation with some of the international acceptable levels. Figure 3 shows where the results of the social risk analysis of S-2, S-8, S-11 and S-15 fall in the social acceptable boundaries of the UK, Hong Kong and the Netherlands. S-6 falls in ALARP zone of Hong Kong and the Netherlands but acceptable boundaries of the UK. In addition, S-9 and S-12 fall in the unacceptable zone of the Netherlands and ALARP zone of Hong Kong, whereas S-3 falls nearly in the ALARP zone of the UK and unacceptable zone of Hong Kong and the Netherlands.

A further risk ranking analysis showed that S-3, S-9 and S-12 produce high societal risks in the unacceptable region of the F-N curve on the basis of the Netherlands criteria. The result indicates that mitigation measures must be implemented on these scenarios for the sake of people's safety. Application of mitigation measures including either enclosure or elevation is expected to reduce the risk of these scenarios to the ALARP region; indicating that further cost-benefit analysis are required.

A study by Gerboni and Salvador in 2009 on hydrogen transportation systems showed that explosion of a tube trailer had an effect distance of 110 m (at 0.07 bar overpressure), a fatality rate of 2.79 fatalities/event and a social risk of 1.12×10^{-7}, which are lower that our results[26]. In the present study, 85% of the desulphurization reactor's content was flammable substances while in the Gerboni and Salvador study only 20% - 60% of the tube trailer content was flammable which led to lower risk.

Additional safety barriers that were proposed on unacceptable scenarios include leakage detection and shut down systems, hydrogen sensors near the desulphurization reactor and reformer, connecting the unit to the automatic emergency shutdown system and the spreading of the manual emergency shutdown switches at different locations across the plant. The application of these measures is expected to prevent continuous hydrogen release from desulphurization reactor and reformer. The elevation of installed equipment is also a key criterion to reduce harm effect distances of hydrogen release as it decreases the congestion of the area.

Decreasing the release slot and the release pipe diameter can lead to smaller harm effect distances. This means that using smaller pipes might be an effective mitigation measure to reduce harm effect distances for severe accidents such as full bore rupture of piping.

The lack of specific databases of hydrogen incidents that are usually used for events frequency calculation and specific individual & social risks criteria for hydrogen process and other process industries in Iran could be considered as the major limitations of the present study. Development of risk criteria for process industries is a key issue for future researches in Iran.

Conclusion

S-3 and S-12 were the main contributors to harm effect distance, indicating the type of risk mitigation measures that should be implemented primarily. Harm effect distances were longer at night while fatality and consequent social risks were higher in daytime weather conditions. Desulphurization reactor and reformer leaks were the main contributors to unacceptable individual risks at the control room; determining the risk reducing measures for the sake of personnel safety. S-3, S-9& S-12 contributed the most to the social risk of hydrogen production process determining the mitigation measures that must be implemented for the sake of people's safety.High purity level of methane and hydrogen gas, high process pressure, large pipe diameter and weather conditions were the most effective parameters in vapor cloud explosion.

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Conflict of interest statement

The authors have no conflict of interest to report.

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