SECURITY RISK ANALYSIS OF A HYDROGEN FUELING STATION WITH AN ON-SITE HYDROGEN PRODUCTION SYSTEM INVOLVING METHYLCYCLOHEXANE

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ABSTRACT

Although many studies have looked at safety issues relating to hydrogen fueling stations, few studies have analyzed the security risks, such as deliberate attack of the station by threats such as terrorists and disgruntled employees. The purpose of this study is to analyze security risks for a hydrogen fueling station with an on-site production of hydrogen from methylcyclohexane. We qualitatively conducted a security risk analysis using American Petroleum Institute Standard 780 as a reference for the analysis. The analysis identified 93 scenarios, including pool fires. We quantitatively simulated a pool fire scenario unique to the station to analyze attack consequences. Based on the analysis and the simulation, we recommend countermeasures to prevent and mitigate deliberate attacks.

1.0 INTRODUCTION

Hydrogen fueling stations are crucial for the hydrogen supply infrastructure for fuel cell vehicles (FCVs). Hydrogen has major characteristic hazards, such as explosiveness and flammability [1,2]. In addition, a hydrogen fueling station stores a large amount of hydrogen compressed to 82 MPa in pressurized storage tanks. Therefore, safety investigations of hydrogen dispersion and explosion accidents at hydrogen fueling stations have been experimentally analyzed to address prevention and mitigation measures [3,4]. Also, useful risk assessment tools, such as FLACS (FLame ACceleration Simulator) and HyRAM (Hydrogen Risk Assessment Model), have been developed for dispersion and explosion simulation [5-8]. Risk assessment has been performed for various types of hydrogen fueling stations, including stand-alone compressed or liquefied hydrogen fueling stations [9-12] and hybrid hydrogen-gasoline fueling stations [13,14]. Furthermore, a simulation-based safety investigation was conducted to analyze the domino effects of toluene and methylcyclohexane (MCH) pool fires on the pressurized hydrogen storage tanks to suggest emergency safety measures [15]. Regulations and codes for hydrogen fueling have already been established in Japan after considerable research and discussion. Only a few incidents and accidents have been reported [16,17], and the causes of them have been analyzed to suggest safety measures [18]. Thus, a hydrogen fueling station may seemingly have low risks related to hydrogen hazards. However, investigations and regulations have mainly focused on safety issues, that is, incidents and accidents caused by unintentional events, such as natural disasters, human errors, and processing problems, that can lead to hydrogen leaks and explosions. The investigations and regulations are very important for risk reduction, but they have not addressed all the risks of a hydrogen fueling station.

Petroleum and petrochemical industries have struggled with safety issues for a long time because the industries store, produce, and transport an enormous amount of flammable, explosive, and toxic materials. Although risk management tended to focus on safety issues prior to September 11, 2001, the World Trade Center attack dramatically changed concerns about security risks to hazardous materials. Security issues went from uninteresting problems to major concerns. Moore [19] noted that we are generally unprepared to deal with security threats and that the new risk paradigm requires a different form of analysis than that for safety risk assessment. Since 9/11, new security risk assessment methods have been developed. Bajpai et al. [20] carried out qualitative security risk assessment for improving site security and pointed out that it is important to implement inherently safe processes for significant risk reduction because it is impossible to completely prevent terrorist attacks. Reniers et al. [21] built on the concept that some well-developed tools from the safety domain can be effectively used in designing a security system for a chemical plant and noted that independent protection layers are not adequate for security issues because security countermeasures need to be interdependent. Other studies have addressed general security assessment methodology [22,23], and some have indicated future directions for safety and security [24]. While petrochemical and petroleum industries recently started to take security risks seriously, this is not the case for industries and institutes related to hydrogen vehicle fuels and hydrogen fueling stations. Petrochemical and petroleum industries are mainly located in remote areas on large tracts of land. This provides considerable intrusion protection and discourages attacks on these facilities. On the other hand, hydrogen fueling stations are mostly built in urban areas, meaning that large amounts of hydrogen are stored near residential areas. These characteristics may make hydrogen fueling stations attractive to terrorists. Thus, the purpose of this study is to qualitatively analyze security risks related to hydrogen fueling stations. In addition, we carried out a detailed consequence analysis using a commercial hazard analysis software tool based on the results of the security risk analysis. Finally, effective countermeasures are suggested for security risk reduction.

2.0 SECURITY RISK ANALYSIS PROCEDURE

We used American Petroleum Institute Standard 780 [25,26] as a reference for the security risk analysis. The standard describes a qualitative methodology of security risk assessment for the petroleum and petrochemical industries. The methodology is a systematic approach for the identification, analysis, and assessment of security issues, and effective security countermeasures can be identified for security risk reduction. Therefore, we applied this methodology to a hydrogen fueling station.

Security risk is defined as the likelihood of a threat successfully exploiting vulnerability and the resulting degree of damage or impact. Therefore, security risk is a function of consequence, vulnerability, and threat that follows the relational expression

$$Rs = \text{a function of } (C, V, T)$$

where:

Rs is the likelihood of a successful act against an asset, including both the likelihood of the act occurring and the likelihood of success causing a given set of consequence;
C is the direct and indirect consequence of a successful act against an asset;
V is the vulnerability of the asset to the act; and
T is the threat associated with the act.

The security risk analysis procedure consists of characterization, threat analysis, vulnerability analysis, qualitative risk estimation, and recommendations for security countermeasures. Characterization defines facility information and identifies assets for risk analysis. Threat analysis is conducted to identify and evaluate potential threats and their actions. The results of threat analysis are described in a threat analysis sheet, which consists of threat, threat motivation, potential actions, threat capability, threat capability ranking (TCR), threat existence level (TEL), and threat ranking (TR). TR is calculated by multiplying TCR and TEL, which are defined in Tables 1 and 2, respectively. Attractiveness analysis is also conducted to estimate the value of a target to a threat. Attractiveness is qualitatively estimated by relative comparison of each asset using the definitions listed in Table 3. Vulnerability analysis is conducted and described in a vulnerability analysis sheet, which consists of threat, scenario, existing countermeasure, vulnerability, consequence level (CL), vulnerability ranking (VR), threat ranking (TR), attractiveness ranking (AR), likelihood level (LL), and risk. CL and VR are defined in Tables 5 and 6, respectively. TR and AR are estimated during the threat analysis. LL is calculated by multiplying VR, TR, and AR, and the LL value is rounded up for conservative risk estimation. From the qualitative risk estimation, security risks are summarized in a risk matrix. In this study, we additionally conducted a detailed consequence analysis based on an identified scenario. Finally, security countermeasures are proposed to recommend a security risk reduction plan.

Table 1 Threat capability ranking

Rank	Level	Description
5	Very high	Threat has a sufficient capability to cause loss of or damage to the asset.
4	High	Threat has a high capability to cause loss of or damage to the asset.
3	Medium	Threat has a moderate capability to attack the asset.
2	Low	Threat has a low capability to defeat countermeasures and attack the asset.
1	Very low	Threat has few capabilities to defeat countermeasures and attack the asset.

Table 2 Threat existence level

Rank (Multiplier)	Level	Description
5 (1.0)	Very high	Credible threat exists against the asset, and the threat attacks every year.
4 (0.8)	High	Credible threat exists against the asset, and the threat attacks every 5 years.
3 (0.6)	Medium	Possible threat against the asset, and the threat attacks every 10 years.
2 (0.4)	Low	Low threat against the asset, and the threat attacks once over the lifetime of a hydrogen fueling station.
1 (0.2)	Very low	There is no threat against the asset.

Table 3 Attractiveness ranking

Rank	Level	Description
5	Very high	Threat would have a very high degree of interest in the asset relative to other assets.
4	High	Threat would have a high degree of interest in the asset relative to other assets.
3	Medium	Threat would have a moderate degree of interest in the asset relative to other assets.
2	Low	Threat would have some degree of interest in the asset, but it is not likely to be greater compared to other assets.
1	Very low	Threat would have little to no interest in the asset.

Table 4 Consequence ranking definition

Rank	Casualties	Replacement cost	Business interruption
5	Off-site fatalities.	Over $1,000,000	From 1 month
4	On-site fatalities	From $100,000 to $1,000,000	From 1 week to 1 month
3	On-site and off-site injuries needing prolonged hospital treatment	From $10,000 to $100,000	From 1 day to 1 week
2	On-site medium injury or off-site minor injury	From $1,000 to $10,000	From a few hours to 1 day
1	On-site minor injury	Up to $1,000	Up to a few hours

Table 5 Vulnerability ranking definition

Rank (Multiplier)	Level	Description
5 (1.0)	Very high	Very ineffective security countermeasures are in place to deter, detect, delay, respond, and recover, so the threat would succeed easily.
4 (0.8)	High	Some security countermeasures are in place to deter, detect, delay, respond, and recover, but these security strategies do not have complete or effective application, so the threat could succeed relatively easily.
3 (0.6)	Medium	Somewhat effective security countermeasures are in place to deter, detect, delay, respond, and recover, these security strategies do not have complete and effective application, so the asset or countermeasure could still be compromised.
2 (0.4)	Low	Effective security countermeasures are in place to deter, detect, delay, respond, and recover; however, at least one weakness exists that a threat would be able to exploit with some effort to evade or defeat the countermeasure.
1 (0.2)	Very low	Multiple layers of effective security measures are in place to deter, detect, delay, respond, and recover from attacks, and the chance that a threat would succeed is very low.

3.0 RESULTS OF SECURITY RISK ANALYSIS

3.1 Characterization

3.1.1 Station model

Figure 1 shows the model of a hydrogen fueling station with an on-site system for producing hydrogen from MCH. The hydrogen supply system includes hydrogen compressor (to 82 MPa), pressurized hydrogen storage tanks, pre-cooler system, and hydrogen dispensers. The hydrogen production system includes MCH supply truck, toluene recovery truck, transfer piping and pump, MCH underground storage tank, dehydrogenation reactor, a heat exchanger, gas-liquid separator, hydrogen compressor (to <1.0 MPa), hydrogen refinery, and toluene underground storage tank. The dehydrogenation reactor produces hydrogen and toluene by MCH dehydrogenation in the presence of a catalyst at 300-400°C. Table 6 identifies the safety measures required for the station by Japanese regulations and security countermeasures.

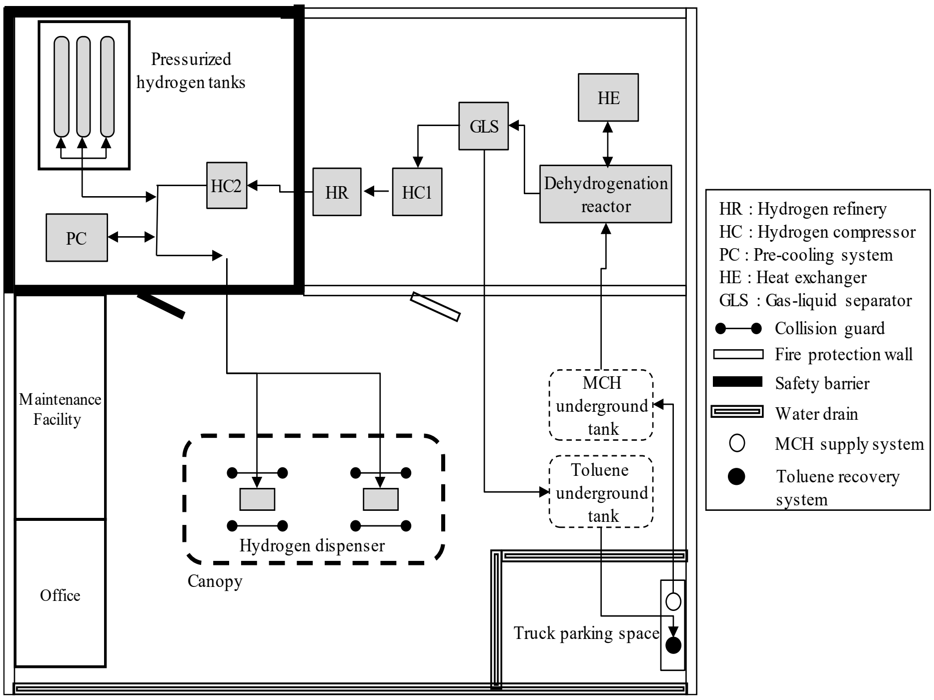

Figure 1 Hydrogen fueling station model with an on-site system for producing hydrogen from MCH

Table 6 Safety measures and security countermeasures

Safety measures		Security countermeasures
■ Collision guard ■ Fire protection wall ■ Safety barrier ■ Water drain ■ Hydrogen detector ■ Water sprinkler system	■ Emergency shutdown system ■ Safety vent system ■ Handheld fire extinguisher ■ Hydrogen flame detector	■ Closed-circuit TV (CCTV) ■ Intrusion detection system ■ Emergency notification system ■ Locked door at fire protection wall ■ Locked door at safety barrier ■ Locked door at office

3.1.2 Asset identification

We identified 20 assets, which are defined as something maintaining the functional capability of the hydrogen fueling station. The function is to constantly supply hydrogen as fuel to FCVs. Table 7 lists the assets identified from the model. Equipment related to hydrogen, toluene, and MCH, such as the dehydrogenation reactor and hydrogen storage tanks, is significantly important to the functional capability. The control room and electric power source are also vital equipment because their loss would interrupt hydrogen fueling operations. Finally, employees and customers are regarded as assets due to the economic purpose of the station.

3.2 Threat analysis

A threat is any adversary who would undertake potential actions to cause the loss of or damage to an asset. Threat categories are external, internal, and collusional (external and internal). A representative external threat is a terrorist, and an internal threat is a disgruntled employee. Collusional is generally assumed to be more dangerous because it combines the ability to inflict damage to assets with an immense knowledge about those assets. Threat analysis was conducted by factors such as motivation to take harmful action, capability to execute the action, and credible existence of a threat.

Table 7 List of assets

#	Asset	Function
1	MCH supply truck	MCH supply
2	Toluene recovery truck	Toluene recovery
3	MCH underground storage tank	MCH storage
4	Toluene underground storage tank	Toluene storage
5	Dehydrogenation reactor	Hydrogen production
6	Heat exchanger	Heat supply to the reactor
7	Gas-liquid separator	Separator of hydrogen and toluene
8	Hydrogen compressor (<1.0 MPa)	Hydrogen compressor
9	Hydrogen refinery	Hydrogen refinery
10	Hydrogen compressor (to 82 MPa)	Hydrogen compressor
11	Pressurized hydrogen storage tank	Hydrogen storage
12	Pre-cooler system	Cooling system for hydrogen
13	Hydrogen dispenser	Hydrogen supply to FCVs
14	Piping	Hydrogen transport among equipment
15	Control system	Equipment controller
16	Employee	Staff operating the station
17	Customer	Hydrogen purchaser
18	Electric power source	Equipment operation
19	Cash	Sale proceeds
20	FCV	Hydrogen consumption

Table 8 shows the results of the threat analysis. We identified seven threats who would deliberately attack the hydrogen fueling station. Terrorist, activist, and disgruntled employee are classic threats. Thief and arsonist were not identified as threats to petroleum and petrochemical industries because of their inaccessible locations; hydrogen fueling stations are built in urban areas and these threats can easily intrude into the station. Disgruntled FCV driver and neighborhood residents are unique threats because they exist in and near the station. For each threat, the table summarizes motivations, potential actions, and capabilities. TCRs to some extent account for the consequences of actions by the threat. For example, a thief has a TCR of 3 because the consequences of theft (financial loss) are less serious than the catastrophic fires that might result from actions by a terrorist, activist, or arsonist. Some threats, such as disgruntled FCV driver and neighborhood resident, may not have special capabilities for attacking assets, but their actions nevertheless could greatly damage equipment, injure employees and customers, and disrupt operations, so their TCR is between that of a thief and a terrorist.

Hydrogen fueling stations have never been attacked by any threats, and the TEL for hydrogen fueling stations is very much lower than that for petroleum and petrochemical plants. However, to perform a conservative analysis, we considered the TELs for hydrogen fueling stations to be the same as those for petroleum and petrochemical plants. From the conservative results, the TEL for terrorist was low because terrorist action is very infrequent, over the lifetime of a hydrogen fueling station. On the other hand, actions by disgruntled employee, thief, and disgruntled neighborhood resident would be expected to be more frequent, so their TELs were set as very high. The TRs were calculated by multiplying TCR and TEL. From the result of threat level, terrorist had a low TR, and arsonist, disgruntled employee, and disgruntled neighborhood resident had a high TR.

Table 8 Results of threat analysis

#	Threat	Threat motivation	Potential actions	Threat capability	TCR	TEL*	TR
1	Terrorist	Has an extremist motivation against corporate activities or national policy.	• Uses explosives or weapons to attack target. • Attacks employee and customer using small arms.	• Has high level of capabilities. • Has organizational support • Has small arms and explosives.	5	2 (0.4)	2
2	Activist	Has a radical motivation against using hydrogen fuels	• Attacks employee, customer, and equipment using small arms. • Reinforces public embarrassment.	• Has high level of capabilities • May have small arms • May spread negative campaign through media.	5	3 (0.6)	3
3	Arsonist	Has an interest in fire.	Starts fires.	Uses a flammable liquid.	4	4 (0.8)	4
4	Disgruntled employee	• Has a sense of dissatisfaction about work. • Has trouble with colleagues or boss.	• Attacks colleague, customer, and equipment. • Sabotages equipment.	• Has technical knowledge to stop operation. • Has access to restricted areas. • May have authority • Likely to use small arms.	4	5 (1.0)	4
5	Thief	Wants money.	Takes money from a cash register and customer.	Likely to use small arms.	3	5 (1.0)	3
6	Disgruntled FCV driver	Feels frustrated by inconvenient hydrogen infrastructure.	Attacks employee, customer, or equipment with vehicle.	Uses FCV as a weapon.	4	3 (0.6)	3
7	Disgruntled neighborhood resident	Opposed to building or operating a hydrogen fueling station.	• Attacks employee and customer with small arms. • Obstructs operation.	• Likely to use small arms. • May invade the station en masse.	4	5 (1.0)	4

*The number in parentheses is the multiplier used to calculate the TR.

The attractiveness analysis was carried out using the relationships between the 20 assets and 7 threats. A representative result of the analysis is shown in Table 9. An AR was assigned for each threat and asset combination. As shown in the table, different threats are attracted to different assets. For example, terrorists are attracted to assets for which the consequences are catastrophic or shocking, while a disgruntled employee would focus on business disruption and personal grudges. Thus, the employee would be attracted to the control system, but a terrorist would likely ignore it, while both would be attracted to fuel systems and employees. However, a disgruntled employee’s attraction to fuel systems would be tempered (AR=3) by the dangers that they pose to anyone trying to sabotage them. An arsonist is attracted only to fuel systems such as hydrogen dispensers, pressurized storage tanks, and the hydrogen production system.

Table 9 Representative results of attractiveness analysis

#	Asset	Threat					
		Terrorist		Arsonist		Disgruntled employee	
		Rationale	AR	Rationale	AR	Rationale	AR
1	MCH supply truck	• Easy access. • High consequences of attack.	5	• Easy access. • High consequences of attack. • No attraction during daylight.	2	Stop operation of hydrogen production system.	3
2	Pressurized hydrogen storage tank	Catastrophic consequences of attack.	5	• Catastrophic consequences of attack. • No attraction during daylight. • Can easily hide inside protection wall.	4	Interrupt supply of hydrogen to FCVs.	3
3	Control system	No attraction.	1	No attraction.	1	• Business interference. • Easy to disrupt.	5
4	Employee	Do enormous harm.	4	No attraction.	1	Do violence to colleagues and bosses.	4

3.3 Vulnerability analysis

Vulnerability analysis identified 93 scenarios using threat and asset combinations with ARs from low to very high level. Table 10 describes representative results of vulnerability analysis. CL, VR, TR, and AR were estimated based on the scenario and their definitions. Risk was analyzed using CL and LL, which is calculated by multiplying VR, TR, and AR and rounding up the result. Details of the scenarios in Table 10 are given below.

In scenario 1, terrorists attack the MCH supply truck using small arms or explosives, and a large amount of MCH leaks from damaged areas. The leaks trigger a massive pool fire or vapor cloud explosion in and around the hydrogen fueling station. Countermeasures have already been installed, but CCTV and emergency contact by employees cannot prevent the action or damage. The emergency shutdown system can effectively mitigate the leak from a damaged hose, but the system cannot stop a leak from the truck body if it is punctured. Hence, the CL is very high, VR is high, TR is low, and AR is very high. The scenario risk was estimated as very high CL and low LL.

In scenario 2, disgruntled neighborhood residents attack the dehydrogenation reactor, and hydrogen, MCH, and toluene leak from damaged areas. The incident would lead to hydrogen explosion and toluene or MCH pool fire, whose consequence is high but not catastrophic because the reactor contains small quantities of hydrogen, MCH, and toluene. The existing station countermeasures would be partially effective. CCTV, an intrusion detection system (IDS), and the emergency contact cannot prevent the action or damage. The fire protection wall and locked door can prevent intrusion into the area surrounding the wall, but the threat would easily intrude to the area if the wall is low and the locked door is breakable. Therefore, the CL is high, VR is medium, TR is high, and AR is low. The risk of the scenario was estimated as high CL and very low LL.

In scenario 3, a thief takes money from a cash register in the office. The attack adversely affects the business operation due to investigation by police. The effect on the operation would be medium because the interruption would be for less than 1 day. CCTV is not effective because it can be used to identify the criminal later, but it cannot prevent the theft. The locked door can prevent intrusion into the office, but the thief can easily break down the door using small arms. Therefore, the CL is medium, VR is high, TR is high, and AR is very high. The risk of the scenario was estimated as medium CL and high LL.

Examples of other scenarios are as follows:

- Disgruntled FCV driver intentionally attacks a hydrogen dispenser using the FCV as a weapon, and hydrogen leaks from damaged areas. The risk is very high CL and low LL because large quantities of hydrogen would leak. The collision guard serves as an effective countermeasure, although the AR of the dispenser is very high.
- Activist vandalizes the toluene recovery truck using small weapons and large quantities of toluene flow from the damaged truck body or hose. The risk is very high CL because a massive vapor cloud explosion or pool fire may occur due to the toluene leak. In addition, LL is low, TR is medium, VR is high, and AR ranking is also high.

Table 10 Representative results of vulnerability analysis

	Threat	Scenario	Existing countermeasure	Vulnerability	CL	VR	TR	AR	Risk	
									CL	LL
1	Terrorist	Attack operating MCH supply truck; MCH leaks from damaged areas.	• CCTV • Emergency contact by employee • Emergency shutdown system	CCTV and emergency contact cannot prevent the action.	5	0.8	2	1.0	5	2
2	Disgruntled neighborhood residents	Attack the dehydrogenation reactor; hydrogen, MCH, and toluene leak from damaged areas.	• CCTV • IDS • Emergency contact by employee • Emergency shutdown system • Fire protection wall • Locked door installed in the wall	• CCTV, IDS, and emergency contact cannot prevent the action. • The threat can climb over the wall if the wall is low. • The threat breaks down the locked door.	4	0.6	4	0.4	4	1
3	Thief	Take money from the cash register.	• CCTV • IDS • Locked door	• CCTV and IDS cannot prevent the action. • Thief breaks down the locked door.	3	0.8	4	1.0	3	4

3.4 Qualitative risk estimation

The risk matrix in Table 11 illustrates the distribution of security risks. The results of qualitative security risk analysis identified two scenarios with very high consequences and high likelihood. One scenario was an arsonist starting a fire at the operating hydrogen dispenser. The reason the risk was very high was that the arsonist can easily access the dispenser due to no obstacles and employees are unlikely to be able to quickly extinguish the fire using a handheld extinguisher. CCTV was installed at the station, but this countermeasure cannot prevent the action. Therefore, the only viable countermeasure is the emergency shutdown system. However, the fire may burn devices related to the shutdown system, leading to a catastrophic event. The other scenario was a disgruntled employee with authority attacking the control system in the office. The event would not lead to hydrogen, MCH, or toluene release, but it seriously affects business by interrupting operations for over 1 month. The employee's operational knowledge makes it easy for them to misuse the control system to disrupt business. CCTV and emergency contact by other employees are partially effective, but these countermeasures cannot prevent the attack. In the next section, we provide a detailed analysis of the consequences of a scenario unique to hydrogen fueling stations using commercial physical effects simulation software.

Table 11 Risk matrix

		Likelihood				
		1	2	3	4	5
Consequence	5	1	25	3	2	0
	4	12	32	4	3	0
	3	1	5	3	2	0
	2	0	0	0	0	0
	1	0	0	0	0	0

3.5 Detailed consequence analysis

We performed a detailed consequence analysis for a scenario in which a toluene recovery truck is deliberately attacked by any threat during pump operation. Figure 2 shows the toluene recovery process, which consists of an underground storage tank, piping, a pump, and a recovery truck. Toluene is produced by MCH dehydrogenation, stored in the tank, and recovered and shipped in bulk to other plants for hydrogenation to MCH. Toluene stored in the tank is transferred to the truck using a pump and piping.

The scenario is unique because the process is new, and the attack leads to massive toluene leaks from the damaged truck or fractures in the piping that connects the tank and the truck. Toluene leakage from the damaged truck body is a common scenario because road transportation of flammable liquids, such as gasoline, has this same risk due to vehicle collisions and rollover accidents. Experience and knowledge on this common scenario have encouraged the implementation of safety measures against the scenario. On the other hand, toluene leakage from damaged piping is specific to hydrogen fueling stations, and this scenario has not been previously analyzed for safety measures and security countermeasures using a physical effects simulation tool.

For this scenario, we focused on thermal radiation from the toluene pool fire using Phast 6.54 [27]. The simulation scenario was that a pipe connecting the pump to the truck inlet was ruptured, toluene continuously leaked, and a toluene pool fire started immediately after the leak began. To evaluate the worst case scenario, we assumed that any safety devices, such as an automatic shutdown valve, were not operated due to equipment failure or vandalization. In the simulation, the scenario type was line rupture, the storage tank volume was 30 kL, wind velocity was 1.5 m/s, Pasquill stability was F, pipe diameter was 3.5 in., leak flow was 800 L/min, pipe length was 2 m, and leak height was 0.1 m.

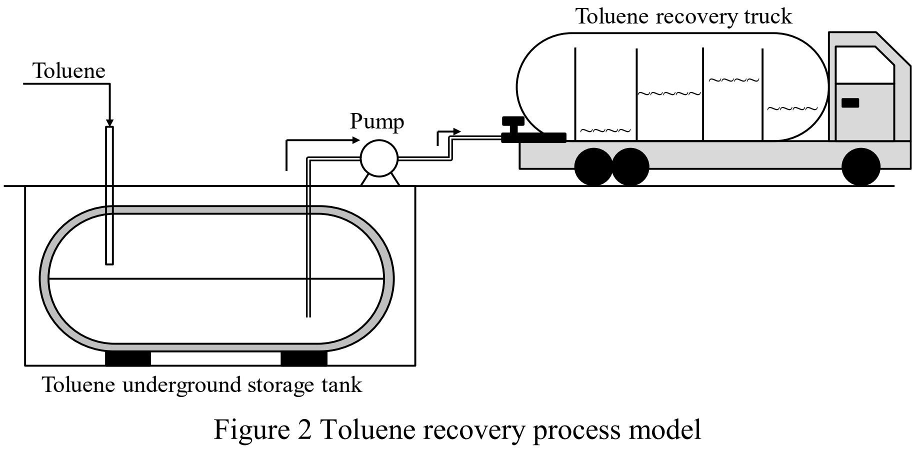

Figure 2 Toluene recovery process model

In the simulation result, the early pool fire diameter was 14.41 m and the flame height was 23.43 m. Figure 3 illustrates the fire's thermal radiation contours for 12.5, 9.5, and 4 kW/m^2. The general range of effects of these thermal radiation levels are as follows: 12.5 kW/m^2 has the minimum energy required to ignite wood and melt plastic tubing, and 4 kW/m^2 will cause pain to personnel if they cannot find cover within 20 s [28]. These results indicate that the thermal radiation can damage equipment and structures near the pool fire. These results should be interpreted as indicative rather than conclusive because the consequences of an actual pool fire strongly depend on the shape of the pool and the simulation result is unlikely to become a reality in the event of an actual pool fire.

Hydrogen fueling stations in urban areas may be surrounded by residential houses, condominium buildings, supermarkets, and schools. The pool fire may not cause injury to persons because people around the pool fire can easily escape and evacuate, but damage to equipment and structures at and near the hydrogen fueling station may be significant. Hydrogen leakage and fire spreading may cause knock-on accidents (i.e., the "domino effect"). In general, knock-on accidents have significant consequence but rare frequency. The pool fire had high consequence, but it was not a catastrophic event in itself. Impact to the hydrogen fueling station carries catastrophic risks, such as physical explosion of hydrogen storage tanks and vapor cloud explosions of toluene or MCH. Hence, risk analysis has mainly focused on the single risk causing catastrophic events, but the pool fire, which is not a catastrophic event, may expand and eventually transform into a catastrophic event by gradual impact to the station and nearby constructions. Therefore, it is necessary to analyze and evaluate not only single risks but also knock-on risks related to safety and security issues.

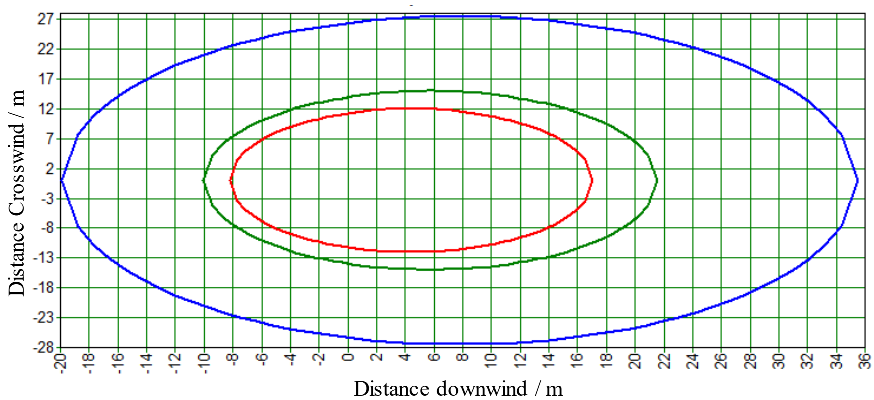

Figure 3 Thermal radiation contour of a toluene pool fire at a height of 0 m, where red, green, and blue contours represent thermal radiation levels of 12.5, 9.5, and 4 kW/m^2, respectively.

3.6 Recommendation for security countermeasure

Qualitative security risk analysis identified many potential vulnerabilities of hydrogen fueling stations. Outside threats can easily intrude into the station, and this intrusion vulnerability is unique for an installation having a large quantity of dangerous chemicals. The station lacks the security gate that is generally installed in petrochemical and petroleum plants. However, as might be expected, it is not practicable to install a security gate at a hydrogen fueling station because it must be accessible to FCV users, that is, the public. Therefore, to prevent attacks, fire protection walls and safety barriers should be tall enough to prevent easy climbing, and strong, locked doors should be installed in these walls to prevent intrusion into equipment areas. Furthermore, to mitigate the sequence of events after an attack, a robust emergency shutdown system is critical for preventing massive leaks. In particular, the hydrogen dispenser and toluene and MCH transfer systems should have reliable shutdown systems because they are vulnerable. We additionally recommend the fostering of a good working relationships among employers and employees for prevention of insider attacks, and the operating company also should make efforts to develop good relationships with FCV drivers and the neighborhoods around fueling stations.

Operating companies should unwillingly accept that attacks and equipment damage are possible, and be prepared to replace damaged equipment and re-open the station as rapidly as possible to minimize losses. Security risk analysis also revealed that it was very important to prevent and mitigate knock-on accidents, which can accelerate and expand negative consequences into the surrounding neighborhood. Mitigation countermeasures are particularly needed because it is impossible to completely prevent deliberate actions. A company operating hydrogen fueling station needs to implement countermeasures against threats, but there are distinct limitations to the prevention and mitigation countermeasures that can be installed in a lot of hydrogen fueling stations. Therefore, the operating company, police, and fire-fighters should cooperate on security issues and prepare for both structural and non-structural countermeasures, such as procedures and training against the various threats. In addition, they should prepare for emergency responses and recovery actions to re-operate the station.

4. CONCLUSIONS

Qualitative security risk analysis was carried out to identify security threats and attack scenarios for a hydrogen fueling station with an on-site system for producing hydrogen from MCH. From the results of analysis, 93 attack scenarios were identified, the consequence risk of knock-on events was pointed out, and we recommended additional countermeasures to prevent and mitigate deliberate attacks from outside and inside the station. Furthermore, it is important for the operating company, police, and fire-fighters to prepare for emergency responses and recovery actions. Risk assessment of both safety and security issues is essential for building a safe and secure hydrogen fueling station. Knowledge from the analysis and the simulation can contribute to security risk reduction for all types of hydrogen fueling stations.

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