Proceedings of the 17th International Symposium on the
Packaging and Transportation of Radioactive Materials
PATRAM 2013
August 18-23, 2013, San Francisco, CA, USA

Extraction and classification of transportation incidents potentially caused by natural events emerged from the Fukushima NPP accident

Yoshihiro HIRAO, Hiromitsu Mochizuki
National Maritime Research Institute, Tokyo, Japan

Makoto Hirose
Nuclear Fuel Transport Co., Ltd., Tokyo, Japan

ABSTRACT

In view of the state of the Fukushima NPP accident, CSS of IAEA has decided on an action plan to review the safety regulations for nuclear facilities. The transport regulations and guides are also included in the plan and Japan, as the country directly concerned, has to be engaged in the task by TRANSSC through a gap-analysis at a specialists' meeting. In arguments of that, it was pointed out that impacts given by natural events should be re-examined and boundaries of test condition between routine, normal and accident should be clarified. These issues were discussed in the technical meeting (TM-44891) held on July 2013.

This study provides a framework for identifying and classifying transport incidents potentially caused by natural events such as extreme earthquake and tsunami, in order to separate significant ones from the others using risk concept. The hazard matrix is proposed for finding potential incidents efficiently and comprehensively. Each incident is roughly rated by two risk indices representing an occurrence frequency and severity of package influence. The risk matrix is then used to classify them by certain risk criteria and clearly show a group of incidents that may have significant risk. In fact, these are a kind of risk-finding and screening process in probabilistic risk assessment.

As a case example showing the applicability of our techniques, practical efforts were made among local experts to find incidents in domestic transport of spent nuclear fuels. As a result, a total of over 300 incidents were identified in terms of 22 types of natural events, four types of accident loads (impact, fire, immersion and burial) and four transport modes (land, sea, cargo and temporal storage). After classification, only 9 incidents were left on a cell group of possibly exceeding accident conditions. Note that the risk is rated at the maximum imaginable if uncertain. Further site survey will be required to know true frequency and severity of such incidents in quantitative manner.

1 Introduction

As far as issues of coverage and technical basis of regulations in the gap-review from the Fukushima accident, Japan's primary evaluation has supported the complimentary use of probabilistic risk assessment (PRA). While natural events and the following incidents can be broadly imagined in the type and range of impact on package, it is impractical and impossible to cover all of them in regulations. In fact, it seems that there are no choice but to use an occurrence frequency for screening if we have to regulate severe conditions potentially caused by natural event of low probability and high consequence (LPHC event). It is essentially difficult to implement external event PRA due to very less information about relationship between frequency and severity. Nevertheless, toward closing the gap-review, it is necessary to provide a framework for identify specific types of incidents that may be subject to regulation in practical manner.

In this study, we have developed process for finding transport incidents potentially caused by LPHC events including huge earthquake and tsunami, and then separating significant ones from the other using the concept of PRA. Actually, it includes well-known technique of classifying incidents/scenarios using the risk matrix, as often seen in an early screening process of PRA. Conventionally, this process will be followed by quantitative analysis of the selected incidents by site survey and walkdown to know their true frequency and severity [1]. That is out of scope in this study.

Finally practical efforts were made among local experts to identify and classify incidents for a case example of domestic spent nuclear fuel (SNF) transport. The results are summarized and incidents of special attention are described.

2 Process of finding incident-risk potentially caused by natural event in spent nuclear fuel transport

Figure 1 shows a scheme of our risk finding process. The task of the first stage is identification of potential incidents caused by natural events. A domain/boundary of evaluation must be defined to specify the range of evaluation. For example, facilities are limited to a vessel on any route and a crane at plant port, both of which are exclusively used. Then, as shown in the next chapter, the hazard matrix helps experts find potential incidents as efficient and comprehensive as possible.

Proceeding to the second stage, every incident identified in the first stage is rated by risk indices and classified on the risk matrix, in order to screen out low-risk incidents by some criteria. The goal of this process is to recognize the remaining incidents of relatively high risk, which will be analyzed quantitatively in the next stage. Two types of risk indices must be defined to represent the rank of frequency and severity of incident, respectively. It is recommended that the definition of rank is easy to understand, and the number of ranks is as small as one can always remember. Experts are asked to rate each incident by assigning one of the ranks of each index. In most cases the rank of severity index can be roughly determined by the exchange of opinions among experts, but otherwise the severest is selected. On the other hand, that of the frequency index is determined from a figure calculated in a semi-quantitative way as described later.

Then the incidents identified above are classified using the risk matrix. The risk matrix has dimensions of (the number of ranks of frequency index times that of severity index). Each of the incidents is placed onto the cell of the matrix corresponding to its own indices. Finally, a group of specific cells are selected by some criteria and only the incidents on those cells are considered to be significant. They are called potential incidents of special attention in this study. The criteria could be, for example, over 10^{-6} per year for frequency and more severe impact on package than accident test condition for severity.

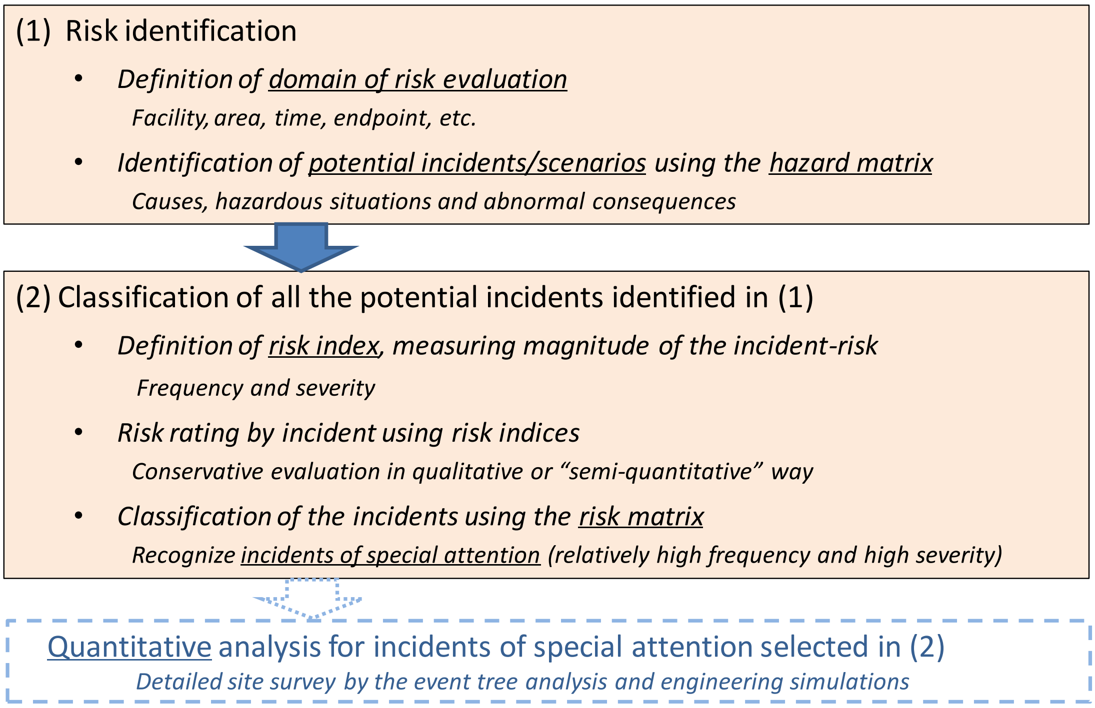

Figure 1. Process of finding incident-risk caused by natural events in SNF transport

3 Techniques of identification and classification of potential incidents

3.1 Identification using the hazard matrix

The hazard matrix has dimensions of the product of numbers of three types of direction words (natural event, accident load and a suffering situation), in which each row shows a combination of type of natural event and accident load to package, each column shows a suffering situation and each element shows the list of potential incidents identified by experts. Experts are asked to add hazardous incidents corresponding to each cell as long as they can imagine. Figure 1 shows an example of identified incidents caused by tsunami. However a practical matrix is extended with as many as the number of natural events. Another purpose of the matrix is to help experts assign the risk indices by incident. The cells of 'SI' and 'FI' are used to rate the severity and frequency of incident, respectively. The indices are described in the next section.

In order to form the matrix, three types of direction words have to be defined. In our example, as shown in Table 2, we have selected types of natural events which could give some impact to package in domestic environment from the list of natural hazards in the NEA report [2]. Next we have defined suffering situations that encounters natural events. Four typical situations are found in domestic transport environment, marine transport by vessel, land transport by truck, cargo work by crane and Onsite storage. Marine transport is divided into two sub-situations, at open sea and inside of the bay including the berth of port. Land transport is also divided into three such as on normal road, on bridge and in tunnel, although there is no tunnel in SNF transport. The onsite storage means temporal storage of small numbers of casks before marine transport in a warehouse of coastal nuclear power plant. This is one of the lessons from the Fukushima accident. In fact tsunami was attacked to the warehouse although packages were totally safe. Lastly, we have defined four types of accident loads eventually given to the package, mechanical load, fire, immersion in water and burial. The former three are popular in test conditions. The burial newly added indicates that surface of package is covered by debris or by other goods [3], as a result of such causes as tsunami, that may lead to a loss of cooling function. This one is also derived from the Fukushima. As an important fact, however, serious pileup and accumulation of debris were never seen at the plant port. In this study, we have never considered combinations of two or more types of loads subsequently given within one scenario.

3.2 The risk indices measuring frequency and severity of incident

Table 3 shows an example of definition of frequency index used in our domestic case. A range of frequency of incident is divided 5 ranks. Most frequent is the rank 3 which indicates more than 10^{-3} per year. It decreases by an order of magnitude down to the rank '0-2' of less than 10^{-6}. Practically, it is convenient to use rank separated by an order of magnitude. The severity index of incident is divided 4 ranks as shown in Table 4. Upper limits of the rank zero, one and two of each accident load indicate the equivalence of routine, normal and accident test conditions, respectively. The level three indicates an incident possibly having more severe condition imaginable. Such incident is also called a bounding case though not truly confirmed. For burial, we decide to use allowed time to package recovery for definition of rank. A limited period of a week in the rank two is tentatively quoted from that for leak rate of A2 value in accident condition.

Table 1. Example of incidents potentially caused by tsunami on the hazard matrix

Situation		Cargo work				Land transpor				Marine transpor								Onsite temporal storage			
Natural event	- Load type	No	Crane	SI	FI	No	Road	SI	FI	No	Open sea	SI	FI	No	Bay	SI	FI	No	Storage building	SI	FI
Tsunami	Mech. Impact	1	package drop	2	0-1	1	Vehicle collision	2	0-1	1	collision with vessel	2	1	1	collision/grounding with a quay	2	1	1	collision with fallen objects by collapse	2	3
		2	hit by a fallen crane	3	0-1	2	Vehicle fall	2	0-1	2	capsizing	1	1					2	collision with debris by tsunami	2	3
		3	collision with equipments	2	0-1	3	Collision with debris/flotsam	2	0-1	3	collision with debris/flotsam	1	1								
		4	collision with debris/flotsam	2	0-1					4	package turnover by acceleration	1	1								
		5	piled upon by vessel aground	3	0-1																
	Fire	1	fire by outflow oil	3	0-1	1	fire by outflow oil	3	0-1	1	fire by outflow oil	2	1	1	fire by collision with quay	2	1	1	fire by outflow oil	3	3
						2	fire by vehicle collision / fall	2	0-1	2	fire by the collision	2	1								
	Immersion	1	fall into sea by drop/collapse	1	0-1	1	vehicle poured and sunk	1	0-1	1	foundering/capsizing	2	1	1	foundering by collision with quay	1	1				
										2	capsizing by cask unlashing	2	1								
	Burial	1	buried in debris	2	0-1	1	buried in debris	2	0-1	1	hold cooling loss by power loss	1	1					1	buried in falling objects by collapse	2	3
										2	hold cooling loss by grounding	1	1					2	buried in debris	2	3
																		3	blockade of air supply by debris	1	3

3.3 Frequency calculation for incident of natural causes

Table 5 shows an example of frequency calculation of incidents caused by tsunami, under conditions of domestic SNF transport from a power plant to a reprocessing plant shown in Fig.2. An annual frequency of incident per year is calculated as follows.

- 'Frequency of natural event per year' x 'Probability of encountering the event during transport' x 'Frequency reduction factor'

Frequency of natural event is estimated either at the maximum of domestic case or on the basis of relevant literatures[4-6], as shown in Fig.3. The probability of encountering the event during transport can be represented by time rate of transport per year in most cases or by deck area rate of vessel per surface of globe in specific case of meteorite. The time rate can be calculated assuming that it takes 30 min per package in cargo work and 3 days average per trip of vessel. A frequency reduction factor represents an effect to prevent incident from progressing till the end by urgent safety measure. Table 6 shows the figures used in our case example. They are estimated differently by safety measure on the basis of a reference data of human error [7].

Table 2. The list of natural hazards and example of selection in domestic transport case

Wind	Strong winds (hurricane), tornado	O	Salt Storm, sand storm	
Temperature	High/low air temperature	O	White frost, soil frost	O
	Extreme air pressure		Surface ice, frazil ice, ice barrier	
	High/low sea/river water temperature			
Precipitation	Extreme rain or snow (snowstorm)	O	Extreme hail	O
	Ice storm, sub-cooled rain	O	Fog	O
Water level	Drought		Low sea/river water level	
	River diversions			
Flooding	High sea/river water level (high tide)	O	Tsunami, other extraordinary waves	O
	Storm surge, strong water current	O	Seiche	
Geology	Seismic events	O	Landslide	O
	Land rise, soil shrink/swell	O	Coastal erosion, avalanche, underwater landslide	
Lightning	Lightning	O		
Meteorite	Meteorite	O		
Volcano	Volcanic phenomena	O		
Biological	Animals		Organic material in water, other biological impacts	
Chemical	Corrosion (from salt water)	O		
Fire	Forest fire	O	Other external fire	O

Table 3. Example of the frequency index for domestic transport case

Occurrence frequency (per year)	Frequency index (FI)
Less than 10^{-6}	*0-2*
10^{-6} *to* 10^{-5}	*0-1*
10^{-5} *to* 10^{-4}	*1*
10^{-4} *to* 10^{-3}	*2*
More than 10^{-3}	*3*

Table 4. Example of the severity index for domestic transport case

Accident load		impact	fire	immersion	burial
assumed conditions		*drop height (meter) on rigid surface*	*atmosphere temperature, burning duration*	*water depth (meter)*	*allowed time to recovery*
severity index (SI)	0	*almost 0*	*normal temperature variation*	*almost 0 (heavy rain)*	*package can be left as is*
	1	*less than 0.3*	*equivalent of minor fire*	*less than dozens of meters (inside bay area)*	*until as long as a month*
	2	*less than 9*	*equivalent of major fire at 800 deg C for 30 min*	*less than 200 (open sea), salvage available*	*until as long as a week*
	3	*possibility of more severe than accident test condition (detail site survey will be required)*			

Table 5. Example of frequency calculation for incident caused by tsunami in domestic case

Natural event (NE)	1. Max freq of NE per year*	Transport mode		2. Time rate per transport per year	3. Max number of transport per year	4. Time rate of transport per year = 2 x3	5. Freq of incident per year = 1 x 4	6. Max frequency reduction factor*	7. Max estimated frequency of incident* = 5 x 6
tsunami	1.5E-03	Cargo work	*plant port*	5.7E-05	12 X 13	1.8E-02	2.7E-05	0.1	2.7E-06
			arrival port	5.7E-05	12 x 13				
		Marine transport		8.2E-03	12	9.8E-02	1.5E-04	-	1.5E-04
		Site storage	*plant*	1**	1	1	1.5E-03	-	1.5E-03

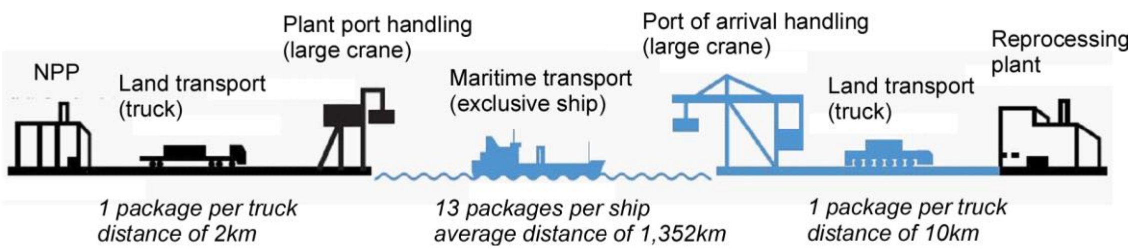

Figure 2. Example of evaluation conditions in domestic transport of spent nuclear fuel

Figure 3. Maximum estimated frequency of severe natural events for domestic use

3.4 Classification using the risk matrix

Figure 4 shows an example of the risk matrix used to classify incidents in our case. After all the incidents are placed onto the cell corresponding to its risk indices, the matrix can help us focus on incidents of interest in specific cells and screen out others.

Considering purpose of this study, we have decided to focus on colored cells of AA, A1 and A2 due to the highest severity. The border of annual frequency is set to 10^{-6} per year, normally regarded as negligible if less than that.

Table 6. Example of frequency reduction factor by natural event in domestic transport case

Natural event	Safety measure	Frequency reduction factor
Sudden change of weather and sea condition	*Creation of task force, Captain judgment*	*Less than 0.01*
Tsunami	*Announcement of Tsunami advisory*	*Less than 0.1*
Chemical influence An external fire	*Creation of task force*	*Less than 0.01*
Tornado, blast , earthquake, landslide, volcano and meteorite	*Creation of task force if sign of event is known*	*Less than 1.0*

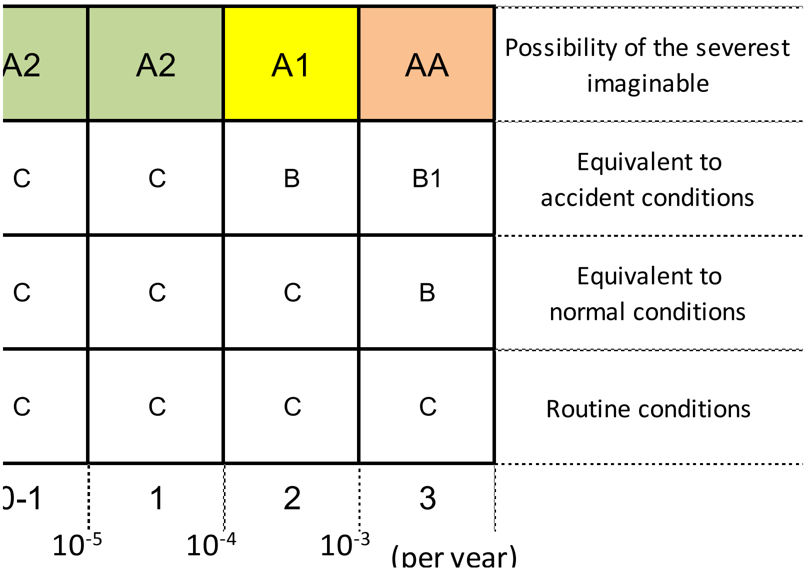

Figure 4. Example of a cell group of significant incidents in domestic transport case

4 Case example of finding incidents in domestic spent nuclear fuel transport

A case example of finding incidents in domestic SNF transport was conducted to show the applicability of our techniques. The transport conditions including route is illustrated in the Fig.2. The setting of the hazard matrix and the risk matrix are shown in Table 1 and Fig.4 respectively. The risk indices of frequency and severity are defined as shown in Table 3 and 4 respectively. Data for frequency calculation are shown in Table 5 and 6, and Fig.3. The number of local experts involved in this project was five in total from agencies concerned.

Table 7 shows a summary of identification in this example. Over 300 incidents were found in total. After all of them were rated, only 9 incidents were left on the colored cells of the risk matrix. None of them were left for marine transport.

Table 8 shows descriptions of those incidents of special attention. Suffering situations include cargo work, land transport and site storage. There are two types of initiating natural events, tsunami and volcano. Concerns on mechanical impact are directly focused on very heavy objects such as vessel and crane, which could possibly hit a package by some cause. Concerns on fire are focused on the existence of large quantity of combustible liquid and gas such as a diesel tank. It is considered that volcanic activities could have some direct impact only if volcano locates within 160 km from the transport area/route.

After this study, for these incidents the competent authority has performed detailed site survey including assessment of impact by computer simulation. Consequently it has been proved that they cannot threaten the package safety in domestic context [8].

Table 7. The number of potential incidents identified first and afterwards classified as ones of special attention in domestic case example

	Cargo work	Land transport	Marine transport	Onsite storage	total
Impact	39 (2)	56 (0)	23 (0)	20 (0)	138 (2)
Fire	5 (1)	37 (1)	17 (0)	6 (2)	65 (4)
Immersion	11 (0)	19 (0)	21 (0)	0 (0)	51 (0)
Burial	7 (1)	23 (1)	3 (0)	22 (1)	55 (3)
total	62 (4)	135 (2)	64 (0)	48 (3)	309 (9)

The number of incidents of special attention is indicated in parenthesis.

Table 8. Description of potential incidents of special attention in domestic case example

Suffering situation	Initiating natural event	Potential incident/scenario	Accident load type	Cell group on the risk matrix
cargo work	tsunami	*hit by fallen objects of crane collapse*	impact	A2
	tsunami	*piled up by a grounded vessel*	impact	A2
	volcano	*fired by pyroclastic flow or fallen ashes*	fire	A2
	volcano	*covered by pyroclastic flow or fallen ashes*	burial	A2
land transport	volcano	*fired by pyroclastic flow or fallen ashes*	fire	A2
	volcano	*covered by pyroclastic flow or fallen ashes*	burial	A2
site storage	tsunami	*fired by outflow oil from nearby tank*	fire	AA or A1
	volcano	*fired by pyroclastic flow or fallen ashes*	fire	A2
	volcano	*covered by pyroclastic flow or fallen ashes*	burial	A2

5 Conclusion

A framework has been developed to identify transport incidents potentially caused by natural events and to separate significant ones from the others using risk concept. It is also proposed to support an existing approach of transport regulations in the domain of natural events. The risk index having small number of ranks based on the grade of test conditions is useful to grasp profile of incident-risk over the domain of transport. However, care should always be taken for oversight of incident and uncertainty of rating. Continual efforts of acquiring knowledge/information are of importance.

A case example of domestic SNF transport was performed to recognize potential incidents of special attention. After this study, towards closing the gap-review of Japan, the competent authority has recently performed detailed site survey for the specific incidents, and it has been proved that they have no influence on the package safety under domestic conditions.

Acknowledgment

I am deeply grateful to Mr. Kazushige Kuriyama of our research group. Without his guidance and persistent help, this paper would not have been possible. I would also like to express my gratitude to Nuclear Fuel Transport Co., Ltd. for their financial support.

References

[1] Addenda to ASME/ANS RA-S-2008 Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications, ASME/ANS RA-Sa-2009 (2009)

[2] Probabilistic Safety Analysis (PSA) of Other External Events than Earthquake, NEA/CSNI/R(2009)4, Nuclear Energy Agency, OECD (2009)

[3] Technical Basis for the IAEA Regulations for the Safe Transport of Radioactive Materials (TS-R-1) Draft, IAEA (2012)

[4] A Pilot Probabilistic Risk Assessment of a Dry Cask Storage System at a Nuclear Power Plant, NUREG-1864 (2007)

[5] Preparation of Methods Regarding Seismic Probabilistic Safety Assessment (in Japanese), JNES/SAE 07-074, Japan Nuclear Energy Safety Organization (2006)

[6] Probabilistic Risk Assessment (PRA) of Bolted Storage Casks, Updated Quantifications and Analysis, EPRI 1009691, Palo Alto, California, EPRI (2004)

[7] Reactor Safety Study. An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, WASH-1400 (NUREG-75/014), US NRC (1975)

[8] M. Hirose and M. Hishida, Review of IAEA Transport Safety Standards in Light of 28 Lessons Learned from Fukushima Daiichi Nuclear Power Stations Accident, Proc. PATRAM2013 (2013)