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Quantitative risk assessment of an urban hydrogen refueling station

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ABSTRACT

Hydrogen is one of important energy source in the next generation of renewable energy. It has powerful strength such as no emission from CO2 for fuel, Nevertheless, many countries have difficulties to expand hydrogen infra due to high risky from hydrogen. Especially, the hydrogen refueling station which is located in urban area has congested structure and high population around, it has higher risk than conventional refueling station. This paper presents a quantitative risk assessment (QRA) of a high pressure hydrogen refueling station in an urban area with a large population and high congestion between the instruments and equipment. The results show that leaks from the tube-trailer and dispenser as well as potential explosion of the tube-trailer are the main risks. For the safety of the station operator, customers and people surrounding the refueling station, additional mitigation plans such as adding additional safety barrier system have to be implemented on the compressor and dispenser in order to prevent continuous release of hydrogen from an accident.

Introduction

As environmental pollution increases from the combustion of hydrocarbon fuels, the demand for energy is expected to shift to renewable fuels such as biomass, solar cell, wind power and hydrogen. Among renewable energies, hydrogen is the only fuel with zero emissions. The advent of hydrogen vehicles is likely to increase the demand for hydrogen and cause the hydrogen market to grow quickly. Hydrogen is not a popular fuel yet for a few reasons, including its flammability and low ignition energy [1,2]. Nevertheless, hydrogen has been used in a wide range of fields, the most well-known being hydrogen fuel cell vehicles (FCV) in Korea. The Korean government has provided support to build, hydrogen refueling stations in many areas, but only a few stations are in operation now. In order for FCVs to become more mainstream, a network of hydrogen refueling stations must be built. For this reason, many risk assessment studies have been conducted on the safe design of hydrogen refueling stations. Chitose et al. suggested the methodology, probabilistic risk analysis (PRA), for hydrogen refueling stations [3]. Risk assessments for high pressure systems were carried out using risk matrix [4]. Other

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alternatives are focused on accidents such as leaks and explosions [5,6]. Various hydrogen refueling station's use of liquid hydrogen, fuel transportation, station size, cost were evaluated also [7–13].

In most studies, the stations are located at large, non-urban site with low populations. Many new hydrogen refueling stations will be installed in urban areas. As a geographical characteristic which has many mountains and small site, the structure of station is congested than general hydrogen fueling station. This could be a cause for a hydrogen explosion. In this study, we applied Quantitative Risk Assessment (QRA) to urban hydrogen refueling stations taking into consideration population levels and explosive potential.

Process description

The hydrogen station, located in the center of an urban area, is mainly used to fill FCVs such as hydrogen buses and cars. There is one tube-trailer in the station, and that is replaced once a month. The urban hydrogen station can serve 10 fuel cell cars and 2 fuel cell buses.

Fig. 1 shows the location and information about the station and its surroundings. The station is, 100 m in length and 65 m in width, is located at the east side of the Seoul-Busan expressway. The north and west sides of the station are located LPG fueling station and temporary office building. At the south and west sides, there are large buildings such as hotels and downtown. This station works at pressures of 350 and 700 bar, but only the 700 bar station are considered in this study. Hydrogen is brought from general company to the station by road trailer, which consists three part tubes. The highest pressure each tube is no more than 180 bar. There is one tube-trailer in total, usually only one trailer inside the station warehouse. The trailer inside the station is connected by a flexible hose, which is connected to compressor. The compressor draws hydrogen from the trailer to fill the accumulator up to a maximum pressure of 700 bar. The temperature will be increased by compressor immediately, so the fuel has to decrease the temperature to fueling. During the process of refueling, hydrogen can be moved from the tube on trailer to dispenser through the pipe, and to fill cars or buses at pressures of 350 bar and 700 bar.

Methodology

QRA procedure

Fig. 2 shows a conventional QRA procedure. QRA is a formal methodology for the risk of potential hazards on processes in the world [14–20]. The first step is called process modeling on the system and is defined for each process in the QRA. Next, we identify hazards in the process. It is necessary to define scenarios from the heat and mass balance to calculate consequence analysis and frequency analysis. Consequence analysis is performed on an amount of damages such as overpressure, heat flux, and toxicity concentration following the defined scenarios. Frequency analysis determines probabilities and hazard event failures for each scenario, such as leaks, gas dispersion and explosions. Risk calculation is performed by combining the results from consequence and

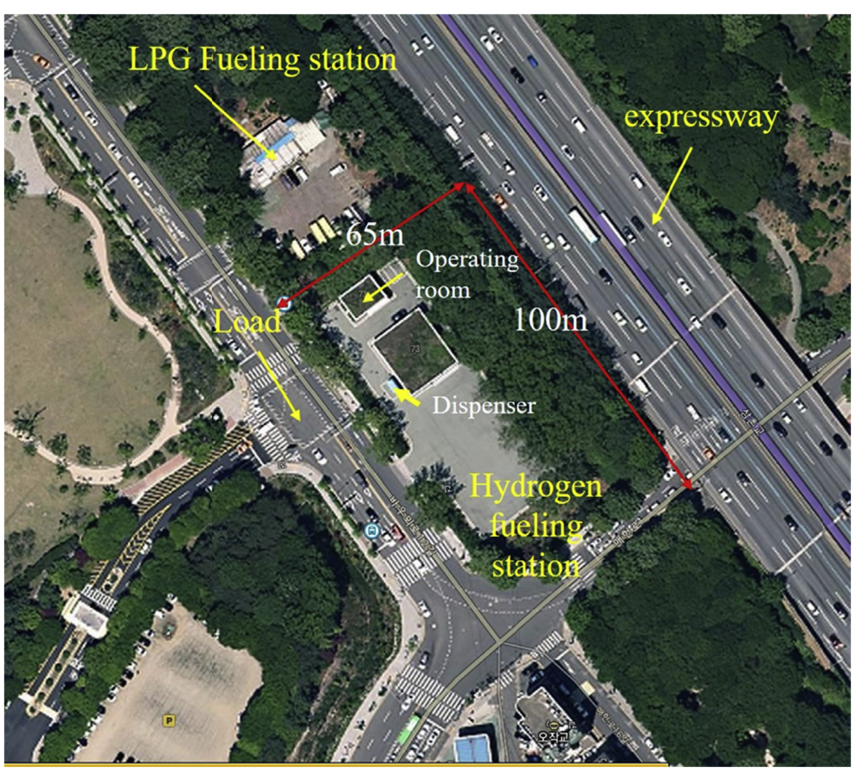

Fig. 1 – Geographical information of hydrogen station and surroundings.

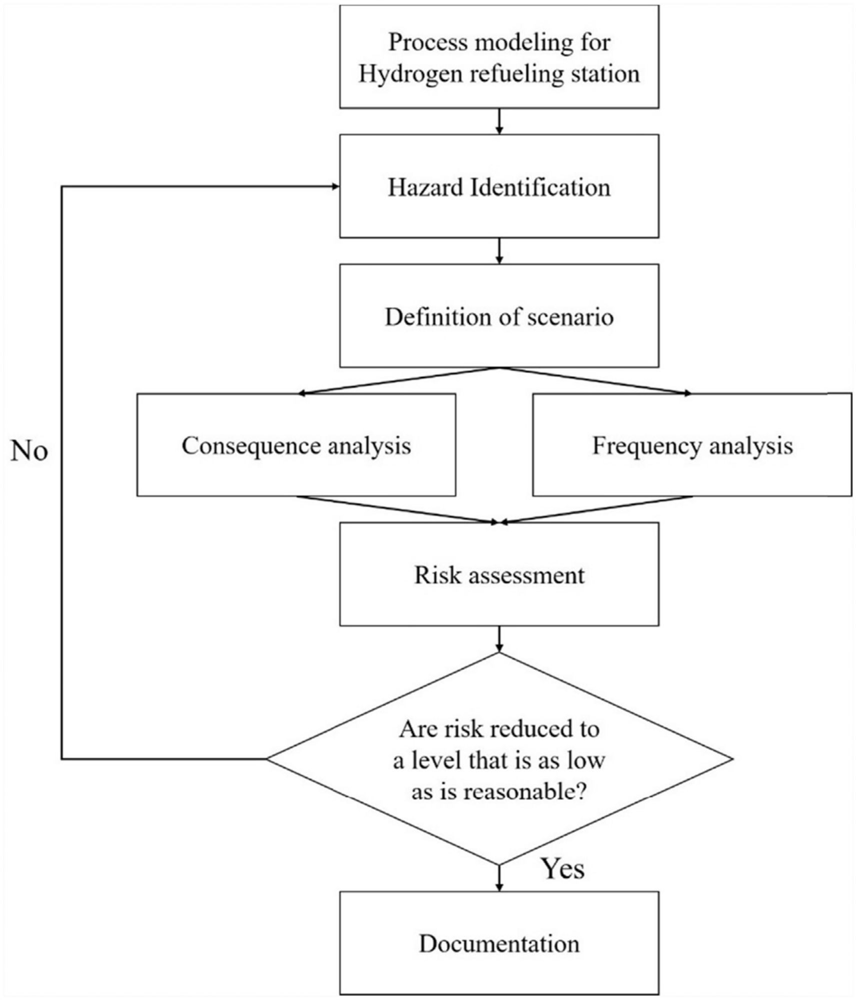

Fig. 2 – Conventional QRA procedure.

frequency analysis, including individual risk (IR) and societal risk (SR). The biggest different between IR and SR is the application of consequence. SR should be considered as a result of risk whether it is acceptable or not.

Layout of the hydrogen refueling station

Fig. 3 shows the layout of the urban hydrogen refueling station, used in this risk assessment. There is an operating room, a chiller for cooling the hydrogen near the operating room, a tube-trailer to store the hydrogen, and a compressor to compress the hydrogen for fueling FCVs. One operator stays in the operating room, and controls the processes and safety of the station. For this assessment, we assumed the number of tube-trailers is assumed is one.

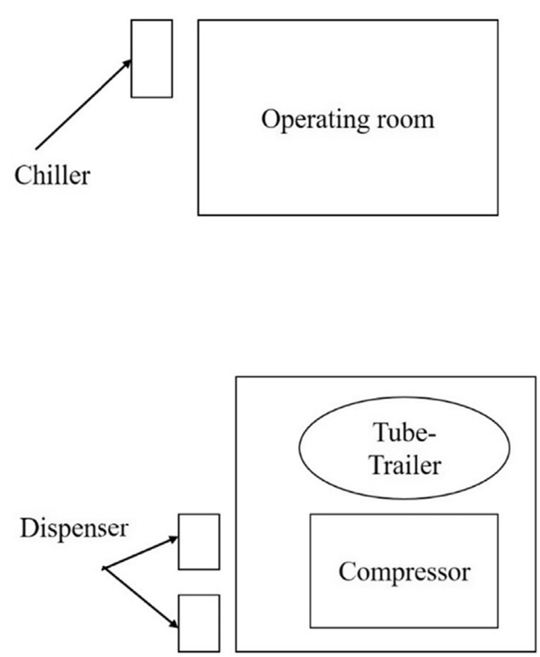

Fig. 3 – Hydrogen station layout.

Process modeling

For the defined scenarios in QRA, the hydrogen refueling process has to be specified (see Table 1). As depicted in Fig. 4, the process is the urban hydrogen refueling station built for hydrogen fueling of South Korean FCVs. The station offers 700 bar and 350 bar hydrogen for fuel to FCVs and bus. The station is located in an urban area near a highway and

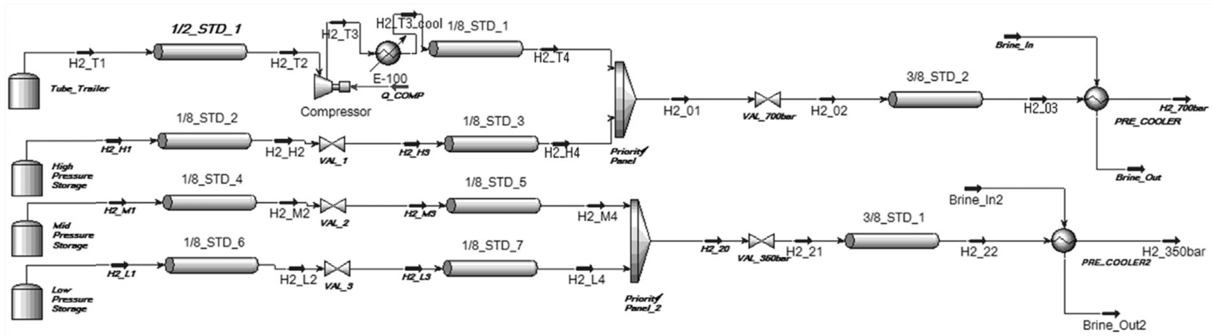

Fig. 4 – Process flow diagram of the hydrogen refueling station.

Table 1 – Heat and mass balance from urban hydrogen fueling station.

	H2_H1	H2_T1	H2_T3_Cool	Brine_In	Brine_Out	H2_700 bar
Temperature(°C)	122.2	25.0	189.8	−40.0	−15.0	15.2
Pressure(bar)	940.0	100.0	939.9	700.0	699.5	699.3
Flowrate (kmole/h)	12.4	12.4	12.4	90.4	90.4	24.8

Table 2 – Accident scenario for an urban hydrogen refueling station [22].

Item	Scenario and descriptions	Release pressure (bar)	Release hole size (mm)
Tube-trailer	Catastrophic rupture	100	N/A
Dispensers	Leak from hole	700	0.11
			1.11
			11.11

building. The pressure system makes high pressure hydrogen for fuel use. The hydrogen is stored 100 bar, 15 °C in general. Extra hydrogen is stored each pressure storage after fueling. The input is supplied from the tube-trailer to the dispenser, which consists of a compressor, a chiller, and a priority panel. The temperature of the components increases, which leads to a high probability of auto ignition. The steam decreases its temperature to 15 °C using brine, the working fluid in the chiller. The output is pressurized hydrogen at 700 bar, 15 °C. Table 2 shows the heat and mass balance for the process. These are used to define fault scenarios using event of defined scenario by process modeling results and calculate consequence and frequency.

Scenario definition

The scenarios and input data shown in Table 2 were used for the urban hydrogen refueling station risk calculations. These were determined by Hazard and operability study(HAZOP), a

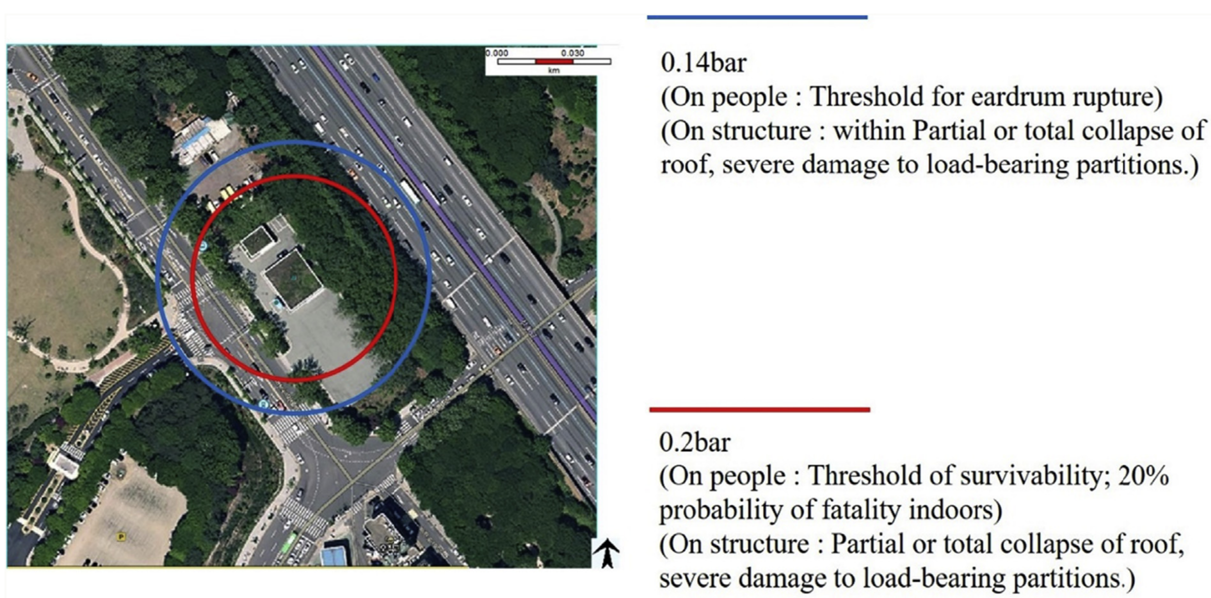

Fig. 5 – Results from overpressure(worst case scenario).

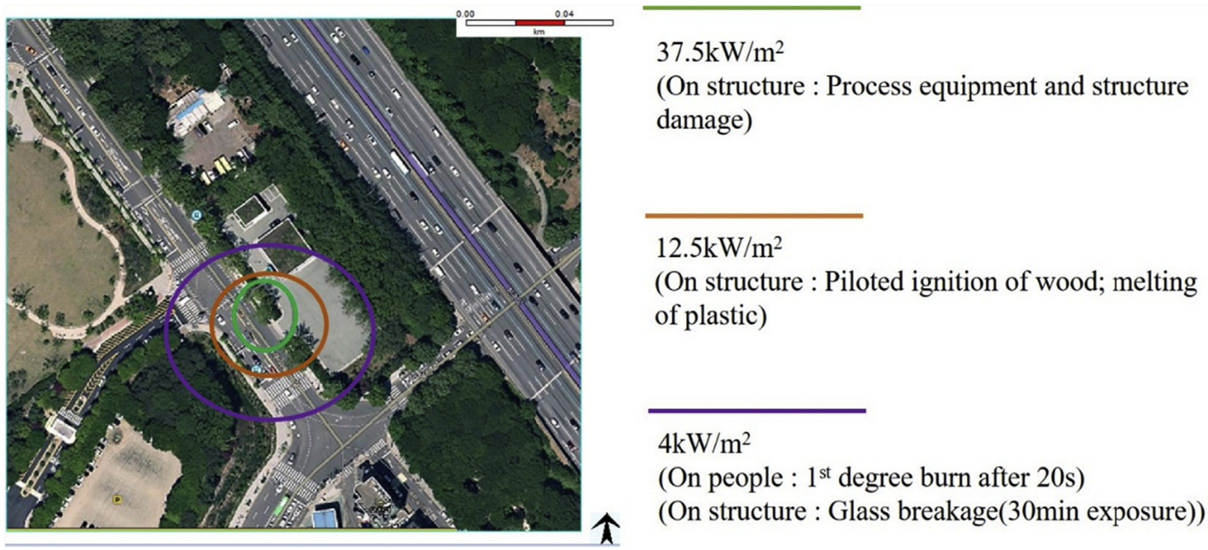

Fig. 6 – Results from heat flux(worst case scenario).

Table 3 – Probit equation [24].

Damage	No.	Equation	Impact
Overpressure	(1)	$P_r = -77.1 + 6.91\ \ln(P_s)$	Death(pulmonary hemorrhage)
	(2)	$P_r = -15.6 + 1.93\ \ln(P_s)$	Ruptured eardrum
	(3)	$P_r = -23.8 + 6.91\ \ln(P_s)$	Damage of structure
	(4)	$P_r = -18.1 + 2.79\ \ln(P_s)$	Damage of glass
Heat flux	(5)	$P_r = -39.83 + 3.0186\ \ln(tQ^{4/3})$	1st burn
	(6)	$P_r = -43.14 + 3.0186\ \ln(tQ^{4/3})$	2nd burn
	(7)	$P_r = -36.38 + 2.56\ \ln(tQ^{4/3})$	Death

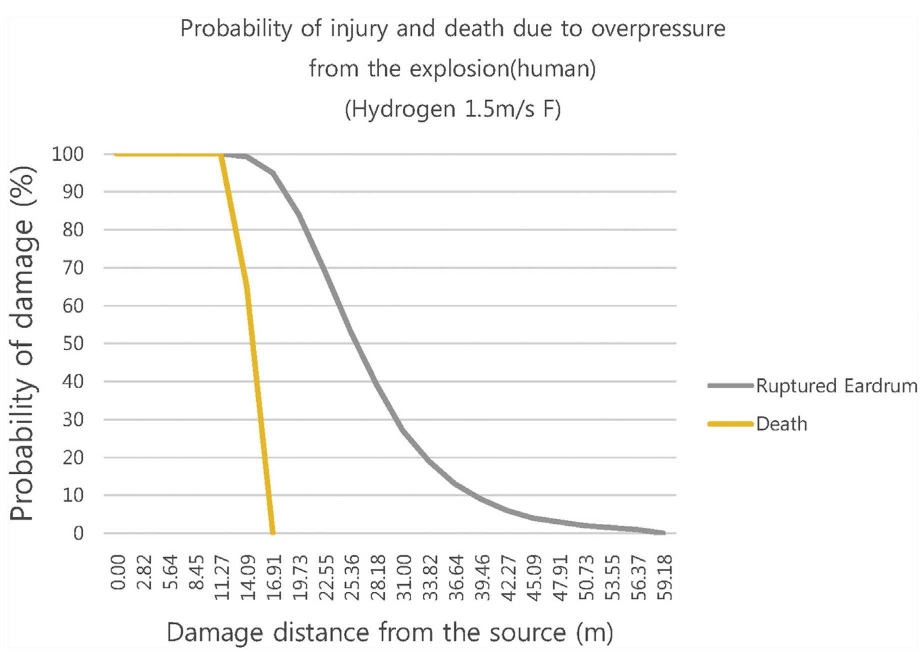

Fig. 7 – Probability of impact of body due to overpressure from the explosion(worst case scenario).

method for determining process hazards. Generally, fire caused by hydrogen leakage is considered the main event concern for a hydrogen refueling station. In open areas and rural sites, stations have enough space and low populations, so they are not built with a congested structure. However, many hydrogen stations are built in small area, urban areas, and the refueling station's structure is highly congested. An explosion occurred in Japan, in an area with low probability

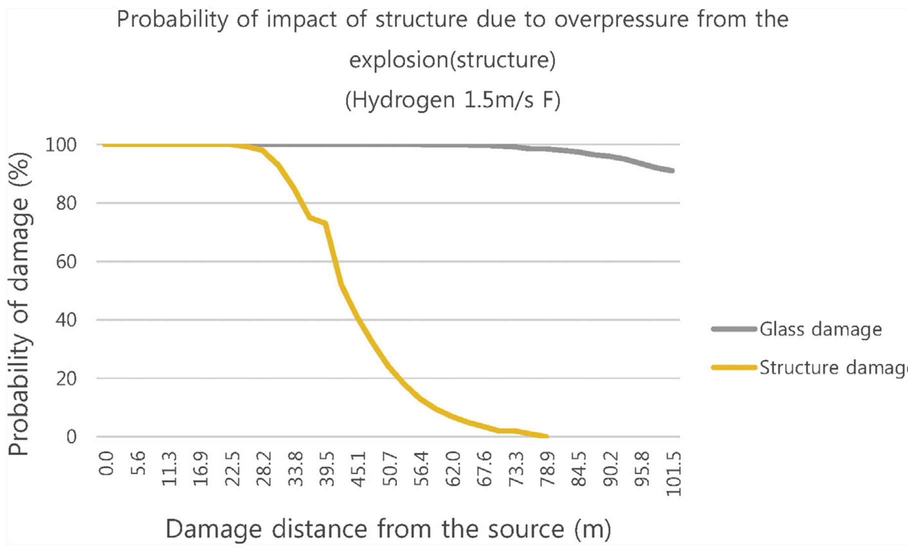

Fig. 8 – Probability of impact of structure due to overpressure from the explosion(worst case scenario).

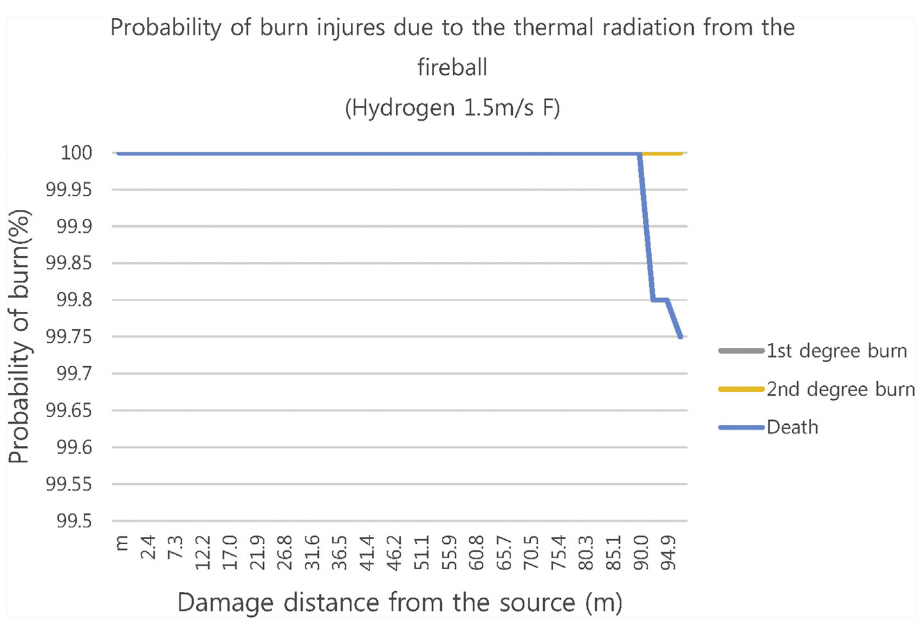

Fig. 9 – Probability of impact of body due to heat flux from the explosion(worst case scenario).

Table 4 – Failure data from HYRAM [23].

Item	Scenario and descriptions	Release pressure(bar)	Release hole size(mm)	Initial failure frequency
Tube-trailer	Catastrophic rupture	100	N/A	1.11×10^{-4} per year per item
Dispensers	Leakage from a hole	700	0.11	9.12×10^{-7} per year per item
			1.11	1.80×10^{-6} per year per item
			11.11	6.43×10^{-7} per year per item

Table 5 – Ignition probability [23].

Hydrogen release rate(kg/s)	P (immediate Ignition)	P (delayed Ignition)
<0.125	0.008	0.004
0.125–6.25	0.053	0.027
>6.25	0.230	0.120

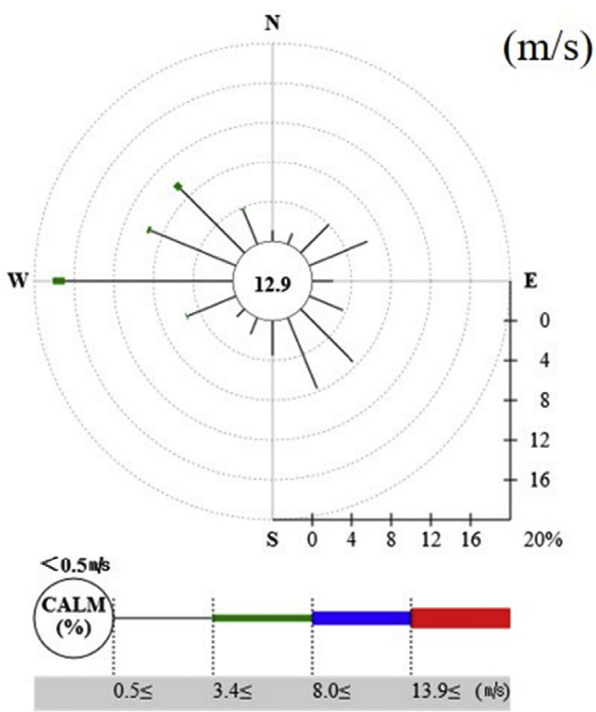

Fig. 10 – Windrose from an automatic weather system (AWS) - data from 2016.

[21], but the explosion accident will be considered to make scenario in urban station. The main accident scenarios are: 1) catastrophic rupture of the tube-trailer, 2) leakage from the dispenser. The leakage hole sizes to leak are considered by HYRAM software [22]. In this study, consequence and frequency analysis is performed and compared for verifying necessary of the safety barrier system application.

Results and discussions

Consequence analysis

The main consequences of these scenarios are explosions from the tube-trailer and leaks from the dispenser hole. Two results of worst case scenarios are shown in Figs. 5 and 6. Fig. 5 shows the results of overpressure from an explosion. The damage estimates for people and structures on overpressure by Purple's book [24]. In this result, the operator and some people near the highway and road experienced eardrum ruptures from overpressure. According to the results in Fig. 6, the operating room is safe from the heat flux, but customers near the road, will experience first-degree burns after 20s.

In addition, we did probit analysis to calculate probability of injury or death according distance. Probit analysis is one of method to risk assessments. The functions consist of heat flux, overpressure and toxic concentration. Table 3 shows probit equation [24]. Equation (1) to (2) are impact of body from overpressure and equation (3) to (4) are impact of structure. Also, equation (5) to (7) are impact of body from heat flux. Fig. 7 shows probit result from overpressure for body. Fig. 8 shows impact of structure from overpressure. Fig. 9 shows impact of body from heat flux.

Frequency analysis

In frequency analysis, initial failure is necessary. In this paper, failure data for each part of the process or scenario was chosen from the HYRAM data, presented in Tables 4 and 5 [23]. It is newer than the data in Purple's book [24] and is focused on hydrogen station failure. The scenarios were chosen based on the basic Purple's book. One part of the scenario shows that dispensers depend on the HYRAM release rate. Contrary to consequence analysis, frequency analysis, information about the weather is necessary. A windrose, is a graphic tool used by

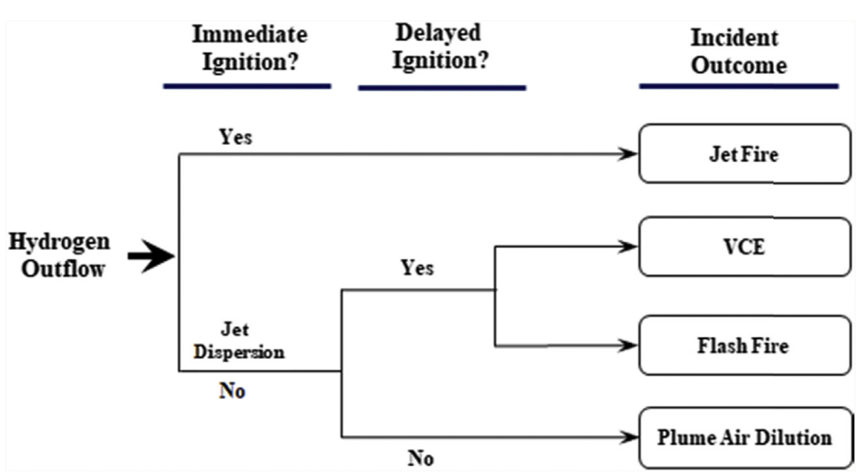

Fig. 11 – Event tree analysis(ETA).

meteorologists to depict wind speed and direction. There are two types of windroses in Korea, an Automated Synoptic Observing System (ASOS) and Automatic Weather System (AWS). A weather forecast notes the weather conditions of the general area, it is used to ASOS. The observations for mean wind speed and direction cover a wind area but we need more specific information for hydrogen refueling station. For this study, we used the AWS type of windrose. Fig. 10 shows the AWS windrose in 2016 near the station. ETA is performed to all of possible accident from all scenario. Fig. 11 is ETA result in this paper.

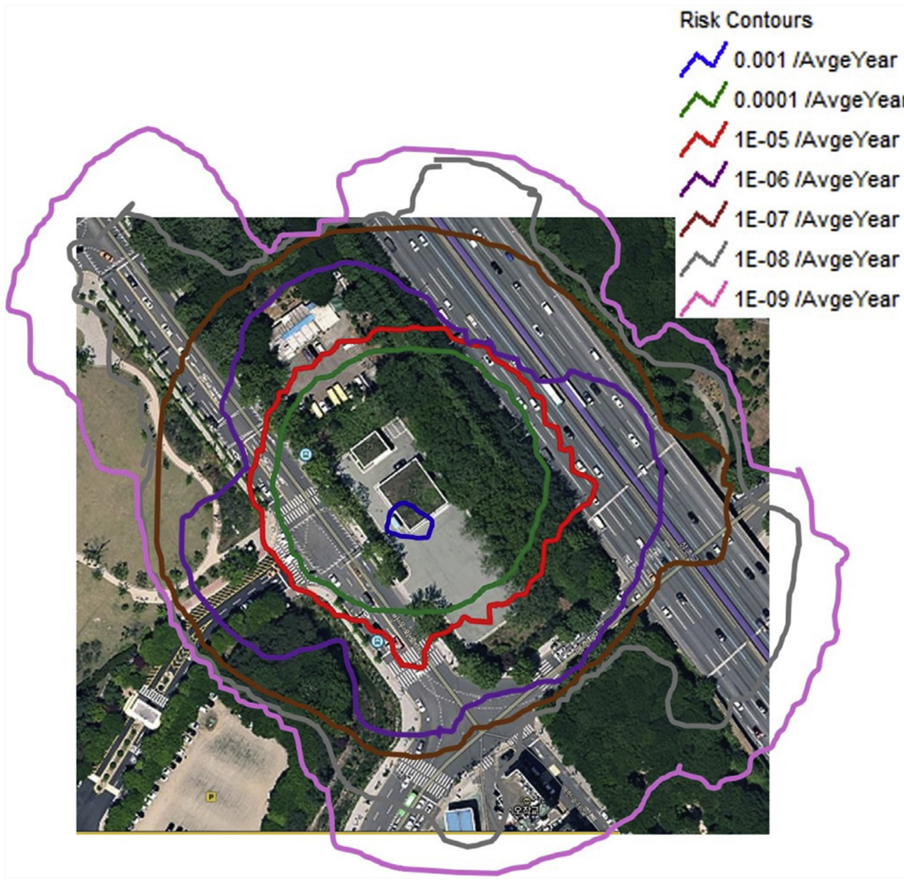

Fig. 12 – Individual risk (conventional).

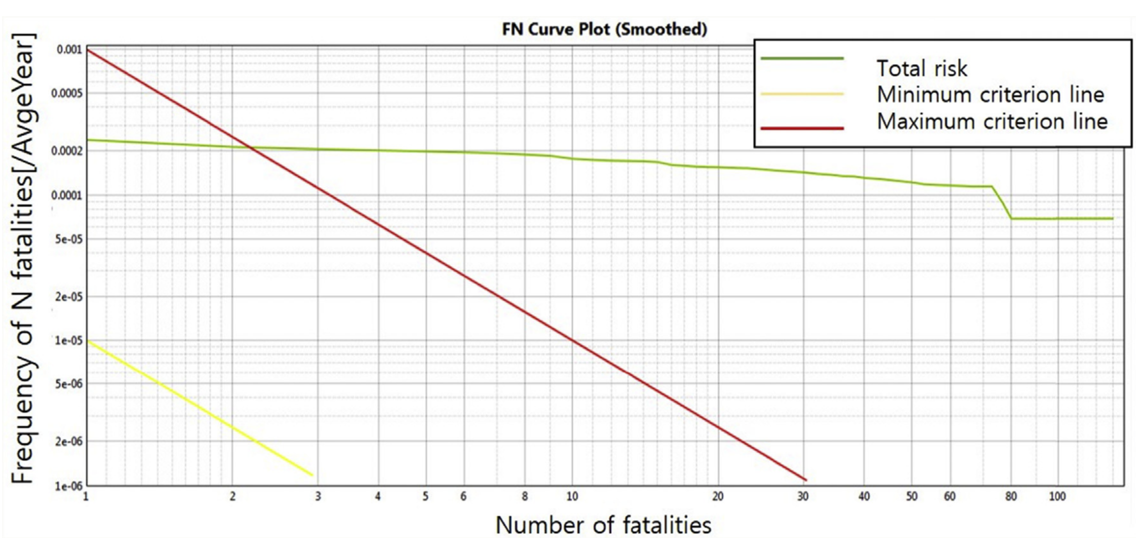

Fig. 13 – Societal risk (conventional).

Risk assessment

Risk analysis included consequence and frequency analysis for the scenario. In this study, SEFETI v7.2 was used for Quantitative Risk Assessment(QRA). Risk analysis input included the operating data for each piece of equipment and the weather conditions. Risk analysis results are shown in Figs. 12 and 13. Fig. 12 shows the Individual Risk(IR) contour while Fig. 13 shows the Societal Risk(SR) as an F-N curve. In the IR contours, differences can be seen depending on location. This risk information can be used for locating safety areas and designing evacuation plans. The results seem dangerous for the tube-trailer because of the large consequences and higher failure rates than for the dispenser. Also, 10^{-6}/year is a reasonable risk, but it is located near the highway. The F-N curve, the upper and lower risk to use as a guideline to assess risk. The upper line and lower lines are the risk criteria where the area between upper and lower is called As Low As Reasonably Practicable(ALARP) reason. Fig. 13 shows that the result of a conventional risk assessment on SR is not located within the ALARP region. This means this system is not allowed in the risk point. The system will be changed to fit within the ALARP region.

Risk analysis considering mitigation

The risk is a combination of frequency and consequence from each scenario. The method of decreasing risk is to reduce consequence or failure. For protection from risk, there are active and passive safety systems. The different point

Table 6 – Probability of a major accident with and without facility safety barrier system [25].

	Without additional safety barrier systems	With additional safety barrier systems
Leak from dispensers (D = 0.11 mm)	9.12×10^{-7} per year per item	$<10^{-10}$ per year per item
Leak from dispensers (D = 1.11 mm)	1.80×10^{-6} per year per item	$<10^{-9}$ per year per item
Leak from dispensers (D = 11.11 mm)	6.43×10^{-7} per year per item	$<10^{-10}$ per year per item
Tube-trailer Catastrophic rupture	1.11×10^{-4} per year per item	$<10^{-7}$ per year per item

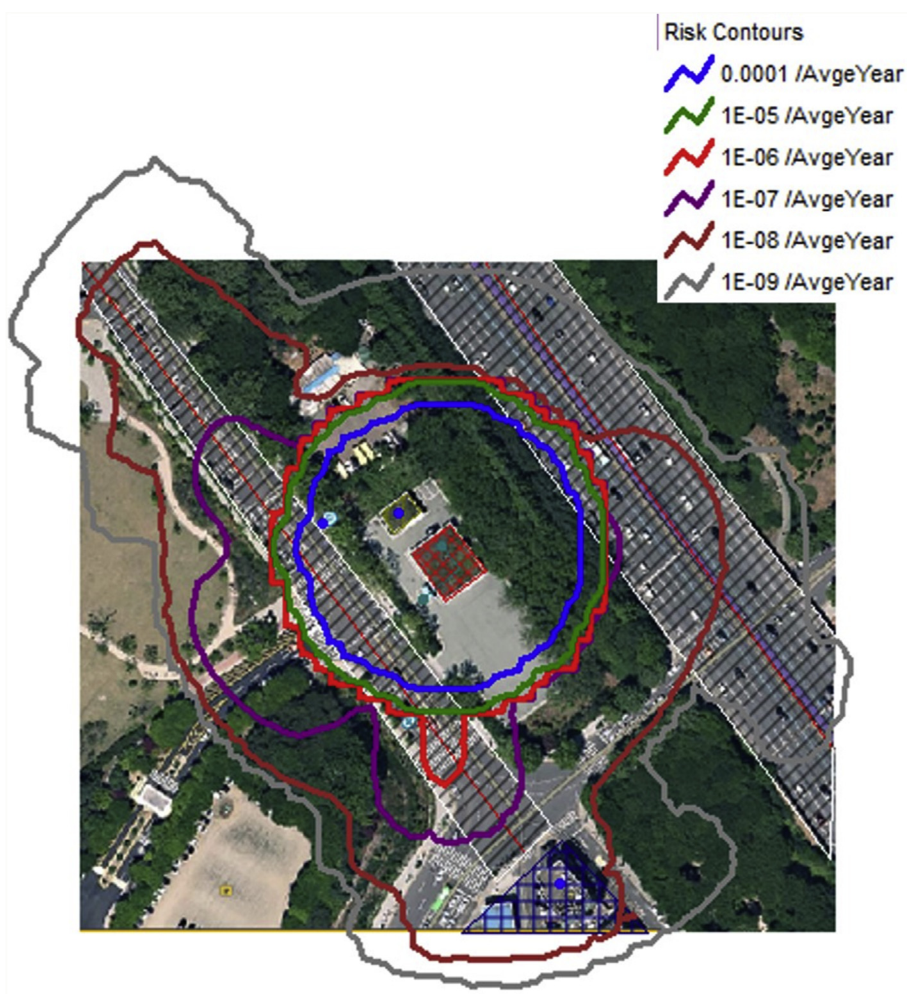

Fig. 14 – Individual risk (mitigated).

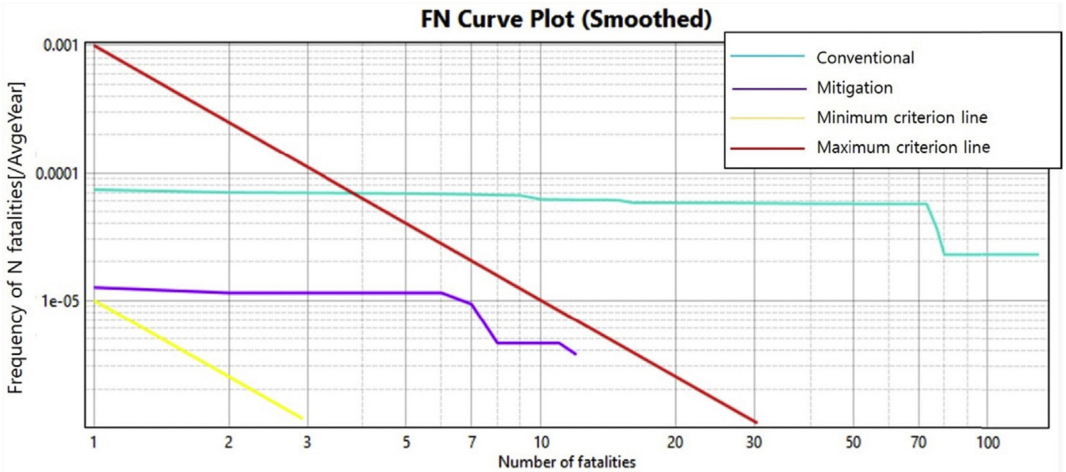

Fig. 15 – Societal risk (mitigated).

Table 7 – Frequencies and probability of fatality of each scenario.

Equipment	Accident	bar	scenario	Barrier	Frequency (/year)	Probability	IR (/year)	SR (/year)
Tube-trailer	Catastrophic rupture	100	N/A	No	1.11×10^{-4}	0.120	1.00×10^{-3}	9.43×10^{-3}
				Yes	$<10^{-7}$	0.027	1.00×10^{-4}	9.43×10^{-4}
Dispensers	Leak from hole	700	0.11	No	9.12×10^{-7}	0.008	1.00×10^{-3}	9.43×10^{-3}
				Yes	$<10^{-10}$	0.008	1.00×10^{-4}	9.43×10^{-4}
			1.11	No	1.80×10^{-6}	0.053	1.00×10^{-3}	9.43×10^{-3}
				Yes	$<10^{-9}$	0.053	1.00×10^{-4}	9.43×10^{-4}
			11.11	No	6.43×10^{-7}	0.053	1.00×10^{-3}	9.43×10^{-3}
				Yes	$<10^{-10}$	0.053	1.00×10^{-4}	9.43×10^{-4}

between active and passive is a target to reduce damage. In the previous sections of this study, we showed how we determine IR and SR. The figures showed that risk reduction is necessary. Passive safety systems are required in many budgets and include building structures, such as fire walls and blast walls. Active safety systems require installation of small equipment that measure material concentrations. Previous research, chose to use safety barrier systems for their active safety system [25]. This shrinkse failure by a factor of 10. Table 6 shows how safety barriers protect facilities during a major accident.

Based on results from the QRA, Figs. 14 and 15 present IR and SR arguments for considering safety barrier systems. In Fig. 14, the maximum contour of IR is 0.0001/year. This is reduced by a factor of 10 compared to a conventional case. Fig. 15 shows that the risk line is moved in ALARP region.

Discussion of risk analysis

In this study, we apply safety barrier system to decrease risk. The mitigation plans have a detection system for hydrogen leakage. Results including safety barriers are shown Figs. 13 and 14. Generally, many QRAs for hydrogen refueling stations, consider jet fire from leakage. These hydrogen stations are located large spaces and in rural site. In urban areas, however, the sites do not have enough space available to install a hydrogen refueling station. More and more, the stations will be located in smaller places. Therefore, the components of the station congest the site. It seems that explosion scenarios are more dangerous than the other cases. To decrease the risk, we applied a safety barrier system in the hydrogen refueling system to detect hydrogen concentration. The mitigation reduces the failure part of risk. The risks represented in Figs. 13 and 14 are where the QRA considers mitigation. After safety barriers are applied to the hydrogen refueling system, the F-N curve moves to ALARP region, meaning the system has reasonable risk and the IR maximum is shown lower around 10 times than in a conventional case. Table 7 shows frequencies and probability of fatality of each scenario.

Conclusions

In this study, we carried out quantitative risk assessment on urban hydrogen refueling systems with respect to population and mitigation. First, an actual case was drawn by process modeling and station description. Second, the QRA method, including consequence and frequency analysis, was calculated with the necessary scenarios to determine the risk of urban hydrogen refueling stations. Because of scenarios with low probability but large consequence, the QRA was made up of unacceptable result. For decreasing the risk, we applied a mitigation and safety barrier system. The system contained certain detectors, such as Emergency Detection System(EDS), which will cause an immediate emergency shut down and will be decrease the frequency and amount of leakage from the hydrogen equipment.

In the comparison between conventional and mitigated systems, the individual results for a mitigated system are decreased 10 times lower than for a conventional system and societal risk results fall within the ALARP criteria. In urban areas, the explosion scenario was used in the QRA because of the crowded hydrogen refueling station structure and the surrounding population important factors in assessing risk.

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Nomenclature

ALARP	As Low As Reasonably Practicable
ASOS	Automated Synoptic Observing System
AWS	Automatic Weather System
EDS	Emergency Detection System
FCV	Fuel Cell Vehicle
HAZOP	Hazard and operability study
IR	Individual Risk
PRA	Probabilistic Risk Analysis
QRA	Quantitative Risk Assessment
SR	Societal Risk
P_r	Probit
t	Time
Q	Heat radiation$\left(\frac{W}{m^2}\right)$
P_s	Overpressure$\left(\frac{N}{m^2}\right)$

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