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CONSIDERATIONS ON REFERENCE LEVEL AND ASSESSMENTS OF RADIOLOGICAL CONSEQUENCES IN EMERGENCY DURING TRANSPORT OF RADIOACTIVE MATERIALS

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ABSTRACT

At the time of the Fukushima Daiichi accident in 2011, radiation exposure to the public was limited owing to prompt and extensive evacuations. However, numerous non-radiological fatalities have been reported since the disaster. One of the major reasons for this tragedy is prolonged evacuations from contaminated areas. Based on this situation, Japan’s Nuclear Regulatory Authority (NRA) held intensive discussions and came to the decision in that the reference level for emergencies of nuclear installations would be increased from 20 mSv to 100 mSv in 2018.

Although large number of radioactive material transport is carried out daily all around the world, the safety record has been excellent for decades thanks to strict international regulations and the assiduous efforts of all stakeholders. Nevertheless, we should not ignore the possibility of an emergency arising during the transport of radioactive materials and it is crucial that appropriate emergency arrangements be established in advance. Particularly, as transport is conducted in public domain, so a cordoned-off area setting an appropriate safe distance around the accident site should be established to protect the public from radiological consequences of damaged packages. However, the appropriate safe distance should adequately take into account non-radiological hazards as well as radiological hazards. Furthermore, any assessment of an emergency’s radiological consequences includes significant uncertainty but the results of the assessment are overestimated too much if all the uncertainties are taken into account conservatively.

This paper proposes a multi-tiered methodology for determining the safe distance based on assessments of radiological consequences with significant uncertainty and appropriate exposure criteria for the public in transport emergencies.

INTRODUCTION

There has never been an incident which led to significant radiological damage to persons or environment during the transport of nuclear materials over five decades. It is thought that one reason for this excellent safety record is that the transport of radioactive material is carried out with appropriate packaging, operation and administrative control, which are based upon the graded approach set out in the IAEA Transport Regulations [1] globally. Typically, Type B packages, which are used to transport of large quantities of radioactive materials (e.g. spent nuclear fuel and high level waste), are required to be able to withstand severe “Accident Conditions of Transport” (ACT) in order to protect the public from radiological hazards. There have been no accidents that have exceeded the ACT during the transport of radioactive materials so far. Nevertheless, we should not ignore the possibility of more severe accidents than the ACT (beyond ACT) because of the significant radiological hazards that the public may be exposed to. That having been said, Paragraph 106 of the latest version of the IAEA Transport Regulations [1] additionally requires that emergency arrangements be put in place to protect people, property and the environment.

Transports are conducted in public domain and restrictions preventing people from getting near damaged packages are important to protect the public from radiological consequences in case of a release of radioactivity. Therefore, national and local emergency arrangements should require that a cordoned-off area be immediately established setting a safe distance from the damaged packages in a transport emergency. However, there is no clear criteria to determine the safe distance in a transport emergency. Assessments of radiological consequences in a transport emergency include significant uncertainty due to the transport characteristics, and it seems difficult to appropriately take into account the uncertainty for the assessments.

LESSONS LEARNED FROM FUKUSHIMA

Impacts of Fukushima Daiichi accident

Owing to the prompt and extensive evacuations out of contaminated areas and the prohibition on taking potentially contaminated food, milk and water from these areas, exposure to the public has been limited. Table 1 [2] shows typical estimates by UNSCEAR of the exposures to residents near the site after the Fukushima Daiichi accident in 2011. According to these estimates, the maximum effective dose of the public is less than 10 mSv and the absorbed dose to the thyroid is also less than 40 mGy, so it is concluded that there is no anticipated radiological impact to health.

Table 1. Estimated settlement-average effective doses and absorbed doses to the thyroid for evacuees for the first year following the Fukushima Accident (Adult, 1 year) [2]

Area	Effective Dose (mSv)	Absorbed Dose to the Thyroid (mGy)
Precautionary evacuated settlements [a]	1.1–5.7	7.2–34
Deliberately evacuated settlements [b]	4.8–9.3	16–35
Other Area in Fukushima prefecture	1.0–4.3	7.8-17

a Precautionary evacuation refers to the evacuation of settlements that was instructed between the 12 and 15 March 2011 as an urgent protective action to prevent high exposure.

b Deliberate evacuation refers to evacuation of settlements (based upon environmental measurements) that was instructed between late March and June 2011.

In the Great East Japan Earthquake which led the Fukushima Daiichi accident, the earthquake and subsequent tsunami killed over 18,000 people (including those missing). Table 2 shows the number of victims in each prefecture (local area). Furthermore, over 3,700 people died due to disaster-related causes after the disaster (related deaths). Victims in Miyagi prefecture account for over half of the total because Miyagi is the prefecture located closest to the epicenter of the earthquake. However, victims in Fukushima prefecture account for around two-thirds of total related deaths, a number greater than those who died or were missing in the disaster itself. Although the causes of related deaths vary, it is clear that one major cause was the extensive and prolonged evacuation from areas contaminated during the Fukushima Daiichi accident. It has been reported that, as of April 2019, there are approximately 48,000 people still living as evacuees from the disaster and approximately 40,000 of them are from Fukushima prefecture.

Table 2. Causalities from the Great East Japan Earthquake

Prefecture	Deaths*1	Missing*1	Related Deaths*2	Total
Iwate	4,674	1,114	467	6,255
Miyagi	9,542	1,219	928	11,689
Fukushima	1,614	196	2,250	4,060
Others	67	4	56	127
Total	15,897	2,533	3,701	22,131

*1: Direct causalities from the earthquake and tsunami [3]

*2: Death after the earthquake due to relocation and disaster-associated causes [4]

Many stories have been reported about related deaths. For example, over fifty patients evacuated from a hospital near the Fukushima Daiichi site died shortly despite having been promptly evacuated because it took very long to transfer the patients to another hospital by a tour bus without medical equipment. And many evacuees became ill due to physical and mental stress caused by prolonged evacuation and living in temporary housing. The number of related deaths is still rising.

Although the extensive and prompt evacuation protected many people from significant radiation exposure, the large number of related deaths points to a serious failure of the emergency measures adopted after the accident from the standpoint of protecting human life.

Discussions on Reference Level in Japan

Taking into account this lesson learned from the facts Japan's Nuclear Regulation Authority (NRA) held intensive discussions on the reference level. IAEA GSR Part7 [5] defines "the reference level: risk or activity concentration above which it is not appropriate to plan to allow exposures to occur and below which optimization of protection and safety would continue to be implemented" and recommends an effective dose between 20 and 100 mSv. As the result of discussions [6], it was decided that the reference level should be increased from 20 mSv to 100 mSv for emergency of

nuclear installations because non-radiological hazards should also be appropriately taken into account. In addition, the importance of sheltering as an emergency measure was also mentioned.
There have been discussions on this issue globally. For instance, a study was conducted in the UK on approaches to justify evacuation quantitatively based on radiological health effects and social/economic costs [7].

CHARACTERISTICS OF RADIOACTIVE MATERIAL TRANSPORT

Possibility of Severe Accidents

Appropriate packaging, operation and administrative controls are required which are commensurate with the potential hazards of the contents in accordance with the graded approach set out in the IAEA Transport Regulations [1]. For example, Type B packages, which are required to be able to withstand the severe ACT, can be used for highly-radioactive spent nuclear fuel. Therefore, practically speaking, it seems very unlikely that significant radioactivity may be released from a Type B package, even if there were any accidents. According to a recent comprehensive study [8] on risk assessment of spent fuel transport in the U.S., it was estimated that "99.95% of accidents would not exceed regulatory requirements." Furthermore, "99.99973% of accidents that are more severe than the regulatory hypothetical accident do not lead to release or loss of lead gamma shielding." A similar risk assessment on maritime transport of spent nuclear fuel was carried out in Japan and no significant risks were identified [9]. After the Fukushima Daiichi accident, the necessity of considering large scale natural events was recognized as something that may trigger a beyond ACT during transport and studies were conducted [10]. However, it was confirmed that no additional requirements need to be added to the current IAEA Transport Regulations [1].

Reference Level for Transport Emergency

The possibility occurring the beyond ACT seems very low. Nevertheless, we should not ignore the possibility of it and should prepare appropriate emergency arrangements in advance. Various kinds of packages are transported around the world and accidents may occur anywhere along transport routes, and circumstances along them may vary widely. It is important to formulate appropriate emergency arrangements that includes establishing a cordoned-off area immediately once a transport emergency arises. Each country establishes its own transport emergency plan based on the radiological assessments for representative packages in appropriate accident scenarios. The extent of the cordoned-off area should be set to protect the public from radiation exposures, but the criteria for public exposure are not same in each country. It has been reported that a criterion of 10 mSv was used for safe distance in France and 5 mSv in Japan [11,12]. However, there is no internationally recommended criterion during a transport emergency. An IAEA document provides safe distances for cordoned-off areas during transport emergencies [13], but it shows no exposure criterion for the public.

Margins of Safety in Package Design

For example, packages for spent fuels are designed to provide necessary safety functions (heat removal, shielding, and containment) when all loaded fuel assemblies have the allowable maximum burnup and minimum cooling time (maximum heat load and radioactivity). However, it is unlikely that, in reality, all loaded spent fuel assemblies will be at the maximum. Furthermore, some conservative assumptions about material specifications and calculation models have been adopted in safety assessment reports (SAR) and it provides some margin of safety.

Table 3 shows examples comparing calculated dose rates stated in the SAR and measured dose rates for NFT type transport casks [11] (Fig. 1). They are widely used to transport spent fuels in Japan and the length is 6 m and the total weight is 100 tons approximately.

According to Table 3, the measured dose rates are significantly less than the results stated in the SAR. This shows that the results of SAR include a significant margin of safety, and The margins includes the difference between design specifications and loaded fuel assemblies as well as conservative parameters in materials and calculation models. They are widely different depending on the contents, package designs and environments and lead significant uncertainty in assessments of radiological consequences in a transport emergency, but need to be taken into account in formulating appropriate emergency arrangements.

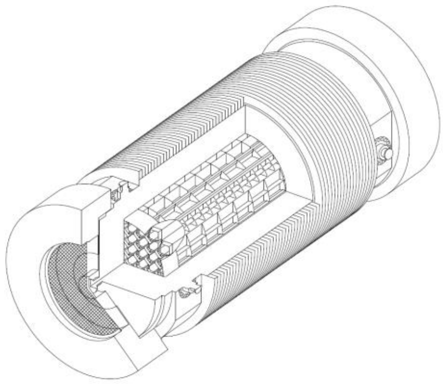

Fig.1. Bird's-eye view of Typical NFT-Type cask

Table 3. Comparison between SAR and measurement results [15]

Unit [mSv/h]

	NFT-14P (14 PWR Assemblies)		NFT-22B (22 BWR Assemblies)	
	SAR	Measurement	SAR	Measurement
Surface	1.109	0.031	0.55	0.0012
1m from Surface	0.0778	0.0039	0.0626	0.0011

Radiological Assessment for Transport Emergency

Radiological assessment for a transport emergency is regarded as different from the assessments for SAR. The SARs demonstrate that specific dose rate limits are satisfied, which entail conservative assumptions and it is to clearly show that there are no significant radiological hazards to the public even in the ACT. On the other hand, more severe conditions (beyond ACT) need to be considered in radiological assessments pertaining to transport emergencies. The assessments should be carried out realistically because if a too conservative (extensive) area is cordoned off, the public and society may sustain unnecessary social and economic damage, which is a lesson learned from the Fukushima Daiichi accident.

Therefore, the possible beyond ACT scenarios should be considered using actual transport routes and realistic parameters. For example, regarding drop events actual characteristics of the ground need to be considered instead of unyielding target used in SARs. And a gasket on the containment system should be used within the applicable temperature range in the assessments of SARs, but actual behaviors beyond the applicable temperature range may need to be used in the assessments of a transport emergency. Additionally realistic calculation models without excessive safety margins should be used. It is important to obtain the realistic assessment results concerning a transport emergency.

However, it is inevitable that average or representative values are used as realistic parameters in the assessments cause uncertainty because of variability of each parameter or difficulty of the prediction of situations on the site. For example, bun-up and cooling time of spent fuel assemblies loaded in each package are different. If average values in the past experiences are used as realistic values and the variability of the contents cause uncertainty of the heat load and radiation source. Another example is atmospheric instability. It is reported that the evaluated exposure can vary more than 10 times by assuming between class A and F of the atmospheric instability [11].

Therefore, the uncertainties are important to evaluate the reliability of the realistic results in transport emergencies. Furthermore, in cases of the beyond ACT, it is also crucial to identify the possibility to reach a cliff edge.

EXAMPLE OF UNCERTAINTIES CONSIDERED

It is challenging to use the results with significant uncertainty to determine the appropriate emergency arrangements. It seems similar to a radiological assessment for final disposal, which comprises significant uncertainty due to the very long time scale and unknown environmental situations deep underground.

The regulatory criteria and methodologies for the final disposal of interim level radioactive waste have been discussed within the NRA. It proposed that criteria based on the ALARA concept and assessments of radiological consequences be carried out in 3 cases based on two scenarios as shown in Fig.2. It comprises the most rational case (Most likely Case) with rational scenario and parameters from scientific standpoint, and the case with same scenario and conservative parameters (Conservative Case). The results of the Conservative Case must satisfy a criterion of the public and should be as low as reasonably achievable. As there is still significant uncertainty in the assessments, it is also required that a hypothetical severe case (Hypothetical Case) be considered and the radiological consequences even according to a more severe scenario and parameters satisfy the regulatory limit to the individual exposure in public [16].

This approach requires minimization of public exposure based on a most rational scenario with conservative parameters (Conservative Case) as well as demonstration of minimum safety even according to the Hypothetical Case.

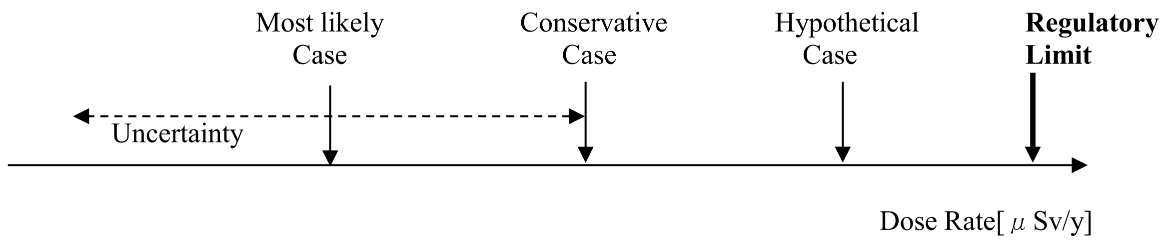

Fig. 2. Draft of approach applying exposure criteria for interim level disposal

PROPOSAL OF MULTI-TIERED METHODOLOGY FOR TRANSPORT EMERGENCY

Overestimation of radiological consequences means underestimation of other risks in an emergency, that is, if the radiological risks are overestimated and an extensivelarge area is cordoned off, the unnecessary social and economic burdens will increase and misunderstanding of the risks about the transport of radioactive materials may spread widely.

However, a realistic radiological assessment of a transport emergency will tend to have significant uncertainty as mentioned above. The author proposes a multi-tiered methodology for radiological assessments in a transport emergency. Three tiers for assessments of a transport emergency are proposed as shown in Table 4.

Table 4 Multi-tiered methodology for radiological assessments in a transport emergency

Tier	Assessment Scenario	Exposure Criteria
Tier 0	Realistic scenario with likely parameters	-
Tier 1	Realistic scenario with conservative parameters	Objective level
Tier 2	Hypothetical scenario with extreme assumptions	Reference level

Realistic scenarios beyond the ACT based on actual transport route and all potential risks, including large-scale natural disasters, with most likely parameters (Tier 0) and the same scenarios with conservative parameters (Tier 1) are considered in the radiological assessments of transport emergencies. The difference between Tier 0 and Tier 1 can shows the extent of the uncertainty of the assessments. Based on that, the safe distance can be obtained to satisfy an exposure criterion for the public (objective level). The objective level set at a level that reasonably minimizes public exposure. In the assessment, conservative parameters are used, but unrealistic assumptions (e.g. unlikely maximum contents, extensive margins of safety) should not be used. It is also very important to confirm where the cliff edge is in the assessment because the cliff edge should be avoided no matter what the situation is, even in an emergency.

However, it is impossible to demonstrate that all possible beyond ACT scenarios have been considered Therefore, radiological assessments based on some hypothetical severe scenarios (complete loss of shielding or release of radioactive material, etc.) are performed and a safe distance satisfying the criteria to avoid serious exposure (reference level) is also determined in Tier 2. The safe distance is finally determined to satisfy both Tier-1 and Tier-2.

The objective level and reference level for a transport emergency should be determined in each country. The reference level may be the same as one for an emergency at a nuclear installation. The objective level should be determined so that both public exposure and non-radiological hazards, which may vary depending on the location and environment of the emergency site, are minimized. For example, social and economic hazards in a rural area may be lower than in an urban area and the safe distance in rural area may be increased if the objective level decreases as appropriate. It is noted that sheltering may be also considered as an effective emergency measures in a transport emergency.

CONCLUSIONS

No severe transport accidents exposing the public or the environment to significant radiological effects have occurred anywhere around the world. Nevertheless, it is necessary to prepare emergency arrangements for the beyond ACT in advance. However, realistic radiological assessments of the beyond ACT may entail significant uncertainty. If all uncertainties are conservatively taken into account, radiological consequences will be overestimated. Overestimation of radiological consequence means underestimation of non-radiological consequences.

Therefore, a new multi-tier methodology for transport emergencies is proposed so that radiological consequences are appropriately estimated even though significant uncertainty is included. Assessments based on a realistic scenario with conservative parameters and a hypothetical scenario are conducted to ensure that public exposure is reasonably minimized and does not exceed the criteria for significant radiological hazard.

Establishment of the balanced cordoned-off area, which is determined based on a safe distance calculated using this new methodology, can protect the public from radiological and non-radiological hazards even in transport emergencies. Additionally, as the impact and uncertainty of each parameter can be considered and the cliff edge can be identified according to the methodology, the critical parameters can be identified and effective emergency responses may be enhanced.

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