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Countermeasures for Management of Off-site Radioactive Wastes in the Event of a Major Accident at Nuclear Power Plants

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Major accidents at nuclear power plants generate huge amounts of radioactive waste in a short period of time over a wide area outside the plant boundary. Therefore, extraordinary efforts are required for safe management of the waste. A well-established remediation plan including radioactive waste management that is prepared in advance will minimize the impact on the public and environment. In Korea, however, only limited plans exist to systematically manage this type of off-site radioactive waste generating event. In this study, we developed basic strategies for off-site radioactive waste management based on recommendations from the IAEA (International Atomic Energy Agency) and NCRP (National Council on Radiation Protection and Measurements), experiences from the Fukushima Daiichi accident in Japan, and a review of the national radioactive waste management system in Korea. These strategies included the assignment of roles and responsibilities, development of management methodologies, securement of storage capacities, preparation for the use of existing infrastructure, assurance of information transparency, and establishment of cooperative measures with international organizations.

Keywords: Major accident, Fukushima Daiichi accident, Nuclear power plant, Radioactive waste, Management plan, Countermeasures

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1. Introduction

According to the International Atomic Energy Agency (IAEA), as shown in Fig. 1, a nuclear emergency is divided into two phases: an emergency response phase and a transition phase. In the emergency response phase, urgent protective actions such as evacuation and iodine thyroid blocking should be taken immediately, within a few hours to one day. Furthermore, early protective actions should be taken over several days to weeks, such as limiting the consumption of food affected by radioactive contamination. Once the radiological situation is controlled, a transition phase follows, which can last from days to years. In this phase, various activities are planned and implemented to meet the safety requirements for declaring emergency termination. The management of radioactive wastes resulting from a nuclear emergency is the most important task in the transition phase, as it determines the timely termination of the emergency and the resumption of the community's socio-economic activity. In some case, radioactive waste management implemented early in emergency response phase will help to minimize radioactive waste generation. Therefore, to systematically manage radioactive wastes, the IAEA recommends that national policies and strategies should be established in advance to prepare for waste management issues to be faced in the transition phase [1].

The issues of radioactive waste management arising from a major accident can be understood from the case of Japan. A major accident is the highest level (7-level) on the International Nuclear and Radiological Event Scale (INES) introduced by IAEA, which is defined as the "major release of radioactive material with widespread health and environmental effects requiring implementation of planned and extended countermeasures". When the Fukushima Daiichi accident was triggered by the Tohoku earthquake and tsunami in 2011, large areas were contaminated with significant amount of radionuclides. Consequently, large amounts of waste were, and still are, being generated both within and outside the nuclear power plant (NPP) boundary. As of November 2014, approximately 8.0×10^4 m^3 of trees and 1.3×10^5 m^3 of debris were stored on-site. It is estimated that additional 5.6×10^5 m^3 of contaminated material will be generated by 2027. Furthermore, it was reported that the amount of soil and other contaminated materials generated by the off-site remediation activities reached approximately 2.2×10^7 m^3 even after appropriate volume reduction [2]. Considering that a 1,000 MWe NPP generally generates a total of $1.5 \times 10^4 - 2.5 \times 10^4$ m^3 of low-level radioactive waste over a 60-year operation period [3], the radioactive waste management followed by a major accident has two main features. One is that a large amount and variety of waste, far exceeding that generated during routine NPP operation, can be generated simultaneously inside and outside the nuclear power plant. The other is that such waste must be effectively managed in very short timeframes compared to the operational lifetime of a NPP [3]. Accordingly, Japan has made considerable efforts to safely manage radioactive waste and contaminated material generated by the Fukushima Daiichi accident. These efforts include the classification, transportation, treatment, storage, and disposal of the waste.

In Korea, however, nuclear emergency countermeasures are focused on responding to the initial stage of the emergency, and practical plans to manage off-site radioactive waste caused by a major accident are insufficient. There has not been enough discussion on whether the existing classification system should be strictly applied to the various types of radioactive waste that may occur in an accident. Considering the current situation in Korea, it is necessary to conduct an in-depth review of radioactive waste management issues in the event of a major accident to establish effective national policies and strategies. In this way, it will be possible to protect the public promptly, reduce the adverse impact on the environment, and minimize socio-economic impact.

In this study, based on recommendations from the IAEA and the US National Council on Radiation Protection Measurements (NCRP) and lessons learned from the Fukushima Daiichi accident in Japan, we developed six important

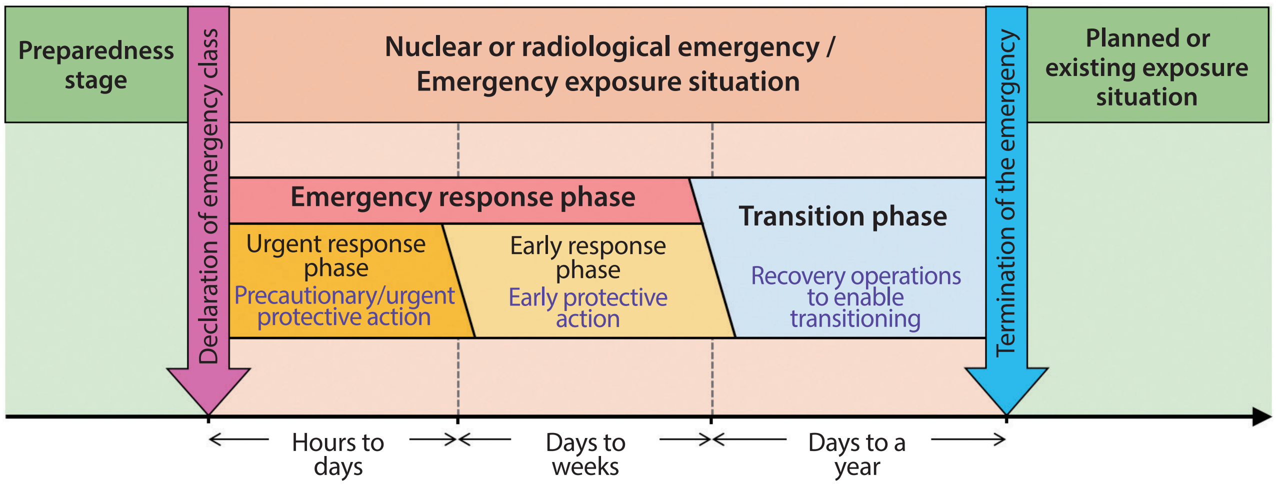

Fig. 1. Sequence of various phases, exposure situations, and protective actions for a nuclear emergency [1].

considerations to establish domestic countermeasures for the management of off-site radioactive waste caused by a major accident. The current status of the radioactive waste management system in Korea was also reviewed.

2. Recommendations Related to Radioactive Waste Management in Emergency

2.1 International Atomic Energy Agency (IAEA)

The IAEA recommends the preparation of countermeasures to effectively resolve the expected problems in the management of radioactive waste in a nuclear emergency, which can be summarized into five points [1, 4]. First, there should be a clear and consistent allocation of responsibilities for radioactive waste management. This includes establishing a unified command and control system to coordinate and cooperate in the implementation of various countermeasures among responsible organizations during the emergency response. Second, the characteristics and volume of waste to be generated in a nuclear emergency should be predicted based on past experiences and hazard assessment. Thus, clear criteria and guidelines for the characterization and classification of waste can be derived. These guidelines should also consider the diversity of the non-radiological properties of the waste. Third, detailed guidelines for handling the waste should be prepared. These guidelines should provide acceptance criteria for existing storage and disposal facilities that will be applied to the waste; they should also provide guidance on how to manage the waste that deviates from the acceptance criteria. Fourth, methodologies should be developed to implement pre-disposal management activities for the waste. These methodologies should identify feasible options such as reuse and recycling to minimize the amount of waste to be managed; they should also cover the necessary equipment, procedures, and training to support management activities. Finally, the limitations of available options and resources for waste management should be considered in advance, and a network for requesting and receiving international assistance should be established. To institute comprehensive countermeasures for radioactive waste management considering these issues, a thorough review of the national legal and regulatory system is required, meaning that the existing national system may need to be partially revised [1, 4].

2.2 National Council on Radiation Protection and Measurements (NCRP)

The NCRP emphasizes the need to develop a regulatory structure based on the intrinsic hazardous properties of radioactive waste, that is, the degree of radiological risk caused by treatment, storage, and disposal of the waste. Furthermore, to effectively manage waste generated by a major accident, the NCRP recommends identifying several important points as follows: the extent and nature of the contamination, available techniques for remediation, effectiveness of remediation. Since contaminated waste management requires full support from the affected communities, the national government should develop waste management plans to make the most of available infrastructures. The plans must consider the site selection and utilization of the storage area in preparation for a large demand of waste storage after a major accident [3].

3. Off-site Radioactive Waste Management After the Fukushima Daiichi Accident in Japan

A large amount of off-site radioactive waste was generated by the Fukushima Daiichi accident in Japan. The waste includes contaminated soil, trees, building debris, and sludge, with an extensive range of physical, chemical, and radiological characteristics that are difficult to manage using conventional infrastructures. Prior to the accident, Japan did not consider recovery measures for a wide contamination area and there was no legal system to deal with the management of waste generated from remediation activities. Therefore, it is necessary to develop national policies and strategies for off-site waste management and create or revise regulations and laws. The management of off-site radioactive waste was systematically implemented by the Ministry of Environment (MOE) with other relevant organizations based on the "Act on Special Measures concerning the Handling of Environment Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District - Off the Pacific Ocean Earthquake That Occurred on March 11, 2011" (hereafter referred to as the Act on Special Measures Concerning the Handling of Radioactive Pollution) [5] which was enforced in January 2012. This act clearly defines the roles and responsibilities of the national and local governments, operating organization, and citizens, and stipulates the waste classification criteria and management methodologies for the classified waste.

An area where waste contaminated with radioactive materials exists is designated as a contaminated waste management area by the MOE. "Waste within the management area" consists of debris from the tsunami, demolished homes, house-cleaning waste resulting from evacuation, and other debris typically associated with natural disasters. The national government needs to manage the waste within the area. Meanwhile, a contamination survey is conducted for incinerated ash, sludge from the water treatment facilities, sewage sludge, and contaminated agricultural products. When the sum of the activity concentrations of ^{134}Cs and ^{137}Cs exceeds 8 $Bq{\cdot}g^{-1}$, items are classified as "designated waste" according to the Act on Special Measures Concerning the Handling of Radioactive Pollution [5]. In addition, the combination of waste within the management area and designated waste is collectively referred to as "specified waste." Fig. 2 illustrates the management flow of off-site radioactive waste generated in Fukushima Prefecture in Japan [2]. If the sum of activity concentrations of ^{134}Cs and ^{137}Cs is less than 8 $Bq{\cdot}g^{-1}$, the normal treatment methods for non-radioactive waste are employed according to the Waste Management and Public Cleansing Act [6]. Conversely, if the sum of the activity concentrations of ^{134}Cs and ^{137}Cs exceeds 8 $Bq{\cdot}g^{-1}$, combustible waste is incinerated. If the activity concentration of incinerated ash or incombustible waste exceeds 100 $Bq{\cdot}g^{-1}$, it is disposed of after interim storage, and if it is less than 100 $Bq{\cdot}g^{-1}$, it is transported to the existing controlled landfill site.

The contaminated areas are divided into two categories

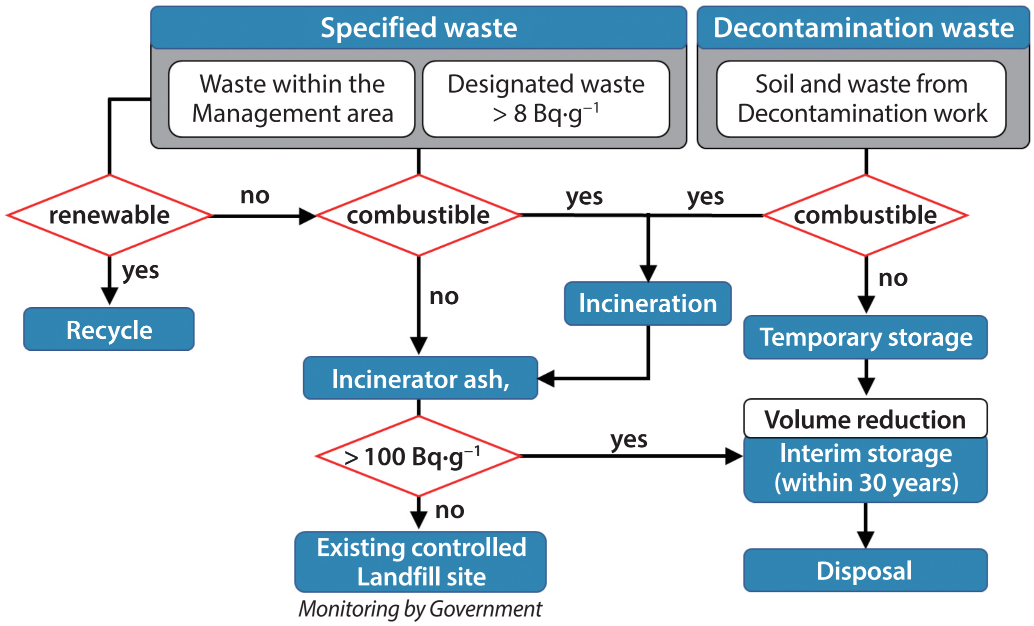

Fig. 2. Flow chart for the management of off-site radioactive waste and contaminated material generated in Fukushima Prefecture in Japan [2].

designated by the MOE to implement decontamination measures. One is the special decontamination area (SDA), which is found to have been considerably contaminated by radioactive materials such that the national government needs to implement decontamination measures, as well as the collection, transfer, storage, and disposal of the decontamination waste. This area is mostly within a 20 km radius from the Fukushima Daiichi NPP. The other is the intensive contamination survey area (ICSA), in which an intensive measurement of the status of environmental pollution from radioactive materials is required, excluding SDA. In this ICSA, relevant municipalities should conduct monitoring surveys to determine whether decontamination should be implemented. After interim storage followed by volume reduction by mechanical crushing or incineration, the waste is disposed of when the sum of the activity concentrations of ^{134}Cs and ^{137}Cs exceeds 100 $Bq\cdot g^{-1}$. If the sum is less than 100 $Bq\cdot g^{-1}$, it is transferred to the existing controlled landfill site [2].

Japan classified a wide variety of contaminated wastes according to the locations where the waste was generated, activity concentration, combustibility, to name a few. Furthermore, for each classified waste, the organization in charge tried to reduce the volume of waste to be managed and put significant efforts into appropriate management. However, not all waste management activities resolved smoothly. It was not easy to obtain the consent of the municipality to incinerate combustible wastes at existing facilities, and in the process of selecting storage sites for wastes continuously generated by remediation activities, there was a delay due to opposition from residents. This demonstrates that waste management activities can proceed favorably only when the cooperation of the relevant local governments and public trust are ensured.

4. Current Status in Korea

4.1 Radioactive Waste Classification and Clearance

According to the Nuclear Safety Act in Korea, radioactive wastes are classified into high, intermediate, low, and very low levels based on the concentration of radionuclides. In addition, if the concentration of radionuclides is less than a certain level, that is, the clearance level, the waste is treated as non-radioactive waste through regulatory clearance [7].

Meanwhile, under normal conditions, Japan specifies a clearance level of 0.1 $Bq \cdot g^{-1}$ for ^{134}Cs and ^{137}Cs among radionuclides [8], which is the same as the clearance level regulated in Korea. However, in the event of an accident in Japan, as described earlier, the classification distinction between radioactive waste to be managed and non-radioactive waste is made based on whether the sum of the activity concentrations of ^{134}Cs and ^{137}Cs exceeds 8 $Bq \cdot g^{-1}$ or not. In other words, Japan has different clearance level criteria for normal and accidental conditions.

As such, when the clearance level criteria for an accident are set relatively high, within a range that reasonable radiation protection is achieved, the amount of waste to be managed as radioactive can be significantly reduced, thereby relieving cost and resource pressure. In Korea, there has been insufficient discussion on whether the existing waste classification system should be directly applied to various types of radioactive waste associated with a major accident.

4.2 Off-site Radioactive Waste Management Plan

In Korea, there are limited plans to systematically manage large quantities of off-site radioactive waste resulting from a major accident. For example, the Nuclear Safety and Security Committee's (NSSC's) Working Manual for Accident from Radioactive Material Release [9], only discusses the duties of the Radioactive Waste Safety Division to comprehensively manage measures related to radioactive waste treatment and disposal facilities in the event of a nuclear disaster. It does not have any definitive explanations about the measures. In addition, in the Action Manual for Accident from Radioactive Material Release, published by Gijang-gun, Busan Metropolitan City [10], which is the largest NPP cluster in Korea, general guidelines for the collection and treatment of radioactive waste are provided. However, it is assumed that the situation generates radioactive waste that can be sufficiently controlled, and therefore, in the event of a major accident, there will be obvious limitations in applying the guidelines to situations in which the volume of radioactive waste exceeds national capabilities and resources.

Thus, it is necessary to predict the volume and type of radioactive waste that can be generated based on the accident scenario, and to develop appropriate management plans and methodologies in cooperation with national and local governments.

5. Countermeasures for Management of Off-site Radioactive Wastes by a Major Accident

Based on the reviews described in the previous section, we developed six important considerations for establishing domestic countermeasures for off-site radioactive waste by a major accident as follows.

5.1 Define the Roles and Responsibilities of Relevant Organizations for the Management of Off-site Radioactive Wastes

The off-site radioactive waste generated by a major NPP accident should be managed under the responsibility of a nuclear power producer. However, as radioactive materials are released into large areas, the local governments of these areas should actively provide management resources. Thus, cooperation between operating organization and local governments is essential for effective management.

To enhance the effectiveness of off-site radioactive waste management, a regulatory framework should be provided for the operating organization and local governments.

For that, responsible national agencies such as the NSSC and MOE of Korea should actively participate in setting up the roles and responsibilities of each organization.

5.2 Develop Management Plans and Methodologies for Estimating Radioactive Waste Based on the Accident Scenario

The various forms of off-site radioactive wastes (e.g., tree, soil, mixed liquid, etc.) generated by major nuclear accidents are difficult to handle with the existing radioactive waste management facility of the NPP. Unless a plan or additional facilities for handling these wastes are prepared at the early stage of an accident, radioactive materials can spread further to the environment, causing secondary waste generation increasing the quantity of radioactive waste to be managed.

Therefore, the forms and quantity of off-site radioactive waste to be managed should be thoroughly estimated based on a conservative accident scenario. Appropriate plans and methodologies should be developed for the earliest stage of an accident based on the estimation. In the management plan, the classification criteria, volume reduction, storage plan, and final disposal methodology for off-site radioactive waste should be included.

For extraordinary forms of radioactive waste that cannot be accepted by existing waste treatment facilities, an R&D plan for treatment methodology, monitoring techniques, and storage capacity securing will be necessary.

5.3 Secure a Site With the Capacity for Safe Storage of Large Waste Volumes Until Treatment Begins

For effective off-site radioactive waste management for large quantities generated in a short period, time-consuming preparatory work such as establishment of legal framework, set-up of roles and responsibilities of relevant organizations, development of management plan, and securing treatment facilities is necessary. If the off-site radioactive wastes remain uncontrolled until the preparatory work is completed, radioactive materials will spread to the environment and increase the volume of the waste.

Therefore, it is necessary to secure storage sites and facilities for off-site radioactive waste at the earliest stages of an accident. To do this, with the cooperation of the local government, a usable site should be secured first, and then a storage facility should be established. For efficient management, the quantity of radioactive waste that needs management by each local government should be assigned by the national government based on a conservative accident scenario.

After securing storage sites and facilities, a control and monitoring plan for safe management of off-site radioactive wastes should be implemented to protect against the release of radioactive material into the environment.

5.4 Establish a Plan to Control and Utilize the Existing Infrastructure Owned by Local Governments

Radioactive waste is treated at a designated facility. However, the facility does not have sufficient treatment capacity to manage a major accident, and more treatment capacity for accident-induced off-site radioactive wastes should be secured. Existing non-radioactive waste treatment facilities should be considered for the treatment of accident-induced radioactive waste with very low radioactivity levels and low risk associated with treatment.

In such cases, controlling and monitoring the effluents from the facilities is essential, and regulatory requirements, such as concentrations of radionuclides at the off-gas outlet or at the effluent, should be set up before the operation of the facilities. In addition, as the facilities are not solely for radioactive waste treatment, the environmental impact should be analyzed first for the introduction of operational criteria that meet the regulatory requirements.

For the utilization of as many existing facilities as possible, the provision of incentives can be considered. However, for safety, record keeping for waste balance and effluent monitoring is mandatory for facility operation.

5.5 Secure Information Transparency to the Public at All Management Stages

As off-site radioactive wastes can be collected, temporarily stored, and treated by local governments, public concerns in each local area will increase. Therefore, for smooth progress, gaining public confidence is critical for each step of waste management. For this, information on the policy or strategy of off-site radioactive waste management should be announced transparently to the public at each step of the process. Based on this, public agreements should be secured.

A plan for public announcement, assignment of community information centers in each local jurisdiction, contents and timing of announcements should be set up first.

5.6 Establish a Network for Requesting International Assistance

The quantity and form of off-site radioactive waste can overwhelm the national capacity of a country. In addition, an objective explanation of the role that international agencies can be effective in securing public confidence.

A system of international cooperation should be established to share technical support for efficient off-site waste treatment, for securing public confidence, and other important functions.

6. Conclusions

In Korea, nuclear emergency countermeasures are mostly focused on responding to the initial stage of the emergency. Practical plans to manage radioactive waste that will be generated in large quantities outside the NPP are insufficient. If radioactive waste is generated over a wide area due to a major accident in Korea, it will inevitably face many challenges for safe management in applying the current routine management system, and the resulting socio-economic cost will be high. It should be recognized that waste management will be the most important and difficult issue faced in the long-term recovery phase to declare the termination of a nuclear emergency. Of course, it may not be possible to develop detailed plans for all aspects of waste management. Nevertheless, it is necessary to establish appropriate management countermeasures in advance to minimize the impact on the public and the environment by responding systematically without delay, minimizing the amount of waste to be managed, and utilizing available resources as effectively as possible.

In this study, six important considerations were developed for establishing domestic countermeasures for radioactive waste management, based on the recommendations of the IAEA and the NCRP, Japan's experiences in managing off-site radioactive waste after the Fukushima Daiichi accident, and a review of the current radioactive waste management system in Korea. In brief, these include assignment of responsibility, development of management methodologies, securing of storage capacity, preparation for use of existing infrastructure, securing information transparency, and establishing cooperative measures with international organizations.

It is hoped that the results of this study can be used to establish a national policy and strategy for off-site radioactive waste management caused by a major accident. Further studies will be followed for more detailed planning based on a major accident scenario.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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