Systematic Analysis of Environmental Release Process and Emergency Response in Chemical Accident

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Abstract

Various harmful substances have been released into the environment due to increased occurrences of chemical accidents. However, only a limited number of the cases have been analyzed from the perspective of health and environmental risks to the general environment. In this study, we conducted questionnaire and interview surveys with site operators to collect information related to substance release processes and responses to them in past accidents. In addition, we extracted factors relevant to the emergency responses to the accidents and systematically analyzed the release processes.

Key words : accidental release, case analysis, chemical substances, emergency response

1. Introduction

Various harmful substances have been released into the environment during chemical accidents such as fires, explosions and spills. The number of accidents at facilities handling hazardous materials has been increasing since the 1990s (Fire and Disaster Management Agency, 2016). Quick and appropriate responses to accidental releases are essential for minimizing health and environmental risks. It is not easy to obtain information on risk assessment due to the difficulty of identifying substances and fluctuations in the amounts released and concentrations in the environment. Therefore, only a limited number of cases have been analyzed from the perspective of risks to the general environment despite the many accidents that have occurred. Systematizing the behaviors of released substances and accident patterns is important for ensuring quick and appropriate responses to accidents.

In this study, we have systematically analyzed the processes of chemical releases and responses of facilities and government bodies to accidents based on questionnaire and interview surveys. The questionnaires were designed to collect a variety of information related to release processes and responses in past accidents. The interview surveys were conducted to obtain detailed information on situations and personal opinions which were hard to obtain from the questionnaire. In addition, we paid attention to practical information that had been useful in responses soon after accidents based on the survey results.

2. Methods

2.1 Questionnaire Survey on Chemical Accidents

For the purpose of collecting information as a basis for categorizing chemical accidents, we conducted questionnaire surveys and interview surveys with site operators about accidents that had occurred in the past. To list up target accidents for these surveys, past accidents in Japan that may have involved releases of chemical substances were extracted from the *Database of Disasters and Accidents* (Accident and Disaster Information Center (ADIC)). These surveys were carried out twice. The first (Survey 1) was conducted in April 2019 and the second (Survey 2) was conducted in April 2020. Survey 1 covered accidents that had occurred in recent years (2017 to 2019) with no limit on the type of industry, and the Survey 2 covered accidents that had occurred at industrial sites involved in “manufacture of chemical and allied products” after 1990 except for cases that would duplicate those in Survey 1. Survey 2 was intended to collect more information about the chemicals released. The number of questionnaires distributed in Survey 1 was 100, and in Survey 2, 51. In both surveys, the interviews were conducted after the questionnaire survey (Survey 1: 20 interviews, Survey 2: 18 interviews).

The questions asked in the questionnaire surveys were mainly concerned with the handling of substances at the time of the accident, the state of the released substances in the environment and the emergency

Table 1 Questions asked in the questionnaire (outline).

No.	Questions
Q1	Were there any investigations or guidance given by administrative authorities after the accident?
Q2	Was a report on the accident prepared by the operator or the administrative authorities?
Q3	Can the report in Q2 be provided?
Q4	What was the cause of the accident?
Q5	Please list substances handled that were related to the accident.
Q6	How much of the substances handled was stored?
Q7	What purposes do the substances handled have in the processes at the site? (e.g., raw materials, by-products, waste products)
Q8	Please list any chemicals that were thought to be unintentionally produced by the accident, if any.
Q9	What is the reason that you judge the unintentionally produced chemicals to have been produced?
Q10	For how long were the substances released after the accident?
Q11	Were any substances released into the general environment during the accident?
Q12	Regarding Q11, what and how much of the substances were released into the general environment?
Q13	Were any concentration measurements performed in the general environment after the accident?
Q14	Regarding Q13, please give the name and concentration of the substance.
Q15	Please describe the time-series transition of events from the occurrence of the accident to the convergence.
Q16	Is it possible for you to cooperate with an interview survey?

responses to the accident. Table 1 outlines the questions.

2.2 Considering Practical Information in Emergency Responses

Based on the results of the surveys in Section 2.1, information desirable to obtain for emergency responses was examined. Methods of identifying released chemicals, considered to be a particularly important factor in conducting environmental surveys, were compared. Here, the advantages and disadvantages of interviews with site operators and utilization of the Pollutant Release and Transfer Register (PRTR) notification data were compared. In addition, examples of other factors and criteria that could characterize chemical accidents were identified.

2.3 Classification of Release Processes and Responses

To manage the risks to the general environment from accidental releases of chemical substances from industrial sites, it is important to analyze systematically the behaviors of substances in the environment from the time of release of the chemical substances to the time of exposure. The concept of a migration process of released substances in environmental media had been brought up in several studies (International Atomic Energy Agency (IAEA), 2002; Moriguchi, 2013; World Health Organization, 2009), but there were differences in the settings of the environmental media. In this study, for the purpose of covering various possible situations, attempts were made to classify the migration processes of substances in the environment and the corresponding emergency responses. Possible emergency responses were listed in consideration of both possible general responses and replies to the questionnaire survey.

3. Results and Discussions

3.1 Analysis of Questionnaire Replies

Table 2 shows the number of replies to the questionnaire survey by industry. In Survey 1, as for classification of industry, “manufacturers of chemical and allied products” (7 respondents) accounted for the highest number of respondents. Next were “manufacturers of petroleum and coal products” (4 respondents), “manufacturers of transportation equipment” (4 respondents), and “waste disposal businesses” (4 respondents). They accounted for about 70% of the total respondents (19 of 29 respondents).

In Survey 1, accidental fires (including explosions) accounted for the majority of cases (27/29). On the other hand, in Survey 2, accidental fires comprised less than 30% (9/34 cases). In many of the cases investigated in this study, especially regarding accidental fires, the reports on the accidents were prepared by the operator or administrative authorities (obtained from Q2 in Survey 1). There were few cases, however, from which information on releases to the general environment could be obtained, because most of the reports were on investigations into causes and suggestions for improvement of facilities and operations.

Regarding whether chemical substances had been released into the general environment or not (Q11), in Survey 1, seven respondents replied “They were released to the general environment,” and about 30% (10 respondents) replied that it could not be ascertained (“Unknown” or no reply). In Survey 2, about 40% (13/34 respondents) replied “They were released to the general environment,” while all other respondents replied “The released substances remained within site boundaries.”

Regarding the handling substances related to the accident (Q12), relatively detailed information was

Table 2 Number of replies to the questionnaires.

Survey	Year	Industrial classification*		Number of replies
		Code	Name	
1	2017–2019	16	Manufacture of chemicals and allied products	7
		17	Manufacture of petroleum and coal products	4
		18	Manufacture of plastic products, except as otherwise classified	3
		21	Manufacture of ceramic, stone and clay products	2
		24	Manufacture of fabricated metal products	1
		25	Manufacture of general-purpose machinery	1
		27	Manufacture of business-oriented machinery	1
		29	Manufacture of electrical machinery, equipment and supplies	1
		31	Manufacture of transportation equipment	4
		55	Miscellaneous wholesale trade	1
		88	Waste disposal business	4
2	1990–2016	16**	Manufacture of chemical and allied products	32

* The industrial classification (code and name) shown in this table are based on Japan Standard Industrial Classification (Ministry of Internal Affairs and Communications, 2013).
** In Survey 2, a four-digit industrial classification was used, but here they are indicated as the main group by the first two digits.

obtained for leakage accidents from "manufacturers of chemical and allied products," but from the others, there were few cases in which details on those substances could be identified. This was because the causal substances in the accidents were often uncertain in the cases of fires or explosions.

Regarding release duration (Q10), in Survey 1, excluding "unknown" cases (9 cases), five cases were "instantaneous releases due to explosions" and 11 cases were "1 to 6 hours," indicating the time it took to extinguish the accidental fires. In Survey 2 where many cases were leakage accidents, many (23 cases) replied "within an hour" (of which one was an instantaneous release), while in one case, it was estimated that leakage due to corrosion of buried piping had continued for several months.

Regarding unintentional reaction products (Q8), in both surveys, about half replied "There was no possibility of producing them." In Survey 1, "Unknown" accounted for about 25% (7/29 cases), while in Survey 2, "Unknown" accounted for only two cases and more than 40% (14/34 cases) replied "There was a possibility of producing them" (due to combustion or unintended chemical reactions). Since Survey 2 covered accidents in chemical plants, it was thought they had knowledge of the substances being handled and reaction products in the accident. Generally, it is thought that unintentional reaction products are generated in accidental fires. In these surveys as well, many of the replies regarding accidental fires were "There was a possibility of producing them." Therefore, understanding of unintentional reaction products in accidental fires is thought to be important.

Regarding measuring concentrations in the general environment (Q13), in both surveys, approximately 25% (Survey 1: 7/29 respondents, Survey 2: 8/23 respondents) replied that it had been conducted in some way after the accident. However, most of these were not conducted by the emergency response, but referred to data obtained by constant monitoring at site boundaries or periodic surveys of the surrounding environment. Estimations of environmental concentrations (model calculations, etc.) had been performed in only two cases in Survey 2.

The results of the questionnaire survey clarified that there were few cases of emergency response that involved environmental monitoring for the general environment. In the interview survey, some site operators said that the emergency responses at the time of the accident had been multiple and complicated, and environmental monitoring was not given very high priority.

3.2 Practical Information for Emergency Responses

The results of questionnaire survey in this study revealed that information on chemical substances released in the course of accidents was unavailable in many cases. Therefore, it is important to establish methods for identifying the chemical substances released into the general environment. The methods currently available to identify released substances are summarized below, along with their advantages and disadvantages.

As to methods of identifying released chemical substances, it is conceivable not only to ask the site operators, but also to use the related notification data on annual emissions or amounts handled.

Interviews with the site operators may provide a possible way to obtain information useful for risk assessment such as on substances handled during the accident, amounts released and so on. However, it is likely that they will not be able to reply immediately after the accident. In addition, even if it is possible, it will take some time to conduct. Therefore, this is not a realistic approach, especially in the case of emergencies.

PRTR notification data in Japan (Ministry of Economy, Trade and Industry, published annually) is readily available. PRTR data cover 462 substances with relatively high environmental risks and provide locations of business sites where they may be released or transferred at normal times. However, an analysis of Survey 1 (Koyama et al., 2019) revealed that only in a few cases were PRTR substances reported by the site operator related to the substances released during the accident. (In Survey 2, many cases had occurred before the start of the PRTR system, so a sufficient comparison could not be made.) Therefore, it can be said that PRTR data cannot always be used effectively regarding emergency responses.

None of the methods shown here is sufficient, so it is not easy to quickly identify a target substance using a single method. To carry out an appropriate environmental survey, the best way at present to estimate the substances that may have been released is by using a combination of these methods. Therefore, it is important to collect and analyze relevant information from before the accident so that the necessary information can be quickly obtained in future accidents or disasters.

There are thought to be some key factors defining the characteristics of chemical accidents, although not all relevant information could be obtained due to lack of information from the questionnaire surveys. These factors may be divided into those related to characteristics of chemicals (e.g., visibility, specific gravity, solubility, toxicity) and those related to characteristics of accidents (e.g., release destination, duration, quantity, types of surrounding areas).

It is important to set criteria for such factors to enable quick and appropriate responses. As an example of criteria for toxicity, there are five levels (A to E) of classification based on the toxicity categories of the GHS classification system (Osaka Prefectural Government, 2014). This classification is useful in that it can be applied to various chemical substances. For substances with high acute toxicity, it may be possible to use criteria for emergency responses such as Acute Exposure Guideline Levels (US Environmental Protection Agency).

As a next step, through a detailed study of these factors and criteria, it may be possible to classify chemical accidents with similar features. In the future, reviewing and classifying the responses actually taken or to be taken in similar cases will make these factors more useful in responses to future accidents.

3.3 Systematic Classification of Environmental Release Processes and Responses

To systematically classify the processes of release of chemical substances, the migration of chemical substances between media is expressed as a matrix in Fig. 1 referring to the migration matrix of radioactive materials (IAEA, 2002). In addition, the possible responses to this are summarized in Table 3 and Fig. 2.

Here, responses are classified into two categories, “Identification” and “Management.” In addition, the responses are separated into what is done for the media and what is done for transfers between the media. Regarding responses for the media, examples of “Identification” responses were “visible observation (smoke, crop damage, etc.),” “atmospheric monitoring” and “atmospheric concentration model calculation,” while an example of a “Management” response was

Accident site	Release	Release				Release	
	Atmosphere	Dry and wet deposition	Dry and wet deposition	Dry and wet deposition	Dry and wet deposition	Dry and wet deposition	Inhalation
	Volatilization	Rivers, lakes	Translocation	Translocation		Translocation	Ingestion (drinking water)
	Re-suspension	Translocation	Forested land	Translocation			Ingestion (forest products)
	Re-suspension	Translocation	Translocation	Farmland			Ingestion (agricultural products)
	Re-suspension	Translocation			Residential areas		
	Volatilization					Sea	Ingestion (seafood)
							The public

Fig. 1 An interaction matrix which describes the migration of released substances in the general environment. The diagonal elements are components of the system and the off-diagonal elements are the interactions between them. To identify the transfer processes the matrix should be read clockwise from the upper left.

"decontamination." Regarding the responses to transfers between media, examples of "Identification" responses included "sensing odors (strange tastes)" and "personal exposure measurement," while examples of "Management" responses included "spraying water in firefighting," "oil fence installation," "mask wearing," "indoor evacuation" and "limiting water supplies."

In "Management" responses, an action may have a new impact on substance migration between media. For example, fire extinguishing activities may reduce the amount transferred to the atmosphere, but they may increase the amount transferred to rivers or lakes or result in releases of other substances. Therefore, it is also important to sort out changes in the transfer process due to passage of time or response actions.

It should also be noted that the process from release to exposure varies depending on the accident type and the location of the release site. Emergency responses also vary depending on the accident type, chemical properties of the substances involved, available capacity to deal with accidents and so on. These classifications of media and migration processes are tentative, and some improvement may be needed. For example, scattering of chemical substances by explosions to forested land from industrial sites is classified as migration via atmosphere, but it may be more practical to classify such short-period migrations as direct migration. The blank cells in Figs. 1 and 2 do not necessarily indicate that a process does not exist or that a response is unnecessary, and it will be necessary to make corrections and additions in the future. To lead to appropriate responses to future accidents or disasters, it will be important to analyze release processes after chemical accidents as comprehensively as possible and examine responses that were (and were not) taken in past cases and the reasons for that.

Table 3 Possible responses for the components of the environmental system in Fig.1.

	Identification	Management
Accident site	On-site personnel interview Use of notification information (e.g., PRTR)	
Atmosphere	Visible plume, Air monitoring, Atmospheric dispersion model	
Rivers, Lakes	Death of fish, Water quality monitoring	Diffusion prevention (e.g., oil fence)
Forested land	Damage to forest	Decontamination
Farmland	Damage to agricultural products	Decontamination
Residential areas		Decontamination
Sea	Death of fish	Diffusion prevention (e.g., oil fence)
The public		

Accident site	Constant monitoring	Constant monitoring					
	Water spray	Interception (e.g., oil weir)			Interception (e.g., oil weir)		
	Atmosphere	Deposition model estimation	Deposition model estimation	Deposition model estimation	Deposition model estimation	Deposition model estimation	Odor, Personal exposure measurement
							Evacuation/ Sheltering, Mask wearing
	model estimation?	Rivers, Lakes					Strange taste
							Suspension of water supply
	model estimation?		Forested land				Strange taste
							Shipment restriction
	model estimation?			Farmland			Strange taste
							Shipment restriction
	model estimation?				Residential areas		
	model estimation?					Sea	Strange taste
							Shipment restriction
							The public

Fig. 2 Possible responses to migration of chemicals. The top half of each square shows the identification responses and the bottom half shows the management responses.

4. Conclusion

We conducted questionnaire and interview surveys on chemical accidents and analyzed their characteristics. From these surveys, it became clear that few environmental surveys on the general environment have been conducted when accidents have occurred, and that the extent of information on released substances varies by industry and type of accident. We have revealed that information from existing notification systems such as PRTR has been insufficient for identifying target substances soon after accidents and it is important to collect information on amounts of chemical substances stored, including non-PRTR substances, for effective responses to accidents. We have also systematically analyzed release processes and the emergency responses to them. Expansion of this information will enable rapid and effective risk management of chemical substances released into the general environment in emergencies.

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