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Quantitative risk assessment of an amine-based CO_2 capture process

Chanhee You and Jiyong Kim†

Department of Energy and Chemical Engineering, Incheon National University,
119 Academy-ro, Yeonsu-gu, Incheon 22012, Korea
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Abstract−This study presents a risk assessment study on an amine-based CO_2 capture process. Based on the critical risks identified by a hazard and operability study (HAZOP) conducted in our previous work, we performed detailed quantitative risk assessment, including frequency estimation using fault tree analysis (FTA) and consequence estimation using the process hazard analysis software tool (PHAST). As a result of our FTA study on explosion accidents in the absorber column as a top event, we identified 25 basic events and eight intermediate events that lead to the top event. The probability of a T-102 explosion was estimated to approximately 3.55E-03 per year, which satisfies international safety regulations. Additionally, we performed consequence estimation for three types of accidents in an absorber, namely toxic substance leakage, explosions, and fireballs, under two different weather conditions, namely modest and worst conditions. It was determined that in the event of a toxic substance leakage accident, the effect zone of acid gas with high toxic substance content is approximately four-times larger than that of raw gas.

Keywords: Quantitative Risk Assessment, Safety, Fault Tree Analysis, Consequence Assessment, CO_2 Separation

INTRODUCTION

CO_2 is one of the main greenhouse gases that can affect climate change [1,2]. Global energy-related CO_2 emissions grew by 1.7% in 2018 to reach a historic high of 33.1 Gt [3]. Increasing CO_2 emissions are driven by increasing energy consumption based on global economic growth, as well as improved quality of life in some countries, which has led to greater energy demands for heating and cooling [4]. Although significant energy efficiency improvements and low-carbon technology deployment has recently led to the stagnation of CO_2 emissions, power sectors that generate electricity through the combustion of fossil fuels (e.g., coal, natural gas, and oil) still account for nearly two-thirds of emission growth as the largest stationary sources of CO_2 emissions [3].

Carbon capture and storage (CCS) has been considered as a practical and efficient technological framework for immediately mitigating CO_2 emissions caused by the use of fossil fuels [5,6]. The technical maturity of CCS technology has the capability to reduce high-concentration CO_2 emissions from power plants by approximately 90% [1,2]. In CCS technology, the CO_2 capture process is a core technology. Post-combustion CO_2 absorption using aqueous amine absorbents is the most well-known and widely used technology based on its technical maturity and low cost [7,8]. The most widely-used amine for post-combustion CO_2 capture is monoethanolamine (MEA). The technical and economic advantages of this amine have been proven by its wide use in gas treatment and in refineries for the removal of acid gases.

A significant number of large-scale integrated CCS technologies are in operation around the world with a total worldwide CO_2 capture capacity of approximately 40,000 tons per year [1,9]. The U.S. DOE announced that approximately \$2.66 billion has been invested for CO_2 utilization since 2010 and the corresponding market of CO_2-derived products is gradually increasing [10]. This market expansion is leading to the full deployment of various CO_2 capture and utilization processes. Particularly as new advanced technologies, CO_2 can be utilized in a variety of ways and products: chemical and fuels (e.g., hydrocarbons, urea, formic acid, methanol, and salicylic acid) production, mineralization processes and beverage and food processing (e.g., acidifying agents) [10]. The CCS capacity has also increased up to an industrial scale; very large-scale amine-based CO_2 absorption (80 ton of CO_2 per day) has been recently accomplished in US and China [11].

Usually, before the scale-up for commercializing, the plant and process should be investigated from the perspective of safety. A lack of information regarding potential risks or past accidents poses a significant challenge for risk assessment [12]. Regardless, there have been several studies on the risk assessment and safety improvement of amine-based CO_2 capture processes. Krzemien et al. quantitatively analyzed the corrosion rates of equipment using aqueous amine solution flows [13]. They also analyzed the vulnerabilities of the CO_2 capture process and identified critical hazards through the HAZOP study [12].

Despite previous studies on the risk assessment and safety improvement of amine-based CO_2 capture processes, there is still a lack of quantitative risk assessment (QRA) studies, which include likelihood estimation using fault tree analysis (FTA) and consequence assessment (CA). FTA, as one of widely used frequency analysis techniques, identifies potential failure mechanisms and quantifies probability of the potential failure modes using failure rate data. While FTA study is very useful to qualitatively and quantitatively assess the likelihood of undesired accidents, the assessment of the severity of undesired accidents should be incorporated into the full

†To whom correspondence should be addressed.
E-mail: jykim77@incheon.ac.kr

QRA study [14]. CA focuses on assessing the consequences of accidents such as to fatalities, economic losses and environmental impacts. Accordingly, CA along with FTA study for frequency analysis within the QRA framework is essential for quantifying the risks and supporting cost effective decisions and strategies for an entire asset lifecycle [15]. The goal of this study was to perform a full risk analysis, ranging from hazard identification to qualitative and quantitative analysis of the frequency and consequence of potential hazards of the amine-based CO_2 capture processes. Furthermore, based on the results of the full QRA study, this study suggests practical recommendations to reduce the risks of the target process for the essential improvement of the safety level. The remainder of the paper is organized as follows: section 2 introduces the QRA methods used in this study and the target process. Section 3 discuss the major results of the QRA study including identified hazards through HAZOP study [16], frequency analysis using FTA and CA using PHAST. Finally, section 4 summarizes major findings of this study and points out the contribution of this study to the safety improvement.

METHODOLOGY AND SYSTEM DESCRIPTION

1. QRA Method

The goal of this study was to perform a full QRA of amine-based CO_2 capture processes. Risk assessment is an essential step for preventing severe accidents and improving safety by managing identified risks. It is important to analyze all possible deviations in process equipment during process operation that can lead to any potential risks [17]. To develop a set of risk acceptance criteria and a suitable risk assessment methodology, we performed four main tasks: risk identification, consequence analysis, frequency analysis, and risk evaluation, as shown in Fig. 1.

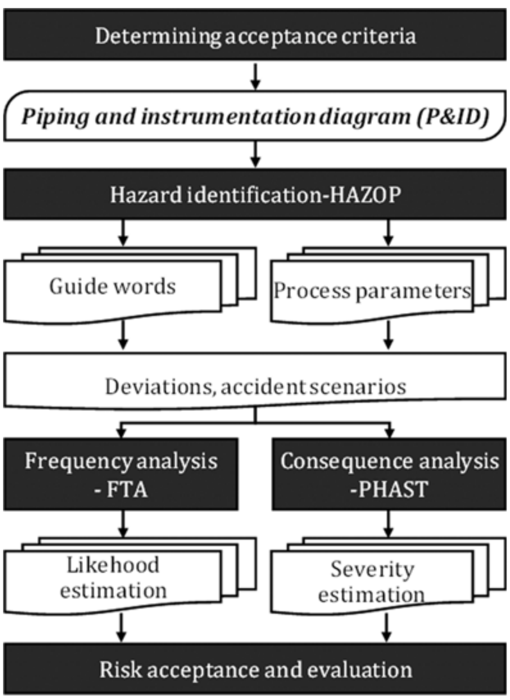

Fig. 1. Procedure and main tasks for risk assessment.

Determining quantitative risk acceptance criteria is important for safety management systems. This task should be accomplished prior to performing detailed QRA. Acceptance criteria are defined based on the safety goals of stakeholders. The results of QRA (process equipment, configurations, and operations) are then compared to the set of risk acceptance criteria to determine if a risk level is compatible with the desired safety goals. If the assessed risk level is too high to satisfy the acceptance criteria, then additional risk management tasks for reducing the risk level should be identified and implemented. Note that the risk acceptance criteria must meet stakeholder goals and satisfy global standard codes [17]. To identify hazards and assess the risk levels of amine-based CO_2 capture processes, we adopted the criteria proposed by the Center for Chemical Process Safety of the United States and the Korea Occupational Safety and Health Agency (KOSHA) of Korea [18-20]. The suggested detailed risk acceptance criteria are defined below.

- Comparing statistics from processes and equipment in existing chemical process industries to derive a historical average risk level.
- Comparing assessed risk levels (likelihood and severity) according to QRA.
- Comparing general risks to society and communities.

As the first step of QRA, a HAZOP study was conducted to identify hazards. HAZOP study is widely used for the systematic diagnosis and identification of operational disturbances and deviations within examined processes. This method is not only useful for identifying health and environmental hazards, but also potential operational issues. It is also a powerful tool for assessing the safety levels of new facilities (e.g., amine-based CO_2 capture processes), where all risks must be identified before a process can operate safely. In the case of amine-based CO_2 capture processes, conducting QRA is difficult based on a lack of sufficient engineering and operation data. QRA should not only be utilized for identifying risks while implementing and executing process, but also for providing reliable methods to improve safety levels.

When performing a HAZOP study, one of the main challenges is the need to demonstrate the process capabilities of a power plant. The risk acceptance criteria for amine-based CO_2 capture processes should be tightened by considering potential impedance to the capability of a power plant to generate electricity, as well as risks to society generated by any potential chemical releases. Therefore, risk assessment of amine-based CO_2 capture processes should cover a range of industrial considerations, such as the potential for spillage, leakage, flammability, corrosion, and the handling of reagents (e.g., MEA), by-products, or waste [13].

As a second step, we analyzed the likelihood and severity of identified hazards by performing a consequence and frequency analysis study. For frequency analysis, we utilized FTA for analyzing the causes of specific risks by adopting a deductive method [17]. FTA is a graphical expression that represents how a top event occurs and systematically estimates the probability of that top event. A specific risk that is identified by a HAZOP study is considered as a top event in a fault tree. Top event probabilities are calculated quantitatively based on the probability (unreliability) of selected basic events. Additionally, FTA can be used to identify the theoretical relationships and contributions of different risk categories (intermediate events and gates), as well as basic events, which are clarified using *AND* operations of multiplication and *OR* operations of summation logic [17,21].

CA, a widely used risk analysis method, evaluates the potential impacts of accidents (e.g., fire, explosion and toxic material releases) on surroundings such as human beings, assets and the ecosystem [22]. If a gas leakage does not lead to other undesired accidents (e.g., a fire), CA for a leakage accident focuses on the evaluation of the concentration distribution of a toxic gas around the leakage area. On the other hand, if a leaking gas causes fire at the leakage source, a CA study for a jet fire is employed. Such fires pose a threat to human beings near the leakage source. The risk of the jet fire can be determined quantitatively by measuring thermal radiation flux. If leaking gas catches fire after it forms a persistent vapor cloud, but before is mixes intensively with air, then a fireball is generated. If leaking gas catches fire after it mixes intensively with air and forms a persistent vapor cloud, it will generate significant flash fires or vapor cloud explosions. For consequence analysis, we adopted PHAST, which is a professional simulator for chemical process modeling developed by DNV GL [23]. This tool is one of the most popular tools for CA and is a powerful tool for predicting effect zones. It in- cludes accurate dispersion, evaporation, and emission rate models.

2. System Description

A simplified flowchart for an MEA-based CO_2 capture process is presented in Fig. 2. More detailed P&ID flow chart for the MEA-based CO_2 capture process is shown in Fig. 3. While a number of absorbents and mixed solutions are under R&D stage, we study adopted MEA (30 wt% solution) as a solvent [5], which is one of the most mature and widely used in real industries. Thus, the MEA solutions are used to remove a high-purity CO_2 from an input flue gas stream with moderate operating conditions [12]. The raw flue gas from a power plant is first scrubbed with circulating water at a temperature of approximately 40 °C to remove impurities. The pretreated raw gas then enters at the bottom of the absorber (T-101) while the MEA solution (i.e., lean amine solvent) enters at the top of the absorber, leading to contact between CO_2 and the MEA solvent in a packed absorber.

Treated flue gas, which mainly consists of N_2 and O_2 with a small amount of water, exits at the top of the absorber after recovering any MEA traces. When an amine stream is loaded with a certain level of CO_2, as is the case with the stream that exits through the bottom of the absorber, it is referred as a rich amine stream. The rich amine that exits through the bottom of the absorber is pumped into the cross-heat exchanger (E-101) to be preheated by a regenerated lean amine solvent before being regenerated in the stripper. In the exchanger, the lean stream is cooled further, reducing its temperature to approximately 40 °C. It then enters at the top of the absorber. The preheated rich amine enters at the second tray of the stripper (T-102) and flows down the column, traveling in the direction of the vapor from the re-boiler at the bottom of the stripper. The overhead vapor from the stripper is cooled and most of the water is condensed out of the low-pressure CO_2 components. The majority of the condensed water reflux returns to the top of the stripper and the remaining water returns to the absorber. The remaining low-pressure CO_2 product leaving the stripper is dried and compressed in the compression section. Table 1 lists the operating

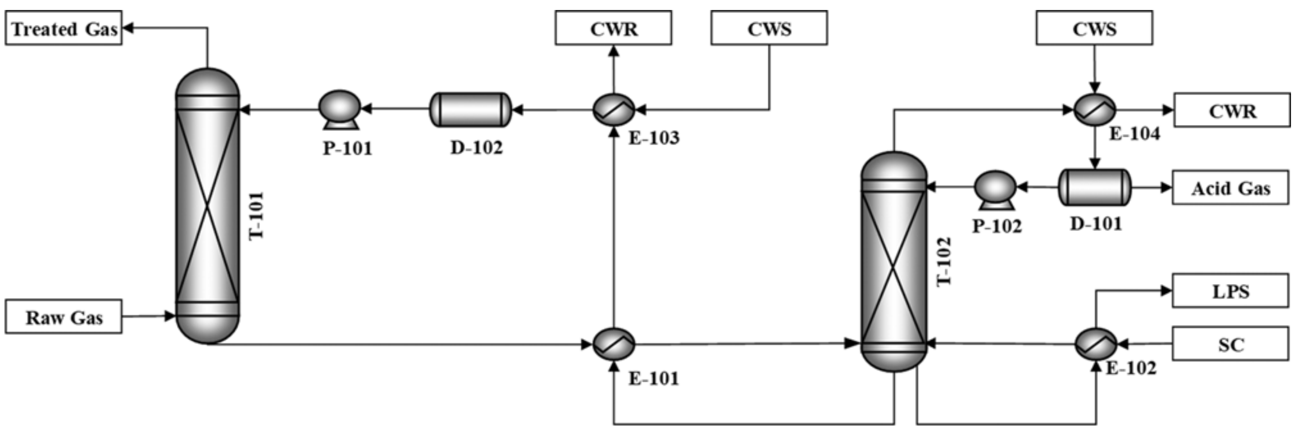

Fig. 2. Simplified flowchart for an MEA-based CO_2 capture process.

Table 1. Operating conditions and media corresponding to the flowchart

Component	Pressure (bar)	Temperature (°C)	Flow rate (kg/h)	Medium
Raw gas to T-101	35.0	25.0	1,200.0	Raw gas
T-101 to E-101	31.0	36.0	44,238.0	Rich amine
T-102 to E-104	1.0	120.0	3,038.0	Amine+CO_2
T-102 to E-102	0.9	50.0	2,869.0	Amine
T-102 to E-101	1.2	125.5	44,051.0	Lean amine
P-101 to T-101	34.6	35.0	44,057.6	Lean amine

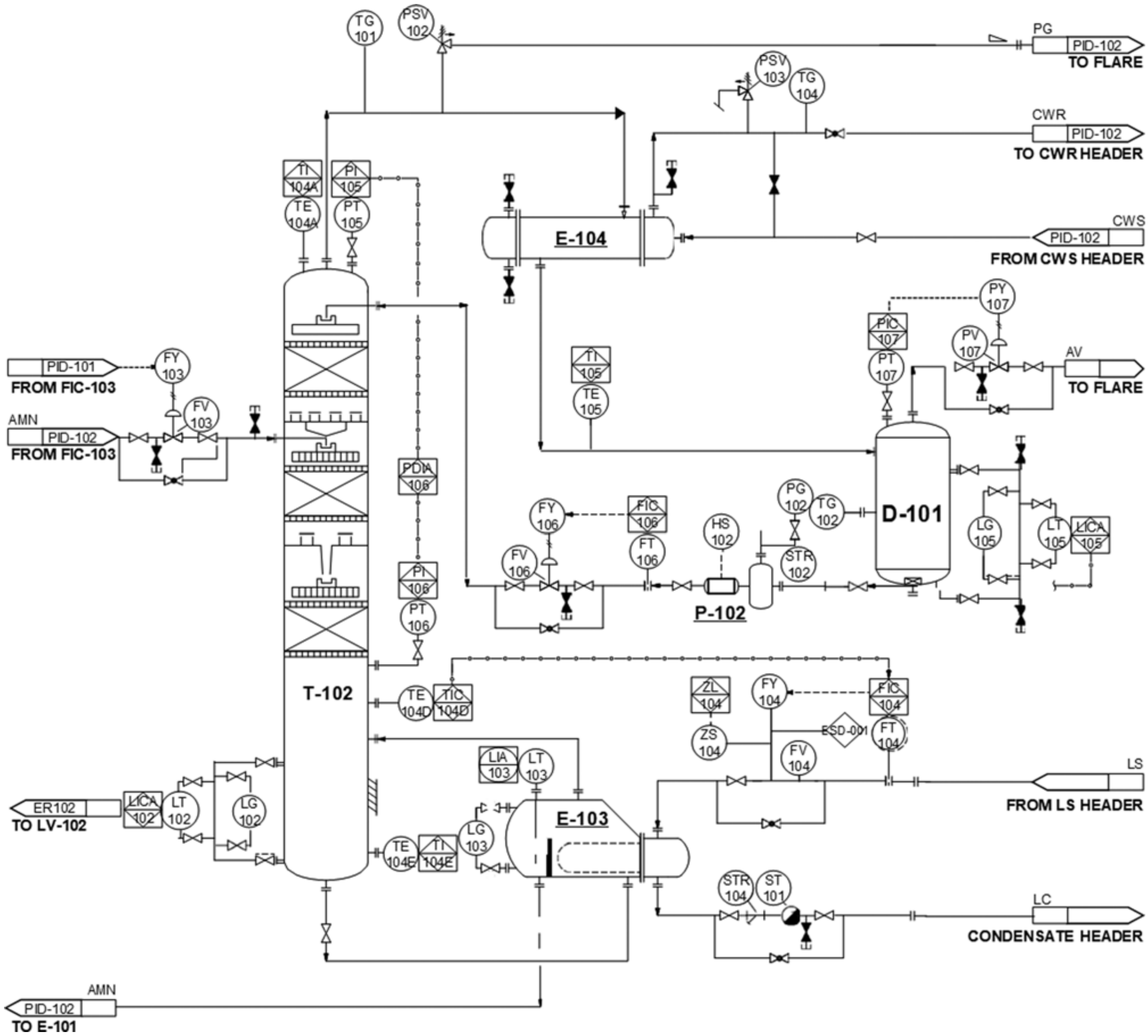

Fig. 3. Piping and instrumentation diagram of T-102.

conditions and medium corresponding to the flowchart.

RISK ASSESSMENT RESULTS

1. Hazard Identification

A HAZOP study was conducted to identify hazards in amine-based CO_2 capture processes. In our previous work [16], we investigated six major nodes and 102 abnormal deviations. As a result, it was determined that T-102 explosions in amine-based CO_2 capture processes carry a high risk (action order 1), as indicated in Table 2. Risk levels are assessed according to severity (S) and likelihood (L), where higher values denote higher rankings. More detailed information regarding our HAZOP study on amine-based CO_2 capture processes can be found in our previous work [16].

Based the results of our HAZOP study, the FTA method was applied to calculate the probability of occurrence of the selected nodes (action order 1) and analyze factors (basic events) that can contribute to the occurrence of a specified undesired event (or top event). In the case of amine-based CO_2 capture processes, five fault trees were analyzed for each top-order node based on the probabilities of the basic events. Table 3 lists the probabilities of occurrence of the basic events involved in the top event of a T-102 explosion [13,24-30].

2. Frequency Analysis

The results of FTA on a T-102 explosion as a top event are presented in Figs. 4 and 5. The top event is broken down into two intermediate events, and each intermediate event is then subdivided into a number of sub-intermediate events, which represent the contributions of the selected basic events. This means that a full fault tree is developed continuously until no remaining intermediate events can be subdivided into basic events. The constructed fault tree includes 25 basic events that lead to explosion accidents for T-

Table 2. HAZOP summary with the selected high-ranked hazards of T-102 [16]

Parameter	Deviation	Cause	Accident scenario	Safeguard	S	L	Rank
Flow	More flow	FV-104 Malfunction (fully open)	Increased rich amine transfer to T-102→ Liquid level of T-101 drop→Raw gas flows into T-102 through E-101 T-102 Rupture by T-102 overpressure	- Level check (LICA-101) - Shutdown (LS-101) - P monitoring (PSV-103)	4	2	III
		FV-105 Malfunction (fully open)	Excessive supply of inlet stream to T-102→ E-102 LP steam over reboiling→T-102 rupture by T-102 overpressure	- P monitoring (PDIA-106) - T monitoring (TIC-104) - P monitoring (PIC-107) - P monitoring (PSV-103)	3	2	II
	No/Less flow	T-102 Packing plugging	Reduced T-102 vent stream→Rupture by T-102 overpressure	- P monitoring (PDIA-106) - P monitoring (PIC-107)	3	2	II
		P-102 Failure	T-102 reflux interrupted→T-102 temperature, pressure increased→T-102 rupture by T-102 overpressure	- Pump monitoring (L-102) - Flow monitoring (FIC-106) - P monitoring (I-105) - P monitoring (PSV-103)	3	2	II
		FV-106 Malfunction	T-102 reflux interrupted→T-102 temperature, pressure increased→T-102 rupture by T-102 overpressure	- P monitoring (PI-105) - Overpressure prevention (PSV-103)	3	2	II
Level	Low level	LT-101 Malfunction	Liquid level of T-101 drop→Continuous liquid level of T-101 level drop Raw gas flows into T-102 from E-101→T-102 rupture by T-102 overpressure	- Flow monitoring (FIC-102) - P monitoring (PI-104)	4	2	III
		LT-104 Malfunction	T-102 reflux interruption→T-102 temperature, pressure increased→T-102 rupture by T-102 overpressure	- Flow monitoring (FIC-106) - P monitoring (PI-105) - P monitoring (PSV-103)	3	1	II
Pressure	High pressure	External fire	T-102 damage due to overpressure	- P monitoring (PSV-103) - Surrounding fire	3	2	II
Temp.	High temp.	TIC-104D Malfunction	Excessive supply of inlet stream to T-102→ E-102 LP steam over reboiling→T-102 rupture by T-102 overpressure	- T monitoring (TIC-104) - P monitoring (PSV-103) - P monitoring (PI-105)	3	2	II
		E-104 Water supply Interruption	T-102 overhead condensing interrupted→ T-102 rupture by T-102 overpressure	- P monitoring (PIC-107) - P monitoring (PSV-103)	3	1	II

102. The FTA of a T-102 explosion was designed to respond to intermediate events, such as over pressurization of T-102, acid gas leakage, corrosion rupture, pump cavitation, and temperature increases in T-102. Intermediate events are defined by various basic events (e.g., corrosion of materials, human error, gasket or flange rupture). Control loops (e.g., FV-SD, FV-CO, and TIC LA in Fig. 3) consist of different mechanical failures, such as control failures, manual human errors, or valve ruptures.

Basic events, such as PDIAI, LICAI, XLI, TII, and FI, are human errors caused when the positioner simply ignores an indicator or alarm. MHE represents a basic event where the valve positioner performs improper manual control. TM is a basic event where the transmitter fails, resulting in a low or high reading. E-101 rupture is a situation defined by full bore rupture around E-101. VR is a basic event representing external leakage or rupture around a valve. PHE is a basic event represent human error during pump operation. PCF is a basic event where positioners have not performed periodic checks on equipment or piping and have ignored the results of periodic checks. Corrosion rupture refers to corrosion by CO_2, H_2S, N_2, and amines on carbon steel materials that are commonly used in pipelines and equipment. As a result of FTA, the probability of the top event (T-102 explosion) was estimated to be 3.55E-03, as shown in Table 4. Because OP T-102 and AGL are the top intermediate events, they have the greatest affect on T-102 explosions. In particular, the probability of AGL is 2.67E-03, which is greater than the probability of OP T-102 (8.79E-04). Additionally, it was determined that the RFG and CR events have the greatest impact on the AGL event. CR is severe based on the high amine concentration (30 wt% MEA solution) and RFG is one of the most common failures during general chemical process operations.

3. Consequence Analysis

Explosions, toxic substance leakage, fireballs, and jet fires are the

Table 3. Probabilities and descriptions of basic events involved in a T-102 explosion

No.	Component	Symbol	Probability(y^{-1})
1	Pressure drop indicating alarm-ignore	PDIAI	1.00E-02
2	Corrosion by materials	CM	1.20E-02
3	Periodic check-off failed	PCF	3.00E-03
4	Manual human error	MHE	2.69E-01
5	External fire	EF	4.38E-02
6	Fire prevention system	FPS	1.75E-04
7	Rupture of flange or gasket	RFG	2.62E-03
8	Pipe leakage	PI	5.95E-06
9	Pipe rupture	PR	8.76E-07
10	Leakage of suction piping	LSP	1.00E-03
11	Manual valve improper control	MVIC	7.30E-01
12	Heat exchanger (E)-101 rupture	ER	9.60E-05
13	E-104 cooling water supply stopped	ECWSS	1.39E-05
14	Control failure	CF	2.90E-01
15	Valve rupture	VR	8.76E-05
16	Transmitter malfunction	TM	4.50E-01
17	Temperature indicator-ignore	TII	1.00E-02
18	Temperature indicator-failed	TIF	4.40E-02
19	Pressure safety valve failed	PSVF	3.65E-03
20	Level indicating control alarm-ignore	LICAI	3.00E-02
21	Feed indicator-ignore	FII	1.00E-02
22	Level indicator-failed	LIF	4.00E-02
23	Pump human error	PHE	3.00E-03
24	Transformer (low voltage)-ignore	XLI	1.00E-02
25	Level switch-failed	LSF	3.00E-01

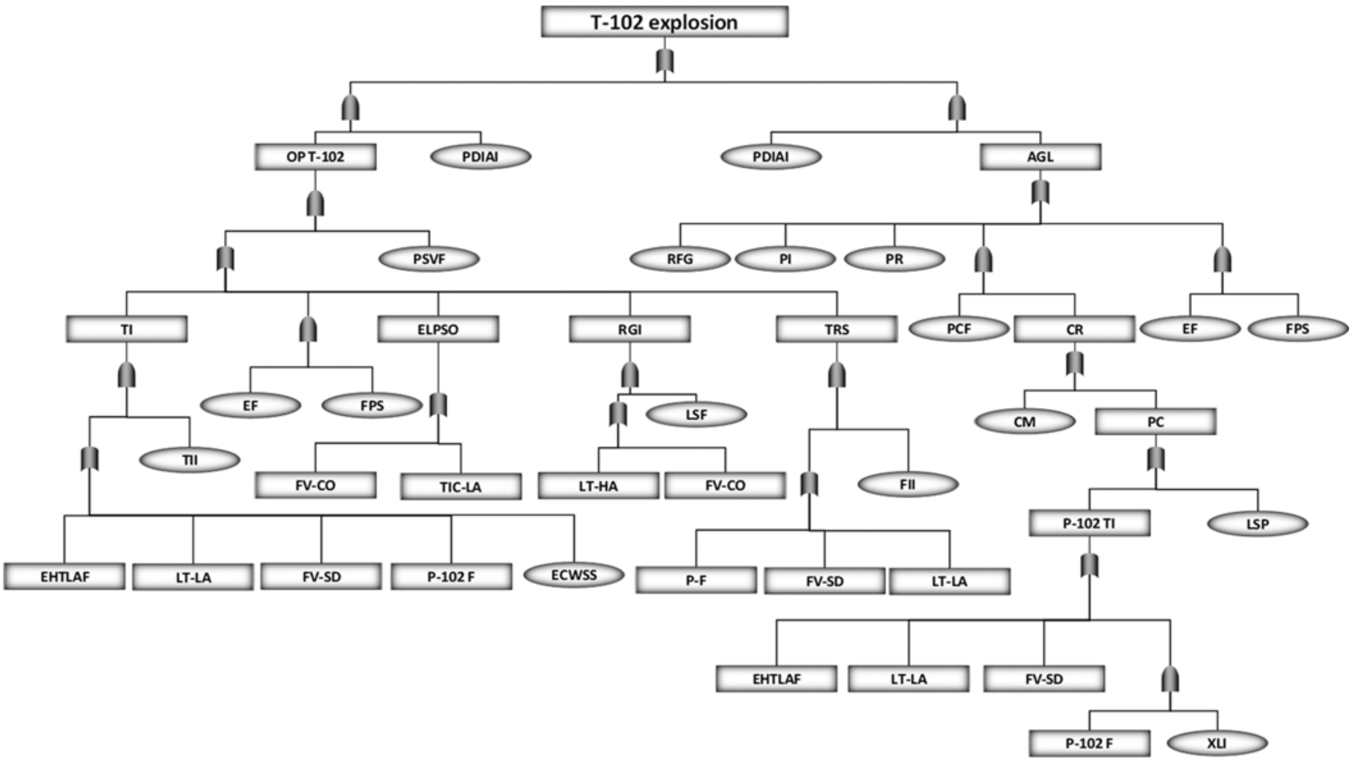

Fig. 4. FTA on T-102 explosions in amine-based CO_2 capture processes.

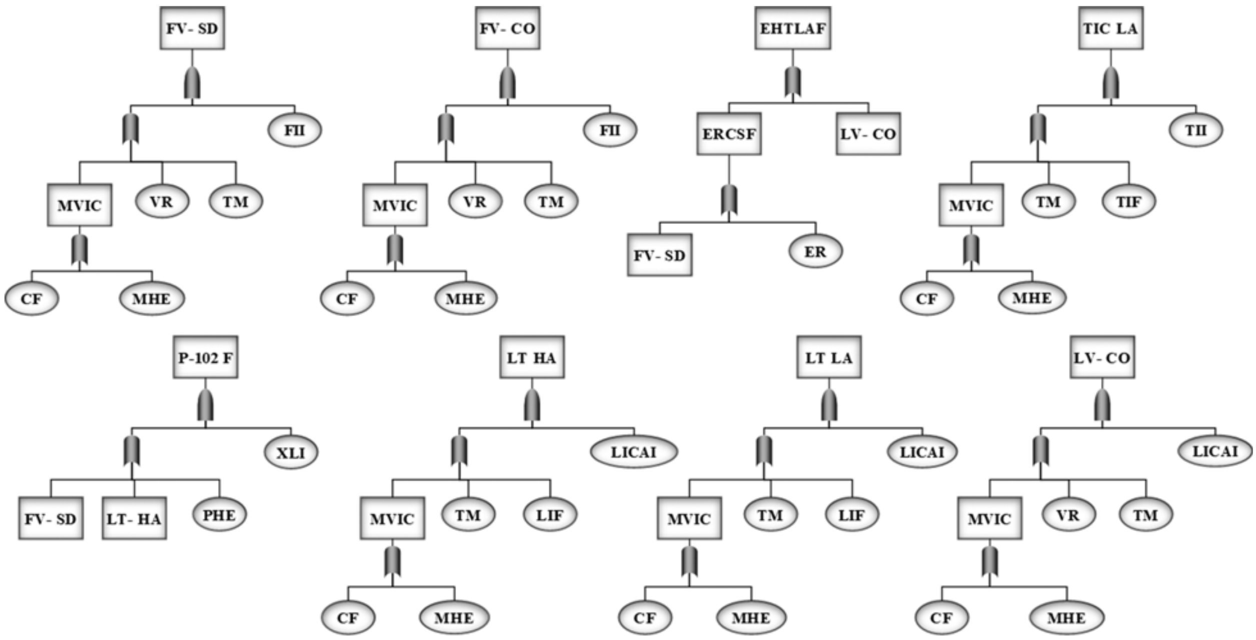

Fig. 5. Intermediate events of FTA on T-102 explosions in amine-based CO_2 capture processes.

Table 4. Calculated probabilities and descriptions of intermediate events and top events

No.	Component	Symbol	Probability (y^{-1})
1	T-102 explosion	Top event	3.55E-03
2	T-102 over pressurized	OP T-102	8.79E-04
3	Acid gas leak	AGL	2.67E-03
4	T-102 temperature increase	TTI	9.62E-04
5	Heat exchanger-102 low pressure stream overdose	ELPSO	2.40E-02
6	Raw gas inflow	RGI	1.45E-02
7	T-102 reflux stop	TRS	4.89E-04
8	Rupture by corrosion	RC	1.19E-02
9	Pump cavitation	PC	9.57E-05
10	Pump-102 temperature increase	P-102 TI	9.57E-02
11	High temperature lean amine flows into E-101	EHTLAF	4.73E-02
12	E-101 reduction of cold stream flow	ERCSF	1.19E-02
13	Feed valve shut down	FV-SD	1.18E-02
14	Feed valve complete opening	FV-CO	1.18E-02
15	Temperature indicating controller lower than actual	TIC LA	1.22E-02
16	Pump-102 failure	P-102 F	5.84E-04
17	Level transmitter higher than actual	LT- HA	3.66E-02
18	Level transmitter lower than actual	LT- LA	3.66E-02
19	Level valve complete opening	LV- CO	3.54E-02
20	Manual valve improper control	MVIC	7.30E-01

main accident types in amine-based CO_2 capture processes based on the physical and chemical properties of acid gas and the amines used [16]. Fireballs and jet fires can cause damage to nearby people and facilities based on the emission of radiant heat. Explosions can cause domino effects and damage multiple facilities, but such effects were not considered in this study because they constitute secondary propagation [17]. On the other hand, the damaging effect caused by toxic substance leakage depends on the concentration of

Table 5. Weather and land conditions for two target scenarios

Scenario	A	B
Wind speed (m/s)	1.5	2.7
Atmospheric stability (A-F)	F	D
Ambient temperature (°C)	34.4	14.1
Humidity (%)	69.0	69.0
Land roughness	Urban	Urban

toxic substances and duration of exposure. A T-102 explosion, which is a main accident, can be categorized according to the type and amount of leakage substances, as well as the type of leakage accident. In this study, we classified accident cases into two scenarios (A and B) according to the criteria of the KOSHA guide, as shown in Table 5 [31,32]. According to KOSHA guidelines [20], this study developed two different accident scenarios (A and B) by assuming two different weather conditions and atmospheric stabilities. The weather conditions for scenario A are an atmospheric stability grade of F and wind speed of 1.5 m/s, which represent favorable conditions. The atmospheric stability grade F represents a very stable atmosphere, which was selected to guide the results of fire and explosion analysis toward conservative values. The weather conditions for scenario B are an atmospheric stability grade of D and wind speed of 2.7 m/s, which represent moderate conditions. Similar to atmospheric stability, the temperature in scenario A is

Table 6. Parameters for accident scenario modeling

Case	Accident scenarios	Accident type	Pressure (MPa)	Temperature (°C)	Leakage hole (mm)	Leakage result (kg/s)
1	Raw gas leakage	Catastrophic rupture	0.883	120	0	0
2	Acid gas leakage	Catastrophic rupture	0.883	120	0	0
3	Acid gas leakage	Leak	0.883	120	50	3.77
4	Acid gas leakage	Leak	0.883	120	25.4	0.94

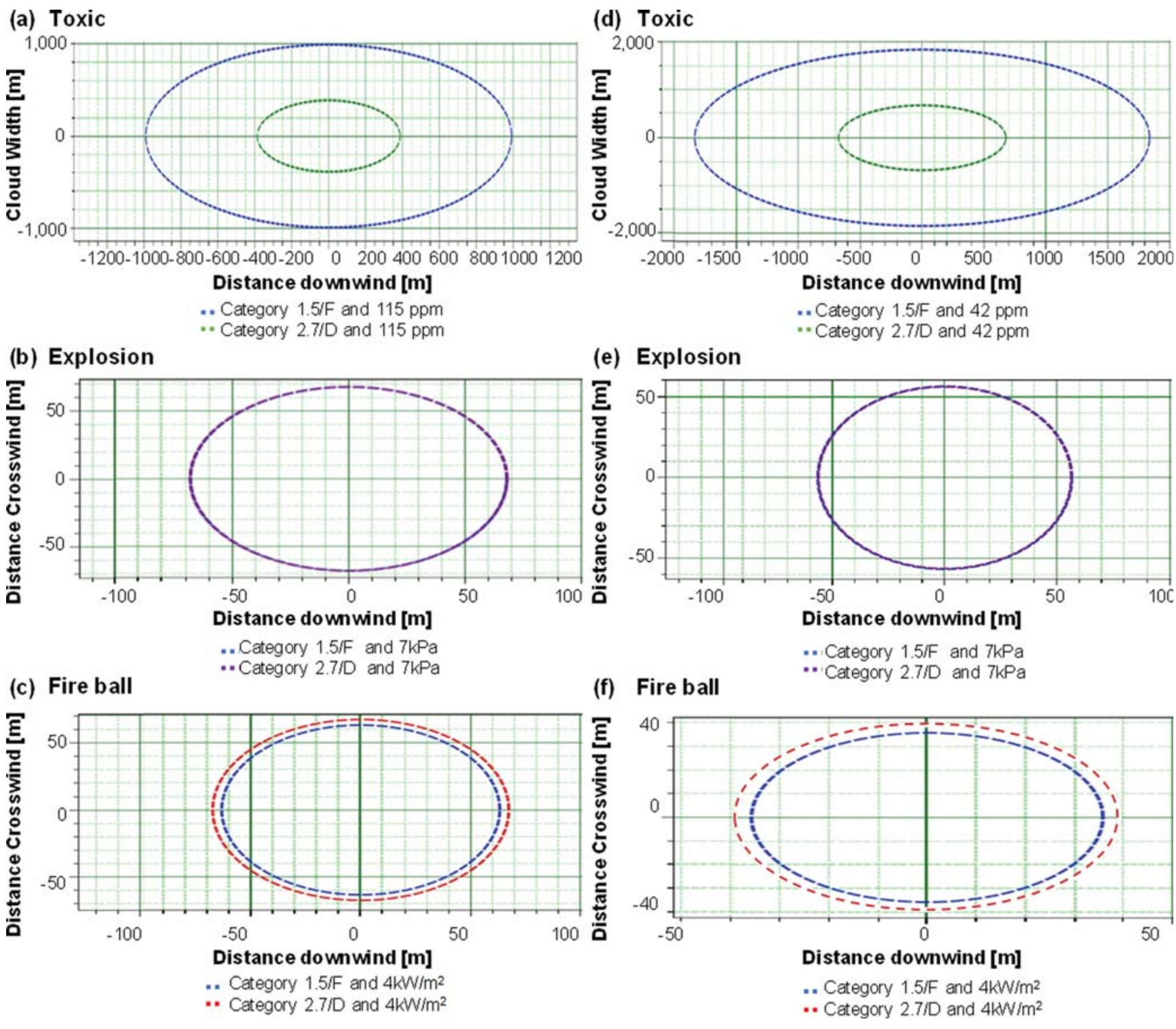

Fig. 6. Comparison of consequence analyses of cases one (left) and two (right) for toxic substance leakage, explosions, and fireball accidents.

assumed to be relatively high, whereas that in scenario B is assumed to be mild. Both scenarios were applied with the average humidity at major industrial sites (e.g., Seosan, Ulsan, and Yeosu) in Korea [33].

Accident consequences depend entirely on leakage properties, such as the size of the leakage hole, which was assumed to be either 25 mm (small) or 50 mm (large size). The location of the leakage was assumed to be constant in this study. Additionally, an end point must be designated, which is an arbitrary point for calculating numerical values, such as endpoint concentration, overpressure, or radiant heat, based on the recommendations from the literature. In this study, the end point for the toxic substance leakage scenario was defined according to the Emergency Response Planning Guideline level two (ERPG-2). The ERPG has levels between levels one and three, which indicate the maximum concentrations to which most people are exposed for an hour, resulting in irreversible symptoms or unrecoverable and severe health effects [34].

Generally, an overpressure of 1 psi has little effect on people or structures but can damage windows and houses. An overpressure of 1 psi is used as the permissible overpressure criterion for the protection of plants and industrial facilities [19]. For an explosion accident, the end point for overpressure was set to 7 kPa, which is similar to 1 psi, according to the KOSHA guidelines [20]. In the KOSHA code, 4 kw/m^2, which is widely used as an endpoint standard for fire scenarios, defines the amount of radiant heat that results in pain and skin swelling if skin is not protected within 20 s [35]. The endpoints for jet fires and fireballs were set to be equal to exposure to 4 kW/m^2 of radiant heat of for 40 s [36]. Table 6 summarizes the assumptions and input values for consequence analysis in four different accident scenarios. In cases one and two,

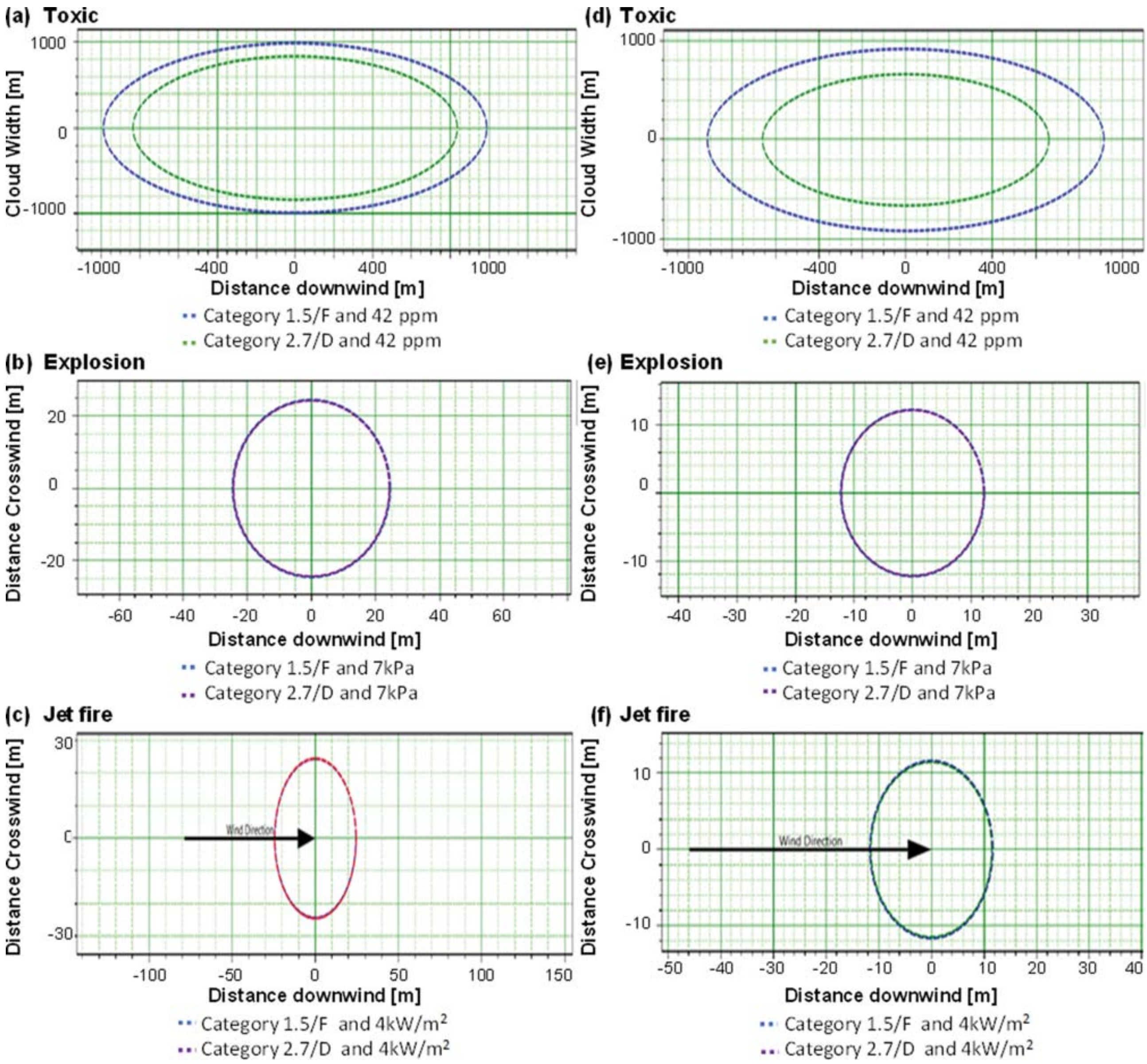

Fig. 7. Comparison of consequence analyses of cases three (left) and four (right) for toxic substance leakage, explosion, and fireball accidents.

the accidental consequences related to leakage substances when a catastrophic tear occurs based on overpressure at T-102 are analyzed. Cases three and four focus on accidental consequences according to different sizes of leakage holes for acid gas leakage. In all cases, the storage amounts were assumed to be 20.75 m^3 [16].

Fig. 6 presents the results (effect zone and safe distance) of consequence analyses of scenarios A and B for three major accident types, toxic substance leakage, explosions, and fireballs, for cases one and two. The safe distances were calculated using the endpoints described above, and the area between the accident point and safe distance was defined as the effect zone. The circles in Fig. 4 represent effect zones for scenarios A and B. Regarding the toxic substance leakage in scenario A for case one, the effect zone has a radius of approximately 1,000 m. Operators within the effect zone must escape this radius within one hour according to the EPRG-2 guidelines. In scenario B, the effect zone has a radius of 400 m. For the explosion accident, scenarios A and B have same effect zones (radius of 70 m), which have the potential for operator fatality. Similarly, the fireball accident for both scenarios was determined to have a consistent effect zone (radius of 60 m). In all cases, the distance to the upper flammability level was determined to be 5 m, meaning flammability is not a major threat compared to other types of accidents.

The results for the three different accidents (toxic substance leakage, explosion, and fireball) according to differences in leakage substances were assessed quantitatively. For the toxic substance leakage accident, case two (scenario with acid gas leakage) has a relatively low value of ERPG-2 compared to case one based on relatively high concentrations of CO and H_2S. The effect zone for case two is four-times larger than that for case one. Similarly, for the explosion and fireball accidents, the effect zone for case one is two times larger than that for case two.

Fig. 7 presents consequence analysis results for scenarios A and B for three accident types (toxic substance leakage, explosion, and fireball) for cases three and four. Most of the results for cases three and four are similar to those for cases one and two. For scenario A, for the toxic substance leakage accident, the effect zone for case three is slightly wider than that for case four. It is noteworthy that large differences in the effect zones for the toxic substance leakage accidents in cases three and four can be observed under severe weather conditions. Similar to the toxic substance leakage accident, the effect zones of the jet fire and explosion accidents for case three are two times wider than those for case four.

CONCLUSION

We performed QRA of amine-based CO_2 capture processes. By utilizing FTA, we calculated the probability of a top event and identified how basic events can contribute to top events. The probability of the top event was calculated to be 3.35E-03 based on contributions from 22 basic events and 19 intermediate events. According to international safety regulations, the probability of a top event that is less than 1.00E-06 indicates that amine-based CO_2 capture processes are sufficiently safe, but top-rated hazards should still be treated properly to improve safety levels. A HAZOP study indicated that operators should be careful to check major nodes periodically (e.g., gasket and flange rupture and corrosion). We also conducted consequence analysis using PHAST for four different cases resulting from a T-102 explosion. Consequence analysis of a toxic substance leakage accident indicated that the effect zone of acid gas with high toxic substance content is approximately four-times larger than that of raw gas. In the cases of explosion and fireball accidents, no significant effects caused by leakage substances were observed.

The main goal of this study was to quantitatively assess all potential risks on the design and operation of amine-based CO_2 capture processes. This goal was fully accomplished, and the major findings of this study can be used to discuss the safety levels of different types of amine-based CO_2 capture processes. Furthermore, this study also contributes to related communities, such as CCS stakeholders and safety engineers, by providing basic data and necessary standards for establishing improved safety management strategies.

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