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Risk Analysis Using Automatically Synthesized Robust Accident Scenarios and Consequence Assessment for Chemical Processes: Process Partition and Consequence Analysis Approach

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Abstract−Consequence analysis and risk assessment are very important in chemical process industries because of the potential risk of hazardous materials. In this paper, we introduce a new system for consequence analysis and risk management (CARM) and propose a new strategy for producing robust accident scenarios in quantitative risk assessment. The suggested synthesis method analyzes process elements and selects and generates robust accident scenarios that simulate the most possible worst-case accident that should be foremost considered. The scenario-reasoning scheme consists of three types of knowledge base (equipment property, material property, and process unit knowledge) and four reasoning algorithms (macro decomposition, equipment screening, equipment behavior analysis, and accident scenarios reasoning). The synthesized result of the analysis enhances the reliability of the generated accident scenario and prevents the risks from being overestimated. The obtained result, as easily confirmed by using CARM, should be more helpful in proper process design and emergency planning.

Key words: Chemical Process Safety, Risk Assessment and Management, Accident Scenario Selection, Equipment Screening and Behavior Analysis, Consequence Assessment

INTRODUCTION

Chemical industries are operating complicated processes with many recycle streams of energy and materials, regulated by environmental and safety considerations. As concerns about the protection from accidents and environmental problems increase, we need better process technology and safety management systems that can deal with process safety more efficiently in real time. Worldwide chemical processes are in need of off-site, as well as on-site, risk assessment. Most governments require industrial companies to submit proper emergency plans through the off-site risk assessment. Korea is also preparing for executing the Integrated Risk Management System (IRMS) along with Process Safety Management (PSM) and Safety Management System (SMS).

These kinds of analyses are helpful in determining appropriate safety devices, capacity of safety facilities, and the minimum distance from residential areas [Chae et al., 1994; Kim, 2000; Jo and Kim, 2001]. Therefore, more and more petroleum and oil/gas companies are adopting these technologies to improve the safety as well as the productivity. However, there have been no systematic approaches or the criteria for generating “virtual” accident scenarios reasonably; and it is still considered very difficult to get a unified or coherent assessment result. Selection of proper accident scenarios is essential for the success of consequence analyses because analysis results may significantly vary depending on the selected scenarios.

To improve reliability in accident scenario selection, we propose a new reasoning algorithm based on process partition and process component analysis. Automatic synthesis of robust accident scenarios and the effectiveness of the proposed strategy will be demonstrated by applications to a system for Consequence Analysis and Risk Management (CARM), developed through co-work with Korea Occupational Safety and Health Agency (KOSHA).

A SYSTEM FOR CONSEQUENCE ANALYSIS

1. Consequence Analysis and Accident Scenario Selection

The off-site consequence analysis technology is a method accepted worldwide for establishing appropriate emergency planning for the off-site area [CCPS, 1992; Khan and Abbasi, 1998]. Due to the limitations of conventional hazard analysis techniques, however, consequence analysis has the same drawback: analysis results differ according to the individual analyst’s view.

In the United States, the Environmental Protection Agency (EPA) announced the ‘RM (Risk Management) Program’ in 1996 [EPA, 1999]; every industrial company is supposed to submit reports about the off-site consequence analysis of the release of specific substances of its domain. The most notable feature of the RM Program is that requires carrying out consequence analysis for a Worst Case Scenario (WCS) and an Alternative Case Scenario (ACS) for each hazardous material. The worst-case scenario is defined as the release of the largest quantity of a regulated substance from a vessel or process line failure that results in the greatest distance to an endpoint. The endpoint is the concentration, explosion overpressure or radiant heat at which serious human health effects or environmental damage could occur from exposure to a release of that substance [Murphy and Zimmermann, 1998]. Usually, for regulated substances, the release distance that impacts off-site areas is fairly long. Parameters required in modeling the scenarios for WCS and

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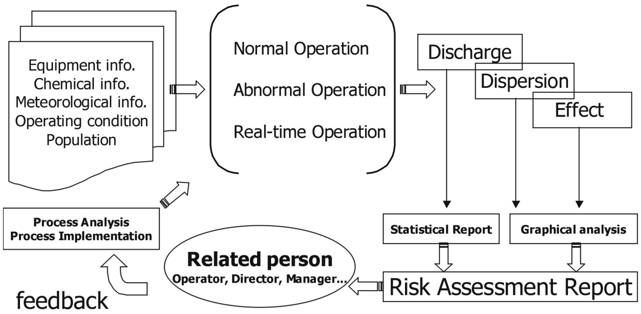

Fig. 1. Overall structure of the consequence analysis.

ACS are similar: the EPA uses EPA's Look-up Table or the EPA's RMP Model, and these are helpful in performing off-site consequence analysis [CCPS, 1994, 1996; Arnaldos et al., 1998].

2. CARM: A System for Consequence Analysis and Risk Management

Overall structure of the consequence analysis is shown in Fig. 1. CARM is a software implementation of those systems, and it can display the extent of damage due to plume, puff, overpressure and heat flux, directly on the computer screen. Using the embedded models with specified accident scenarios, discharge information and weather parameters, it generates output for risk analysis. The risk analysis module then calculates probit values, and if we execute ETA (event tree analysis) or FTA (fault tree analysis) together, CARM can calculate the risk for the selected scenario. In case of an emergency, it can also indicate escape routes for local residents and approach routes for the fire engines and rescue teams for better control and management of the accident.

CARM consists of a material database and various modules for discharge calculations, dispersion calculations, heat effect calculations, overpressure effect calculations and wind field calculations. The discharge module calculates discharge rate and exit state such as pressure, temperature, liquid fraction, etc. It considers 12 cases of discharge scenarios: whether equipment has accumulation or not, whether it suffers from rupture or leakage, and whether the phase of outflow is liquid, gas or aerosol. The dispersion module consists of a light gas model and a dense gas model. The heat effect model consists of three models: fireball, jet fire and pool fire. Each model can generate the footprint of heat flux and graph of heat flux by distance. The overpressure effect module consists of VCE (vapor cloud explosion), BLEVE (boiling liquid expanding vapor explosion), and pressurized vessel explosion.

SYNTHESIS OF ROBUST ACCIDENT SCENARIOS

1. Problems in the Establishment of Accident Scenarios

The most important part in a consequence analysis program is to determine accident scenarios that are likely to occur in a process. Generally, there are three kinds of methods in deciding accident scenarios: qualitative methods, quantitative methods, and methods using past accident data. HAZOP study and What-If analysis are examples of qualitative methods. Event Tree Analysis (ETA) is an example of the quantitative method. Accident data of five years in the similar process are analyzed and used as the imaginary scenario in the past accident data based method.

Each method has its own fortes and drawbacks, and it is difficult to apply these methods in real consequence analysis because there is no systematic selection criterion for the scenarios. In qualitative methods, only the kinds of accident results are presented and they can be hardly applied in ranking or selecting accident scenarios. In quantitative methods like ETA, results change according to the selection of the initial event. In the RM Program, WCS is calculated only by using the maximum capacity (i.e., not using the state information of the process or operational condition), and the result tends to be more overestimated than the real case. Therefore, to overcome these drawbacks, a method is required that is based on qualitative results, which considers the process conditions, material properties, equipment behavior, etc., and is able to apply the result in a quantitative manner.

The result of off-site consequence estimation is presented as toxicity level, heat radiation or overpressure, and used as the basis of emergency planning. Thus, when an accident occurs, we can analyze the unit or equipment that affects the surrounding area. Existing methods for calculating the risk depend heavily on the individual analyst's view in generating and selecting accident scenarios - the calculation shows a variety of results. Sometimes, heavier risk in a process is overlooked, because the status of the process might not have been considered. Therefore, we should consider chemical properties, meteorological conditions and the equipment behavior to accurately calculate the effect on the surrounding area in the off-site consequence estimation.

2. New Reasoning Method for Improved Accident Scenario Selection

To improve reliability in accident scenario selection, we propose a new reasoning algorithm through process partition and process component analysis. Process elements are analyzed and then the proposed strategy selects and generates the robust accident scenario of a worst case that is most likely to happen and should be foremost considered (This concept is being extended by using statistical methods, but that part is not included in this paper).

2-1. Scenario Reasoning: 3 Knowledge Bases and 4 Reasoning Algorithms

The proposed scenario reasoning scheme, shown in Fig. 2, consists of three types of knowledge base (KB) and four reasoning algorithms: equipment property KB, material property KB, and process unit KB [Frank, 1990], with algorithms of macro decomposition, equipment screening, equipment behavior analysis, and accident scenarios reasoning. The equipment property knowledge base

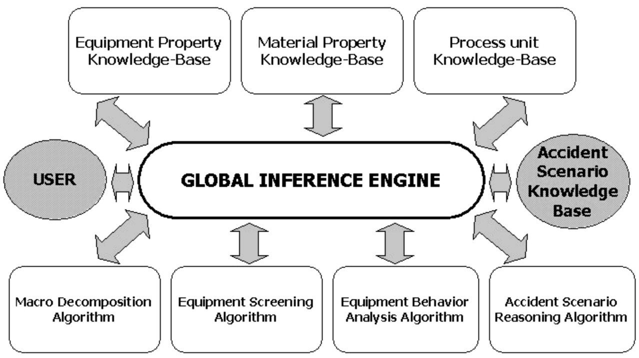

Fig. 2. The proposed scenario-reasoning scheme.

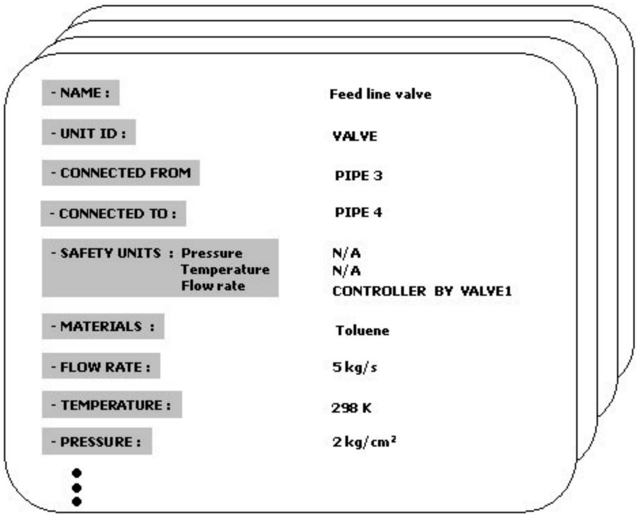

Fig. 3. Part of the equipment property knowledge base.

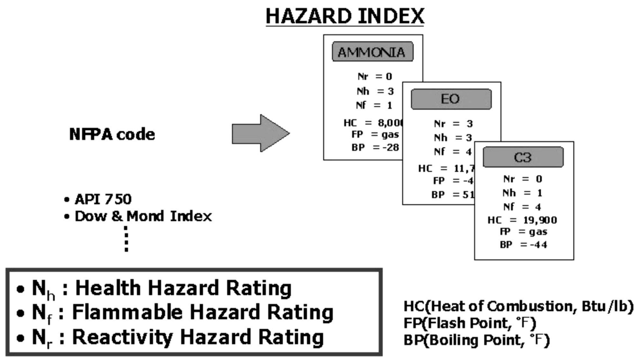

Fig. 4. Elements of the material property knowledge base.

N_r \ N_f	0	1	2	3	4
0	1	1	2	3	4
1	1	1	2	3	4
2	2	2	4	6	9
3	3	3	6	9	12
4	4	4	8	12	16

Fig. 5. Multi-property matrix.

contains equipment properties such as name, unit ID, handling materials, operating condition, flow rate, safety devices, age, etc. (Fig. 3 shows a part of equipment property knowledge base). The material property knowledge base uses the National Fire Protection Association (NFPA) rating to describe toxicity, reactivity and flammability of handling materials; and the modified multi-property matrix, shown in Fig. 5, describes the multi-property of materials having various properties (see Fig. 4 for the elements of the material property knowledge base). The process unit knowledge base consists of the functions of units and the topography and meteorological characteristics of the surrounding area.

2-2. Synthesis of Accident Scenarios

Accident scenarios are synthesized according to the following steps: (1) macro decomposition, (2) micro decomposition using the equipment screening algorithm, (3) equipment behavior analysis using the root cause and effect reasoning for the failure mode of the selected equipment, (4) accident reasoning, and (5) the consequence analysis for the selected scenarios. Fig. 6 shows the steps involved of the reasoning algorithm.

In macro decomposition, process units are selected according to their functions and the meteorological condition of the site. For decomposition, the chemical plant is classified into the feed system, reaction system, separation system, storage system, and utility system. First, we consider the main system of all units. Meteorological characteristics and the surrounding conditions are also considered: the main unit is defined, and meteorological characteristics and the topography of the selected unit are considered. The procedure

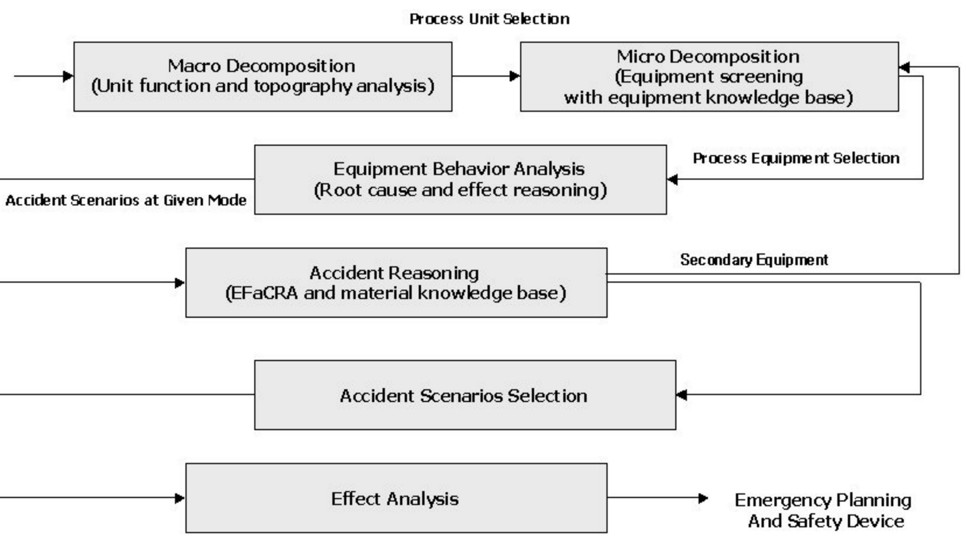

Fig. 6. Steps involved of the reasoning algorithm.

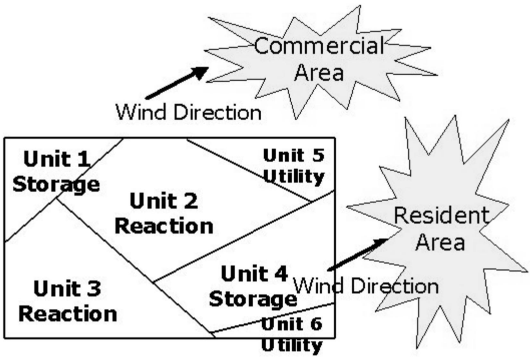

Fig. 7. Unit selection using process partition.

of selecting units through functional decomposition is represented in Fig. 7. We can see that units 2, 4, 5 and 6 give notable potential hazards, resulting in damage in the surrounding area of interest. Considering that units 5 and 6 are utility units with minor risk compared with main units, we can determine that units 2 and 4 from the macro decomposition may have strong impacts in causing major damage to the surrounding area.

In the second step, we propose an Equipment Screening Algorithm (ESA), with equipment property knowledge base, analyzing the process condition and selecting the process equipment of higher-priority risk ranking. Equipment characteristics such as material property, flow rate, operating condition, capacity, safety devices, age, and accident history are analyzed by using ESA, which is a sequential reasoning method. This algorithm is divided into two parts: consequence analysis and probability analysis. Consequence analysis includes material property, flow rate, and operation condition. Probability analysis includes safety devices, age, failure rate, accident history, and repair history. In case of the material property, we use the NFPA code to confirm the flammability and toxicity; the criterion of this property is more than 3 NFPA rating. In the next stage, we consider whether the equipment is with high flow-rate or capacity. Equipment operated at high pressure or temperature is determined. In the fourth stage, we decide whether the selected equipment has safety devices. In the fifth stage, we consider the failure probability through the equipment age and failure rate. Finally, the accident history and the repair history for individual pieces of equipment are considered. The analyzed process elements are ranked, and risk grades are determined. According to the grades, risk assessment is performed. Fig. 8 shows all stages of the sequential reasoning in ESA.

In the equipment analysis using the equipment behavior algorithm, the effect estimation for the equipment selected in the equipment screening part is accomplished: equipment with high severity is researched to find a detailed accident scenario. We use effect analysis for the failure mode of the selected equipment to identify single equipment failure modes and each failure mode's potential effect on the system and the plant. This mode describes how equipment fails, and is determined by the systems response to the equipment failure. Table 1 shows an example of failure modes for the equipment behavior, and Fig. 9 depicts the equipment behavior analysis for the selected equipment. In the scenario selection, we infer possible effects depending on the failure mode of the equipment. Possible scenarios for each failure mode are so variable that risk rankings are assigned according to the potential hazard of material and the magnitude of abnormal situations. Table 2 shows an example of the failure mode and scenario selection procedures.

In the accident-reasoning algorithm, we infer the possible accident due to equipment behavior and material property. For example, if the ultimate effect is valve breakage, we may infer that the

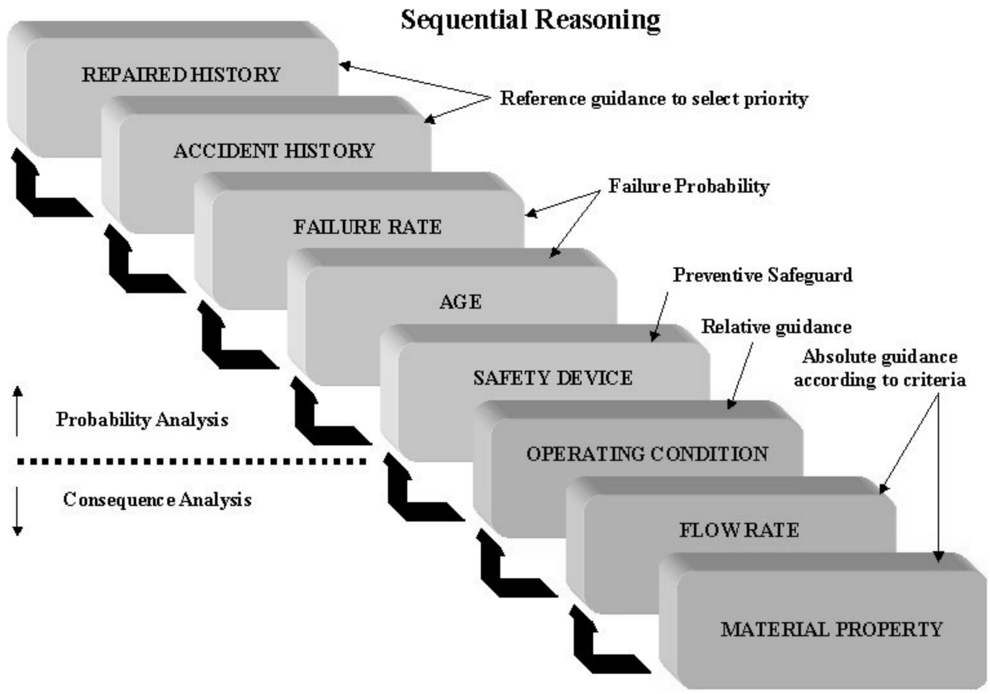

Fig. 8. The sequential reasoning scheme of ESA.

Table 1. An example of failure modes for equipment behavior

Equipment	Valve	Pump	Heat exchanger
Failure mode	Open	Fail on	Leak/rupture (tube to shell)
	Close	Transfer off	Leak/rupture (shell to tube)
	Rupture	Seal leak/Rupture	Plugged
	Leak	Pump casing Leak/rupture	Fouling

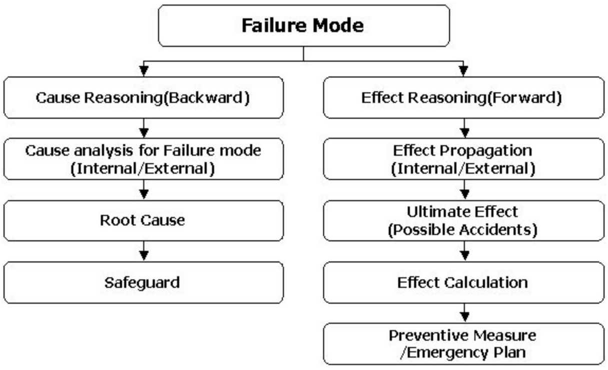

Fig. 9. Equipment behavior analysis for selected equipment.

possible accident is fire or explosion when the material is flammable:

(1) Valve leakage+toxic materials (N_h>2) ⇒ personnel injury
(2) No inlet flow+pump ⇒ pump damage and malfunction
(3) Downstream equipment breakage+flammable materials (N_f> 3) ⇒ fire or explosion

CASE STUDIES

1. LPG Storage Facility

The objective system of this case study is one of typical LPG transportation and storage facilities, including a propane underground cavern, propane coalescer, propane dryer, and propane storage tank, as illustrated in Fig. 10.

1-1. Accident Scenario Selection using the Proposed Method

In step I (macro decomposition), the entire process is decomposed into unit processes, and process units are selected according to their functions and the meteorological conditions around the area. The second step is the micro decomposition step. Through this step, ESA is applied to the 5 valves, 3 pumps and 1 heat exchanger, which have been selected as the most influential process components in

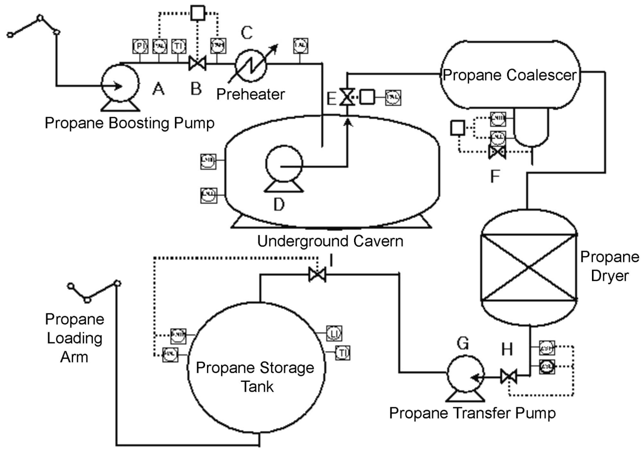

Fig. 10. Schematic of an LPG storage facility.

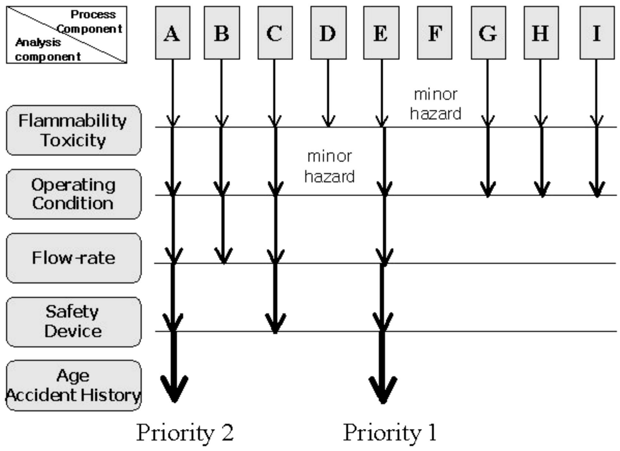

Fig. 11. ESA application for the LPG facility.

the off-site area when an accident occurs. The result is shown in Fig. 11; accidents due to pump A and valve E are the most hazardous ones. In the equipment analysis step, the analysis is performed to the process elements chosen in the micro decomposition step, and the elements are ranked and risk grades are determined. Table 3 shows a part of the analysis. In step IV (scenario selection), according to the result of step III, propane releases due to the rupture of valve E or the open of valve E caused by the failure and rupture of pump sealing are selected as the most suitable accident scenarios.

The next step is effect analysis: a consequence analysis is performed by using the scenarios chosen in the accident reasoning steps. CARM has been developed as part of this study, and Figs. 12 and 13 show the quantitative analysis result obtained by using CARM for the explosion of the LPG facility. Similar analysis results can

Table 2. Example of scenario selection for a failure mode

Identification	Mode	Effect	Material	Risk ranking
Valve A on the chlorine line	Fail open	Excess flow of chlorine to the heater	Chlorine	C
		May cause a high level in the cleaning bed	Excess chlorine and water	D
	Fail closed	No flow of chlorine to the cleaning bed	Water	Minor
		Excess water flow to the cleaning bed	Water	Minor

Table 3. Scenario selection for LPG facility

Identification	Mode	Effect	Material	Risk ranking
Valve E on the liquefied propane line	Fail open	Excess flow of propane to the propane coalescer	Propane	Minor
		May cause a high pressure in the propane coalescer	Propane	B
		May cause a rupture in the propane coalescer	Propane	A
	Fail closed	No flow of propane to the propane coalescer	-	Minor
		Closed the valve in feed line	-	Minor
	Rupture	Large release of propane to the surrounding area	Propane	A
Pump A on the liquefied propane line	Fail open	Excess flow of propane to the propane underground cavern	Propane	Minor
	Fail transfer off	No flow of propane to the propane underground cavern	-	Minor
	Seal rupture	Large release of propane to the surrounding area	Propane	A

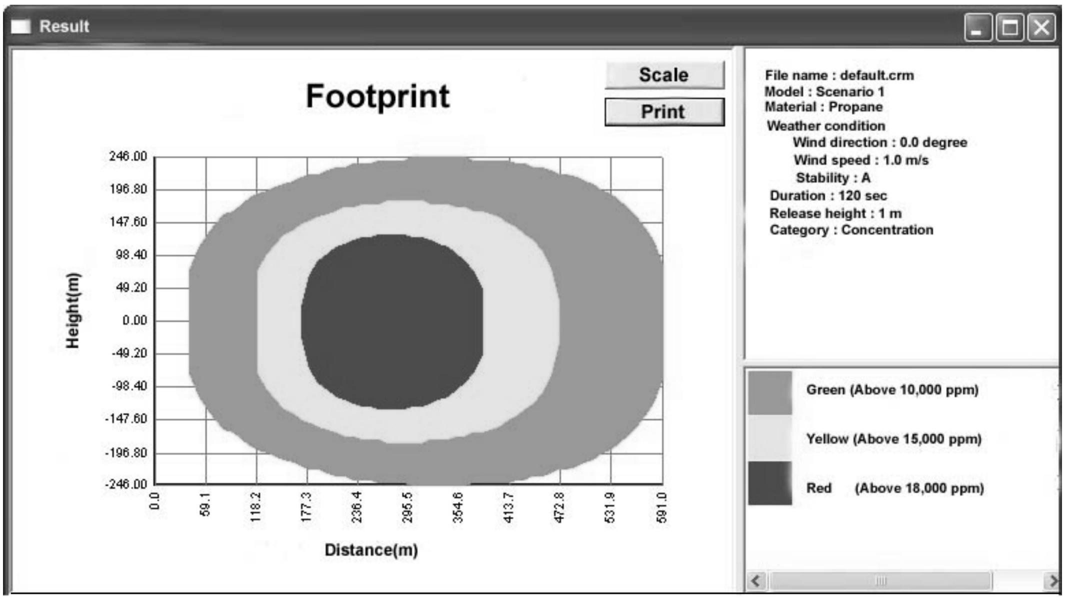

Fig. 12. Footprint of the VCE of the LPG facility.

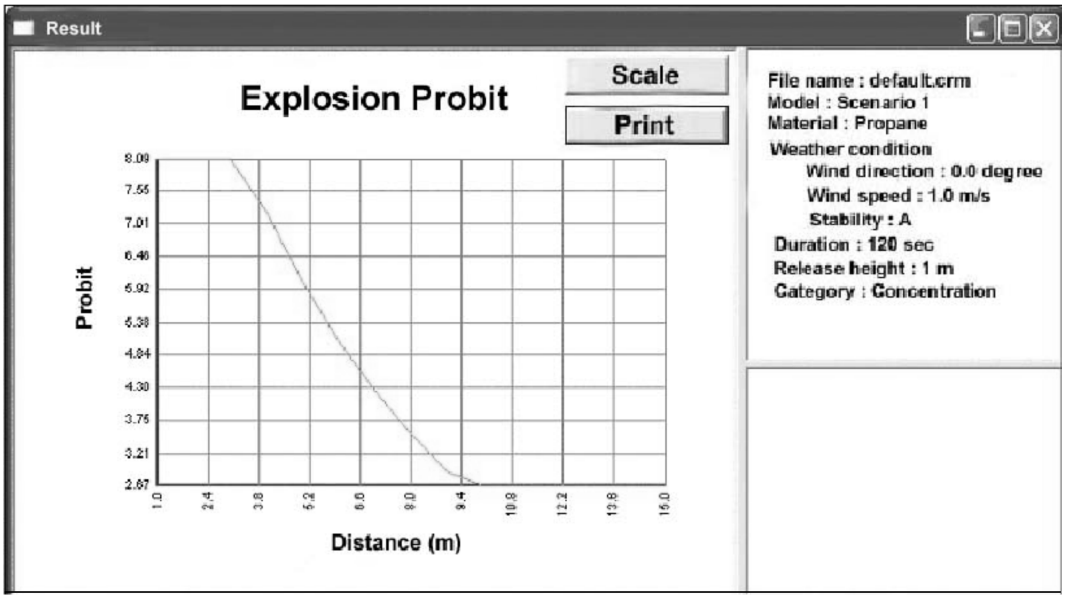

Fig. 13. Probit value of the explosion of the LPG facility.

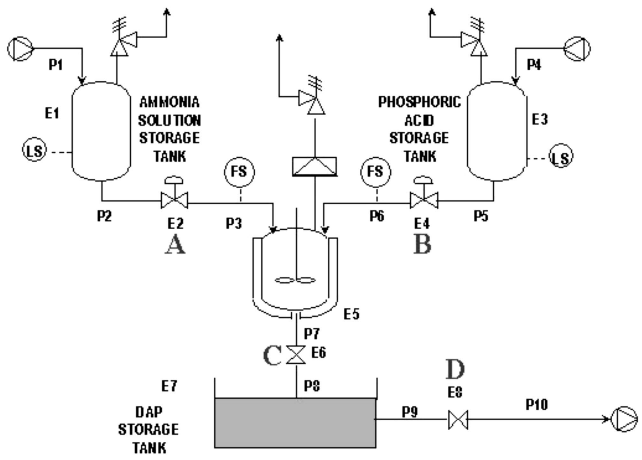

Fig. 14. Process diagram of the DAP process.

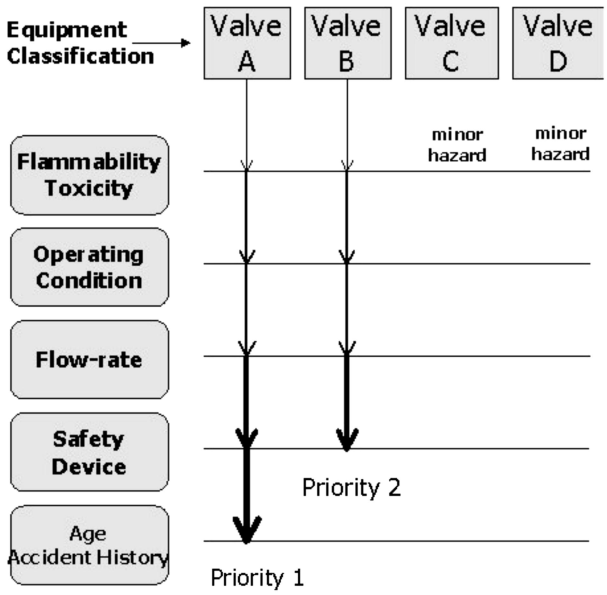

Fig. 15. ESA application for the DAP process.

also be obtained by using several commercial software packages available today.

2. DAP Process

To illustrate the effectiveness of the proposed system again, let us consider the diammonium phosphate manufacturing process (DAP) shown in Fig. 14. This process is cited from a case study of the Center for Chemical Process Safety (CCPS), American Institute of Chemical Engineers.

This process is comprised of common process units such as pumps, pipes, tanks, reactor, and valves. In this process, a phosphoric acid solution and an ammonia solution are provided through the flow control valve to an agitated reactor. The ammonia and phosphoric acid react to form diammonium phosphate (DAP), a non-hazardous product. The DAP flows from the reactor to an open-top storage tank. If too much phosphoric acid is fed to the reactor, an off-specification product is created. If both the ammonia and phosphoric acid flow rates increase, the rate of energy release may accelerate, and the reactor, as designed, may be unable to handle the resulting increase in temperature and pressure. If too much ammonia is fed to the reactor, unreacted ammonia may carry over to the DAP storage tank. Any residual ammonia in the DAP tank will be released into the enclosed work area, causing personnel exposure.

2-1. Accident Scenario Selection using the Proposed Method

In step I (macro decomposition), the entire process is decomposed into unit processes, which are selected according to individual function and the meteorological conditions around the area. Step II is the micro decomposition step. Through this step, ESA is applied to the four valves that have been selected as the most influential process components in the off-site area when an accident occurs. Accidents due to valve A and valve B are the most hazardous ones (see also Fig. 15 for the ESA application to the DAP process). In step III (equipment analysis), the analysis is performed on the process elements chosen in step II, and the elements are ranked and risk grades are determined. Table 4 shows a part of the analysis. In step IV (scenario selection), according to the result of step III, ammonia release due to the rupture of valve A is selected as the most suitable accident scenario. Step V is effect analysis: a consequence analysis is performed by using the scenario chosen in step IV, using the same approach mentioned in the previous case study 4.1.

CONCLUSIONS

A strategy for producing robust accident scenarios in the quantitative risk analysis, which are performed in the process design or operation steps, has been proposed and tested, using a developed consequence analysis and management system, against one of the

Table 4. Scenario selection for the DAP process

Identification	Mode	Effect	Material	Risk ranking
Valve A on the ammonia line	Fail open	High pressure and high temperature in the reactor if the phosphoric acid feed rate is also high	Ammonia	C
		Excess flow of ammonia to the reactor	Ammonia & DAP	D
	Fail closed	No flow of ammonia to the reactor	-	Minor
		Phosphoric acid carry-over to the DAP storage tank	Phosphoric acid & DAP	D
		May release to the enclosed work area	Phosphoric acid & DAP	D
	Leak (External)	Small release of ammonia to the surrounding area	Ammonia	B
	Rupture	Large release of ammonia to the surrounding area	Ammonia	A

LPG facilities and the DAP process. The obtained result of the systematic synthesis should enhance the reliability of the generated risk scenarios and prevent the risks from being overestimated; the result should be more helpful in the proper process design and emergency planning. The proposed strategy and the developed system are being integrated as part of the government-supported, quantitative process hazard analysis system, IRMS, and expected to be successfully applied to the most mandated, off-site consequence analyses in Korea. The hazard analysis module of IRMS proposes reliable scenarios, the consequence analysis module calculates the size of consequence, and the frequency analysis module generates the probability for the selected scenario. Then these results are delivered to the display to show risk contours and suggesting emergency plans.

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