Waste Contaminated with Radioactive Material from the Fukushima Dai-ichi Nuclear Power Plant Accident

–Relation between Amount of Radioactive Material in Waste and Related Laws–

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In the Fukushima Daiichi Nuclear Power Plant Accident, a considerable amount of unplanned radioactive materials were emitted into the environment, creating waste contaminated by radioactive materials. To address this situation, the “Act on Special Measures for Debris Management” was established on August 26th 2011, paving way for managing waste and soil contaminated by radioactive materials. However, specific management and disposal methods have not been clearly defined. Waste management planning is steadily advancing, which will likely lead to reasonable and realistic methods for restoration. This commentary explains the relation between the waste contaminated by radioactive materials in the Fukushima Daiichi Nuclear Power Plant Accident and the related laws as they stand today.

I. Generation of Waste

On March 11th 2011, the unprecedented Great East Japan earthquake caused Tokyo Electric Power’s Fukushima Daiichi Nuclear Power Plant accident (referred to as the Fukushima Nuclear Plant Accident), which led to a considerable amount of unplanned radioactive materials being emitted into the environment. These materials were deposited over a wide range of areas depending on the topographical and meteorological conditions, contaminating soil, crops, and water and creating various wastes contaminated by radioactive materials. Before the Fukushima Nuclear Plant Accident, an emission of such a large amount of radioactive material outside of the radiation facility was not anticipated and there were no laws for regulating it. On August 26th 2011, the first law regarding management of environmental pollution due to nuclear accidents, the “Act on special measures for managing environmental pollution by radioactive material released by Nuclear Power Plants Accident” (hereinafter, the Act on Special Measures for Debris Management), was established, paving way to manage debris and soil contaminated by radioactive material; however, specific management and disposal methods have not been clearly defined.

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1. The Waste Management Act and Disaster Waste

The law regarding general waste management is the “Waste Management and Public Cleansing Act” (hereafter, the Waste Management Act). This law defines “waste” as “garbage, over-sized garbage, cinder, sludge, human waste, waste oil, waste acid, waste alkali, animal carcass, and other garbage and worthless materials in solid and liquid forms (excluding radioactive materials and materials contaminated by the same),” and as such, “radioactive waste” is excluded from the subjects of regulation of this act. The Waste Management Act designates “general waste,” which must be treated by the local municipality, and “industrial waste,” which must be treated by companies, but treatment of industrial waste is often entrusted to waste management companies. If industrial waste forms majority of waste, which includes small amounts of general waste, it is treated as “industrial waste,” and in the opposite case, it is treated as “general waste.”

Waste generated by disasters, e.g., earthquakes, tsunamis, and floods (which is left outside), including debris and wood chips from destroyed buildings, concrete, and metal pieces, is called “disaster waste.” The management responsibility of it is held by the municipality in which the disaster occurred. In the Han-Shin Awaji Earthquake disaster in 1995, more than 8 million tons of disaster waste was generated, leaving the many issues to be solved, such as securing of disposal sites and transportation routes and inter-municipality collaboration. The management of disaster waste incurs tremendous costs, making it difficult for the affected municipalities to take on the full responsibility. Thus, it was necessary for the government and community as a whole to manage the issue.

Furthermore, since the Waste Management Act is a general law, wastes subject to the regulation of a special measures law are managed according to special regulations.

2. Radioactive Waste

Radioactive waste is generated from the use of nuclear energy in Nuclear Power Plants and nuclear fuel cycle facilities as well as from the use of radioisotope in universities, research facilities, and hospitals. “High-level radioactive wastes” refers to vitrified high-level radioactive liquid waste generated from reprocessing of spent nuclear fuel, while other types are called “low-level radioactive waste.” Radioactive waste is primarily regulated by Act on the Regulations of Nuclear Source Material, Nuclear Fuel Material and Reactors (hereafter, the Nuclear Reactor Regulation Act), and Act on Prevention of Radiation Hazards due to Radioisotopes, etc. (hereafter, the Radiation Hazard Prevention Act).

3. Contaminated Waste Generated by Radioactive Materials from Fukushima Nuclear Plant Accident

Table 1 shows the waste contaminated by radioactive material from the Fukushima Nuclear Plant Accident, categorized by generation type.

Radioactive waste within Tokyo Electric Power’s Fukushima Daiichi Nuclear Power Plant is generated as a by-product of the operation of the Nuclear Power Plant and is regulated by the Nuclear Reactor Regulation Act. The Act on Special Measures for Debris Management requires that the management plan for waste generated in restricted areas and planned evacuation areas and contaminated by radioactive materials to such an extent must be set by the Minister for the Environment and that the waste must be managed by the government. Waste beyond the criteria of radiation level generated outside the restricted and planned evacuation areas is also managed by the government. Other low-contamination waste contaminated by radioactive materials is managed according to the Waste Management Act. In other words, such waste is managed by the municipality or the related companies themselves. According to the Act on Special Measures for Debris Management, the low-contamination radioactive waste generated inside the radiation facility due to the Fukushima Nuclear Plant Accident can be treated by the Act on Special Measures for Debris Management, but there is no clear definition of the act.

Table 1 Waste contaminated by radioactive materials from the Fukushima Nuclear Plant Accident

Location	Subject waste	Regulation
Inside nuclear power plant	Radioactive waste	Nuclear Reactor Regulation Act
Inside restricted area and planned evacuation area	Waste potentially contaminated to an extent that requires special management	Act on Special Measures for Debris Management
Outside restricted area and planned evacuation area	Waste exceeding certain criteria of radiation level	Act on Special Measures for Debris Management
Unspecified	Low-contamination waste from Fukushima Nuclear Plant Accident	Waste Management Act
Radiation facility	Low-contamination waste from Fukushima Nuclear Plant Accident	Nuclear Reactor Regulation Act or Radiation Hazard Prevention Act (no definition in Act on Special Measures for Debris Management)

II. Radionuclide and Concentration in Waste

1. Radionuclide from Fukushima Nuclear Plant Accident

According to the “Report of Japanese Government to the IAEA Ministerial Conference on Nuclear Safety” created in June 2011 by the Government Nuclear Emergency Response Headquarters, the total activities of radionuclides emitted into the atmosphere from the Fukushima Nuclear Plant Accident were 1.6×10^{17} Bq for ^{131}I and 1.5×10^{16} Bq for ^{137}Cs; in addition, after the beginning of April, the emission activity of ^{131}I reduced to 10^{11} Bq–10^{12} Bq.

At that time, the major issue was the surface contamination of crops by radioactivity due to rain and snow. The subject radionuclide was ^{131}I, which has a high level of emission. However, the half-life of ^{131}I is 8 days and the current subject radionuclides of issue are ^{134}Cs and ^{137}Cs. The contaminated materials are leaves, soil, and sewage in areas with a relatively high concentration of radionuclides and incinerated ash with concentrated radionuclide from incinerating general waste. On August 29, 2011, the Ministry of the Environment published a report “On the management of waste potentially contaminated by radioactive materials in general waste incineration facilities,” which contains a “Table of measurement results of radioactive cesium concentration in incinerated ash in general waste incineration facilities in 16 prefectures” up to August 24, 2011, which shows that the maximum ^{134}Cs and ^{137}Cs concentrations in the prefectures ranged widely from 196 to 95,300 Bq/kg. Based on the report, the number of cases with higher than 8,000 Bq/kg and with higher than 100,000 Bq/kg, and a maximum concentration in 16 prefectures are shown in **Table 2**. The management of soil with concentrated radioactive materials due to decontamination of top soil is also an issue. **Table 3** shows the radioactive cesium in agricultural soil in the prefectures shown in the report “Making a distribution map (radioactive cesium concentration map in soil) of radiation by the Ministry of Education, Culture, Sports, Science and Technology" announced by the Ministry of Education, Culture, Sports, Science and Technology on August 30, 2011.

Table 2 Radioactive cesium concentration in incinerated ash in general waste incineration facilities (number of cases and maximum concentration)

(^{134}Cs+ ^{137}Cs)

Prefecture	Over 8,000 Bq/kg (cases)	Over 100,000 Bq/kg (cases)	Maximum (Bq/kg)
Iwate	0	0	30,000
Miyagi	0	0	2,581
Akita	0	0	196
Yamagata	0	0	7,800
Fukushima	23	0	95,300
Ibaraki	10	0	31,000
Tochigi	3	0	48,600
Gunma	2	0	8,740
Saitama	0	0	5,740
Chiba	8	0	70,800
Tokyo	1	0	12,920
Kanagawa	0	0	3,123
Niigata	0	0	3,000
Yamanashi	0	0	813
Nagano	0	0	1,870
Shizuoka	0	0	2,300
Total	49	0	

(Based on "Management of waste potentially contaminated by radioactive materials in general incineration facilities")

Table 3 Analysis of value of radioactive cesium in agricultural soil (Concentration of radioactive cesium corrected on June 14)

	Number of measurement subjects	Bq/kg(^{134}Cs+ ^{137}Cs)
Miyagi	65	24–2,215
Fukushima	361	ND–27,981
Ibaraki	62	ND–632
Tochigi	48	ND–3,971
Gunma	13	55–688
Chiba	30	19–777

(From "Making of a distribution map (radioactive cesium concentration map in soil) of radiation by the Ministry of Education, Culture, Sports, Science and Technology")

ND: "no detection" but not zero. This report does not indicate the detection limit.

2. Regulated Concentration

The Radiation Hazard Prevention Act defines radioisotopes as “those with the quantity and concentration exceeding that specified by the Ministry of Education, Culture, Sports, Science and Technology.” In cases involving multiple radioisotopes, they become subjects of regulation if the sum of the ratio of their quantity to the specified quantity exceeds 1. The subject quantity is the total quantity in one facility. For various scenarios, the regulation values are set such that public exposure dose becomes less than 10 μSv/year under normal operations and 1 mSv/year for accidents. Each regulation concentration (exemption level) of ^{134}Cs and ^{137}Cs is 10 Bq/g.

According to “Ideas for the future treatment of by-products such as the water supply and sewage from which radioactive materials were detected” proposed by the Government Nuclear Emergency Response Headquarters on June 16, 2011, “Points to be cautious about storage, temporary storage, and transporting dehydrated sludge” include abiding by the related regulations on Regulation on Prevention of Ionizing Radiation Hazard (Ionizing Radiation Regulation). In the Ionizing Radiation Regulation, the regulation concentrations of both ^{134}Cs and ^{137}Cs are 10 Bq/g.

Radioactive waste exempted from the regulation include those contaminated by nuclides for positron computerized tomography (PET-nuclides), or the so-called PET wastes. Waste contaminated only by PET-nuclides whose half-lives are between 2 and 110 min, such as ^{15}O and ^{18}F, can be removed from radioactive waste when the number of atoms of the subject nuclides is below 1. According to the Radiation Hazard Protection Act, “PET-nuclides and radioactive wastes contaminated by PET-nuclides after 7 days of storage are not regarded as radioactive wastes.” In this case, radioactive wastes can be removed from regulation subjects only through decay storage at storage facilities.

The Reactor Regulation Act has a clearance policy which states that radioactive waste can be removed from subject waste if the quantity of activity in the radioactive waste goes below a certain threshold due to decay and decontamination. The clearance policy makes it possible to recycle radioactive waste, or if recycling is not reasonable, dispose of the same as waste for which there is no need for considering radiation protection. The clearance standards are set such that, no matter how the materials are reused and disposed, the level does not exceed the annual exposure dose for public of 10 μSv (1 mSv for scenarios with a low probability of occurrence). Each clearance concentration of ^{134}Cs and ^{137}Cs is 0.1 Bq/g. According to the Reactor Regulation Act, to implement clearance, it is necessary for the nuclear company to determine that the radiation concentration of the waste materials does not exceed the clearance standard and for a regulatory organization such as the government to verify (verification evaluation system). In other words, verification for execution of clearance requires decisions by both the nuclear company and regulatory organization such as the government. A similar clearance policy will be implemented for the Radiation Hazard Prevention Act as well.

Standard concentrations related to the Fukushima Nuclear Plant Accident include the temporary standard value for radioactive cesium in food. With an annual exposure dose of 5 mSv, the sum of ^{134}Cs and ^{137}Cs is 200 Bq/kg for drinking water, milk, and dairy products and 500 Bq/kg for vegetables, grains, meat, egg, fish, and others. In addition, the index for the transfer of radioactive cesium from paddy soil to rice is 0.1 and the maximum allowed value of radioactive cesium concentration in soil for planting is 5,000 Bq/kg. **Table 4** shows the regulation concentrations of ^{134}Cs and ^{137}Cs and those related to the Fukushima Nuclear Plant Accident.

Table 4 Comparison of radioactive cesium concentrations

		^{134}Cs	^{137}Cs
Radiation Hazard Prevention Act	Regulated concentration	10 Bq/g	10 Bq/g
Ionizing Radiation Regulation	Regulated concentration	10,000 Bq/kg [*1]	10,000 Bq/kg [*1]
Reactor Regulation Act	Clearance standard	0.1 Bq/g	0.1 Bq/g
Food temporary standard	Drinking water	200 Bq/kg [*2]	
	Milk	200 Bq/kg [*2]	
	Vegetable	500 Bq/kg [*2]	
	Grains	500 Bq/kg [*2]	
	Meat/fish	500 Bq/kg [*2]	
Soil allowed for planting	Maximum	5,000 Bq/kg [*2]	
Radiation Hazard Prevention Act	Removal standard of PET waste	Number of atom below 1 (only for PET-nuclides, e.g., ^{15}O and ^{18}F)	

[*1] From “Ideas for future treatment of by-products such as water supply and sewage from which radioactive materials were detected.”

[*2] ^{134}Cs + ^{137}Cs

3. Waste Disposal

According to the “Ideas for future treatment of by-products such as the water supply and sewage from which radioactive materials were detected,” the following guidelines have been established. Waste such as dehydrated sludge with the total concentration of ^{134}Cs and ^{137}Cs below 100,000 Bq/kg, which are buried under the condition that an appropriate long-term dispersal plan will be established and the site will not be used for residence will cause annual exposure dose for public near the burial site to be below 10 μSv. Because a site where burials of different conditions were created needs long-term management and it is the necessity for examination of environmental conservation, waste such as dehydrated sludge with the total concentration of ^{134}Cs and ^{137}Cs below 8,000 Bq/kg, for which the calculation shows that the annual exposure dose of the operators of the disposal of it will not exceed 1 mSv, can be buried with an appropriate disposal plan for placement of soil layer and waterproof measures (disposal in a control-type landfill site). Until the safety of use of the site will be secured, the management of the site should involve necessary treatments, such as monitoring of radiation and facility management.

Dehydrated sludge with a total concentration of ^{134}Cs and ^{137}Cs higher than 8,000 Bq/kg and lower than 100,000 Bq/kg is to be temporarily placed in a control-type landfill site at a certain distance from the site boundaries depended on the concentration until safe disposal can be secured. However, according to “Management of waste potentially contaminated by radioactive materials in general incineration facilities,” as of August 2011, such treatment has not been reported to be appropriately implemented.

The report “On the maximum radiation concentration limits for burial disposal of low-concentration radioactive solid waste” put forth on May 21, 2007, by the Nuclear Safety Commission requires that the maximum concentration limits be set for each disposal method of low-concentration radioactive waste, which can be disposed by burial. The concentrations are set for three types of methods (trench disposal, pit disposal, and subsurface disposal) for low-concentration radioactive waste with different nuclides. The threshold dose for burial disposal is 10 μSv/year. The verification of contents such as nuclides and their quantities in radioactive waste to be dispersed and monitoring after burial are necessary. **Table 5** shows the maximum concentrations limits in trench burial and pit burials, which are obtained in a relatively near-surface ground, as well as the concentration in the treatment of water purification waste soil.

Table 5 Comparison of ^{137}Cs concentrations for disoposal

		^{137}Cs
Maximum concentration limit[*1]	Trench disposal	1×10^{8} Bq/t
	Pit disposal	1×10^{14} Bq/t
Treatment of water purification waste soil[*2]	Stored in a facility capable of radiation shielding	＞100,000 Bq/kg[*3]
	Temporal storage in control-type landfill site	≦100,000 Bq/kg[*3]
	Burial disposal at control-type landfill site	≦8,000 Bq/kg[*3]

[*1] Based on “On the maximum radiation concentration limits for burial disposal of low-concentration radioactive solid waste”
[*2] From “Ideas for future treatment of by-products such as water supply and sewage from which radioactive materials were detected.”
[*3] ^{134}Cs＋^{137}Cs

III. Future Prospects

Considerable radioactive material was emitted into the environment due to the Fukushima Nuclear Plant Accident, and considerable various waste was generated, including disaster waste contaminated by radioactive material. The conventional laws were not established assuming these events that can generate such waste. As such, various measures were planned and implemented during the emergencies during the accident as well as after matters were settled. As for the future disposal of waste contaminated by radioactive materials, however, the main subject nuclide is ^{137}Cs, which requires long-term management. From the perspective of radiation protection, it is necessary to ensure consistency between the management of “radioactive wastes” and management of waste contaminated by nuclide emitted from the accident, which will lead to the understanding of citizens. Thus, reasonable and effective waste measures are needed.

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Commentary

Lessons Learned from the Initial Response to Nuclear Disaster caused by Fukushima Nuclear Power Plants Accident

–Monitoring and Use of Radiation Information–

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The results of actual environmental radiation monitoring and the series of responses to accidents and disasters have been examined in a parallel fashion to investigate how the understanding of the radiation information was made via environmental radiation monitoring and a System for Prediction of Environmental Emergency Dose Information (SPEEDI) during the initial stage of the accident at the Fukushima Daiichi Nuclear Power Plant. It was discovered from the discussion that a significant amount of time was required for establishing the emergency monitoring system of the Government Nuclear Emergency Response Headquarters and that the proposition of plans and execution of emergency monitoring could have been significantly improved by examining emergency monitoring performed by the Tokyo Electric Power Company and Fukushima Prefecture as well as the SPEEDI results.

I. Introduction

Based on the experience attained from the JCO accident, the government has reinforced the disaster protection function of the system by enacting the Act on Special Measures for Nuclear Emergency Preparedness and reviewing the Basic Disaster Management Plan (the nuclear emergency response version) to enforce a swift initial disaster response as well as collaboration between the government and local public bodies. In particular, with regard to the emergency response measures for preventing damage escalation, the government has placed importance on the following aspects and has been working to improve the effectiveness of these aspects: implementation of emergency monitoring; an emergency response support system (ERSS) for monitoring the nuclear reactor condition; preparation of a System for Prediction of Environmental Emergency Dose Information (SPEEDI), which predicts the behavior of radioactive materials in the atmosphere; and collection of accident information and radiation information in nuclear power plants via by inspections for the operational safety program.

The nuclear accident at the Fukushima Daiichi Nuclear Power Plant on March 11, 2011 was one of the largest accidents in the world, which exceeded the predictions, and it is important

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to examine how the nuclear disaster response system in this country functioned to understand its effectiveness and improve current response system, which assumed that "accidents can happen." Even today, there are various protective measures in place for the areas surrounding the facility, which is under a state of emergency. While it might be premature to investigate the protective system as a whole since various protective actions are in progress under the emergency declaration, it is important to examine the radiation information collected as well as the measures taken during a nuclear emergency wherein considerable amounts of radioactive materials are emitted to the environment during the initial stage to understand the actual condition of the nuclear disaster.

During the accident, radiation information monitoring was required to be performed during station blackout as well as during the ensuing aftershocks, which caused many difficulties. In this commentary while taking the difficult operation conditions into consideration, the author identifies the actions taken by the Nuclear Emergency Response Office after the onset of the accident and the operated emergency monitoring and attempts to clarify the relations between these conditions for the effective monitoring of initial radiation information during such a disaster.

II. Monitoring of Emergency Radiation Information

1. Emergency Monitoring

Monitoring of radiation information is done as a basis for planning protective measures such as evacuations at the time of declaration of a state of emergency as well as for evaluating the effect of radioactive materials and radiation on surrounding residents 1). The implementation method is divided into two phases according to the importance of these phases when deciding the protective measures during the initial stage: phase 1 is initiated immediately after the onset of emergency, whereas phase 2 is initiated when the emission of radioactive materials and radiation has been certainly reduced; this phase is intended to monitor the effect on the surrounding areas. Speed is of importance during phase 1, while accuracy is important during phase 2. The measurement items, locations, sample collection locations, and measurement methods for each phase are detailed in the environmental radiation monitoring guidelines. During the monitoring conducted during phase 1, measurements of the following are made: (a) air dose rate of radioactive noble gases, (b) radioiodine concentration in the atmosphere and environmental samples, (c) uranium and plutonium concentration in the atmosphere, and (d) concentration or α-ray surface contamination density of uranium and plutonium in environmental samples.

In the monitoring conducted during phase 2, the following additions are made to the measurement items, for which the concentrations of radioactive materials in environmental samples are measured: soil, crops, livestock, raw water (rivers and purification plants), and fish (in case of leakage into the rivers and oceans). Emergency monitoring is conducted stepwise according to the phases by specifying the target radioactive materials; for this purpose, the efficiency and swiftness of emergency actions during disaster responses is taken into consideration.

2. SPEEDI Network System

During an emergency, protective measures are taken based on the expected concentrations of radioactive materials and exposure dose rates of residents' in the surrounding areas. The prediction results obtained using the SPEEDI and the measured values monitored at several points in the surrounding areas are considered. SPEEDI has been installed and maintained by the government and local public bodies as a method to obtain information regarding the concentrations of radioactive materials and predicted doses in the surrounding area. For the sake of swiftly deciding upon protective measures, the environmental radiation monitoring guidelines hold that during a nuclear emergency, it is one of the duties of radiation protection groups in the government's nuclear emergency countermeasure office and local countermeasure offices to use this system for estimating dosages of residents; however, it is often difficult to quantitatively determine the information about emission sources during the early stages of a disaster. In such cases, it is advisable to work on the emergency monitoring plan, which includes the predicted figures for a unit amount of emission in terms of direction and location where monitoring should be reinforced as well as the monitoring items. Furthermore, since the calculation of SPEEDI is not always appropriate due to the differences between the predicted and actual meteorological conditions, the guidelines mention the need for repeated verification of the results based on the actual meteorological data.

III. Environmental Radiation Monitoring at the Early Stage of a Disaster

1. Environmental Radiation Monitoring by Companies

Figure 1 shows the change in the air dose rate measured using a monitoring car (MC; operated by the Tokyo Electric Power Company) since the onset of a disaster2). The air dose rate shows the background (BG) level from the arrival of a tsunami until the early morning of March 12, which slowly increased during the early morning of the 12th and reached its first peak of 386 μSv/h at 10:30 am near the main gate. After that, the air dose rate continued to vary by approximately a few hundred μSv/h, reached a high dose rate of approximately 12 mSv/h in front of the main gate on March 15 at 9:00 am, and measured approximately 11 mSv/h after being measured again on 16th at 12:30. Such abrupt changes in the air dose rate around the facility boundaries have been examined in relation to (a) the plant phenomenon

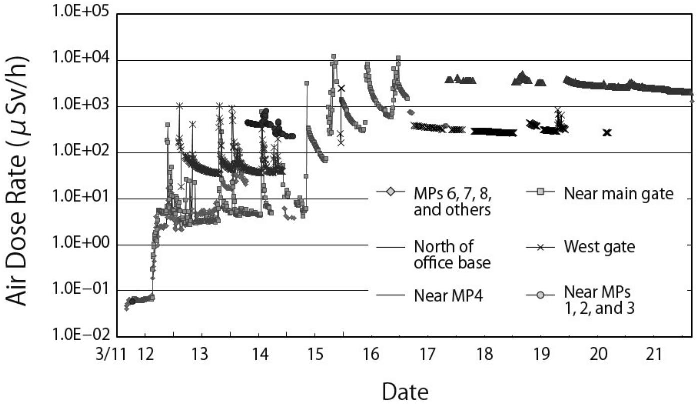

Figure 1 Change in air dose rate near the plant facility boundaries2)

after the earthquake and (b) meteorological conditions. In addition, the measurement results in Figure 1 show a change in the air dose rate in multiple directions around the same time period. For example, on March 14, the air dose rates at monitoring posts (MPs) 2 and 4 and at the main gate changed at the same time, indicating the possibility that radioactive materials scattered in multiple directions. This indicates the possibility that pollution caused by radioactive materials advanced at the same time over a wide range near the facility boundaries.

2. Environmental Radiation Monitoring in Fukushima Prefecture

Figure 2 shows the environmental radiation monitoring results obtained from seven locations in Fukushima[3)]. The results show measurements of approximately 20 μSv/h in Minamisoma City at around 21:00 on March 12, and 24 μSv/h as measured in Iwaki City at around 4:00 on March 15. The former measurement is likely to be due to south winds early evening on the 12th and the latter due to the north winds that had been blowing since the previous day (the 14th). Later, the air dose rate in Shirakawa City increased, followed by an abrupt increase in Koriyama City and Fukushima City. These changes are likely due to the east winds that were blowing during the daytime on the 15th, which then changed into southeast and south-southeast winds. After 16th, the air dose rate began to indicate a downward trend apart from Minamisoma City and Iwaki City, where large changes were observed.

3. Disaster Countermeasure Office Response

Table 1 summarizes the response measures after the earthquake, abnormal phenomenon in the nuclear power plants, and environmental-radiation-monitoring-related items[4)]. Table 1

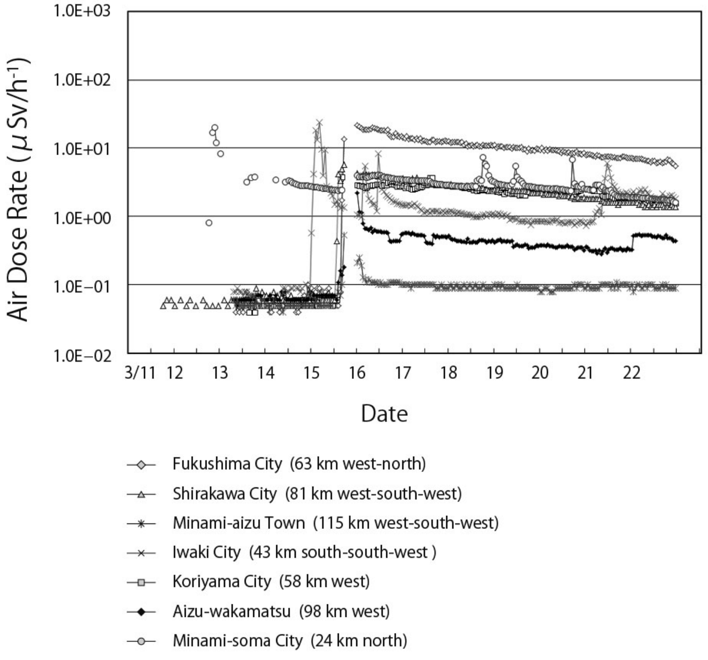

Figure 2 Environmental radiation monitoring results at seven locations in Fukushima Prefecture[3)]

also indicates that the function of MPs at the facility boundaries was maintained immediately after the earthquake, but the monitoring function was lost after the station blackout due to the tsunami. In addition, the loss of ERSS functionality after the earthquake meant that the act of conducting quantitative calculations using SPEEDI became more difficult. Later, a state of emergency was declared and the Government Nuclear Emergency Response Headquarters and the Local Nuclear Emergency Response Headquarters were established, but the air dose rate around the facility was at approximately the BG level. In the early morning on the 12th, the staff of the prefecture, the Japan Atomic Energy Agency (JAEA), and the National Institute of Radiological Sciences (NIRS) gathered at the Fukushima Nuclear Center (Okuma Town), but the assembling rate of the ministries and government offices was low and onsite delegation of Nuclear Safety Commission members was not made. At this time, the Local Nuclear Emergency Response Headquarters, which was temporarily moved to another location, returned to the emergency countermeasure office base facility (OFC), but the air dose rate around the facility boundaries was several times as high as BG. On the afternoon of the 12th, a hydrogen explosion occurred at Unit 1 and the air dose rate at this time exceeded 100 times as high as BG. In the evening of the same day, the air dose rate exceeded 1000 times as high as BG and an evacuation order was issued to the residents within a radius of 20 km from the nuclear power plants.

Table 1 Disaster response implemented immediately after the earthquake and environmental radiation monitoring[4)]

Date and time	Countermeasures	Abnormal phenomenon at facility	Environmental radiation monitoring
11th 14:46	Onset of earthquake	Reactor shutdown; emergency response support system (ERSS) fails to function	No abnormality at monitoring posts (MPs) in surrounding monitoring areas
15:30	Arrival of tsunami	Subsequently, station blackout occurs	
15:42	Establishment of Ministry of Economy, Trade and Industry Nuclear Emergency (onsite) countermeasures office	MPs do not function; measurement performed using monitoring cars (MCs)	In total, 23 out of 24 MPs in the prefecture did not function
16:36 17:00	Establishment of countermeasures office in official residence Vice Minister of Ministry of Economy, Trade and Industry departs for Emergency countermeasures office (OFC)	Impossible to pour water using the emergency core-cooling system (ECCS) ; inability to make quantitative prediction using the System for Prediction of Environmental Emergency Dose Information (SPEEDI)	
19:03	Declaration of state of emergency, establishment of the Local Nuclear Emergency Response Headquarters (onsite), appointment of a person as the acting director general	Blackout; malfunction of emergency power supply causes the inability to communicate from OFC, so directors move to the prefecture nuclear center (Okuma Town)	
20:50	Evacuation order by the governor for residents within the 2-km radius		
21:23	Evacuation order for those within the 3-km radius and sheltering order for residents within the 10-km radius	Difficulty in cooling Unit 1	
12th 00:00	Vice minister arrived at the prefecture nuclear center (Okuma Town) ; staff of JAEA and National Institute of Radiological Sciences also arrived	Low initial assembly rate of staff of related organizations; no onsite delegation of emergency response measure officials	
03:20	The Local Nuclear Emergency Response Headquarters returns to OFC	Emergency power supply recovers in OFC; satellite communication system is enabled	

Date and time	Countermeasures	Abnormal phenomenon at facility	Environmental radiation monitoring
05:44	Evacuation order to residents within the 10-km radius	Increase in pressure in primary containment vessel (PCV) ; difficulty in use of plant information, ERSS, and SPEEDI at OFC	Increase in air dose rate near facility boundaries
		Government office of Minamisoma City, acting as OFC facility, cannot be used due to earthquake and tsunami response	
15:36		Hydrogen explosion at Unit 1	
18:25	Evacuation order to residents within the 20-km radius.	Consideration of disasters caused due to accidents in other reactors	At 20:00, air dose rate increases in Minamisoma City
13th			First emergency monitoring information (>30 μSv/h) in some areas)
14th 07:30	Announcement of monitoring information by Nuclear and Industrial Safety Agency	11:01 Hydrogen explosion in Unit 3	MC dispatch 1 (three cars) and dispatch 2 (four cars)
15th	Removal of staff from OFC	Explosion at Unit 4 Explosive activity at Unit 2	Detection of high concentration of radioiodine and cesium from surface soil and plants
	Establishment of overall countermeasures office for the Fukushima Nuclear Power Plant Accident		Measurement by 15 MCs (Ministry of Education, Culture, Sports, Science and Technology, JAEA, Fukushima Prefecture, National Police Agency, Ministry of Defense, and electric companies)
11:00	Sheltering order to residents within a radius between 20 and 30 km; the Local Nuclear Emergency Response Headquarters moves to the Fukushima government office		Collection of soil and plants (insufficient monitoring at the Local Nuclear Emergency Response Headquarters due to earthquakes)
20:40			Measurement of 330 μSv/h at three points near Namie Town
16th	Announcement of dose rate measurement results near Namie Town by Ministry of Education, Culture, Sports, Science and Technology		Start of emergency monitoring in the prefecture
	Organization of roles within the government (Ministry of Education, Culture, Sports, Science and Technology and Nuclear Safety Commission)		Start of radiological survey of raw milk and radiological survey of tap water
17th	Daily announcement of environmental monitoring by Ministry of Education, Culture, Sports, Science and Technology		Start of radiological survey on vegetables
18th	Request for the introduction of integrating dosimeters or for the increase in measurement frequency		Collection and analysis of dust, environmental samples, and soil
20th			Contamination verified in soil and weeds in areas 40 km northwest
21st	Ministry of Education, Culture, Sports, Science and Technology "Establishment of monitoring planning for areas 20 km or more from Fukushima Daiichi Nuclear Power Plant"		Soil plutonium analysis
23rd		Announcement of SPEEDI calculations	Start of sea area monitoring

On the 13th, radiation monitoring was performed by the Local Nuclear Emergency Response Headquarters. The measurements exceeding 30 μSv/h were made in some areas and were reported by the Nuclear and Industrial Safety Agency in the early morning on the 14th. This was the first time that the values related to environmental radiation monitoring were announced by the Government Nuclear Emergency Response Headquarters. At this point, an air dose rate of approximately 0.9 mSv/h was measured near the facility boundaries. From that day onward, the Government Nuclear Emergency Response Headquarters prepared several MCs to enhance the environmental radiation monitoring. On the 14th and 15th, explosions occurred at Units 3, 4, and 2 in succession and radiation measurements performed using many MCs (15 cars) and as well as measurements of soil and plants were initiated. On the 15th, soil and plants were collected for emergency monitoring, but the monitoring activity by the Local Nuclear Emergency Response Headquarters was insufficient due to the effect of the earthquake and other disasters 4). Moreover, a dose rate of 330 μSv/h was measured in Namie Town on the early evening of the 15th. Following this, allocation of roles in terms of environmental radiation monitoring was made within the government on the 16th and the Ministry of Education, Culture, Sports, Science and Technology was placed in charge of implementing and directing emergency monitoring and announcing the related reports. On the 21st, the Ministry of Education, Culture, Sports, Science and Technology finalized and announced the "Fulfillment of the monitoring plan for areas 20 km beyond the Fukushima Daiichi Nuclear Power Plant." Based on the above series of events, the establishment of an emergency monitoring system was attempted around this time, though the process still lacked a solid system in terms of selecting the measurement locations and items.

IV. Discussions and Lessons

1. Time Lag until Emission of Radioactive Materials

So far, it has been thought that when an abnormal event occurs in a nuclear power plant, there is a certain amount of time lag until an abnormal emission of radioactive materials and radiation into the surrounding areas occur. The monitoring data obtained this time indicate that the air dose rate started to increase around the facility boundaries from approximately 4:00 am on the 12th, ~13 h after the onset of the earthquake, and the dose rate of a few μSv/h continued at the same measurement location, occasionally reaching a value of several hundred μSv/h. This indicates that there was a time lag between the establishment of the precautionary office due to the abnormality notification and the emission of radioactive materials in the facility. However, from the perspective of implementing protective measures, it is important to accurately correlate the phenomenon inside the reactor to the increase in the air dose rate around the facility boundaries in the relatively early stages before the explosion at Unit 1. This is crucial to determine the possibility for regulating the phenomenon inside the reactor, which can affect the surrounding areas as well as the examination of effective disaster countermeasures.

2. Initiation of Emergency Monitoring

In nuclear disaster prevention, decisions during an emergency are made based on (1) radiation dose rate near the facility boundaries and (2) observed phenomena (onset of events at nuclear power plants and nuclear-related facilities indicating a large emission to the outside areas). This time, the declaration of a state of emergency was made based on the criteria regarding the latter aspect. When declaring a state of emergency, the heads of the assigned governmental organizations and local governmental organizations have the responsibility to implement emergency countermeasures. This was the case even for the accident this time in which the air dose rate was as low as BG near the facility boundaries. Therefore, in the case of an emergency, the Government Nuclear Emergency Response Headquarters and the Local Nuclear Emergency Response Headquarters need to immediately organize an emergency monitoring system and implement it. From an observation of the series of events from such a perspective, even when dose rates of several tens of μSv/h (occasionally mSv/h) were measured near the facility boundaries on the 13th (Figure 1) and dose rates of several μSv/h were measured in Minamisoma City (Figure 2), it is not necessarily the case that emergency monitoring was planned and implemented to evaluate the effect of the radioactive materials and radiation from the nuclear facility on the surrounding residents until 13th from countermeasures mentioned in Table 1.

Figures 1 and 2 and Table 1 show that the initial results of emergency monitoring were obtained in the early evening of the 13th; the measured values of Fukushima environmental radiation monitoring abnormally increased around the same time of the 15th (a few mSv/h were observed around noon near the boundaries of the facility), and a measurement of 330 μSv/h was made in Namie Town in the evening of the same day, indicating an abrupt change in the situation. The government attempted to establish an emergency monitoring system under such conditions (the roles of related governmental organizations in emergency monitoring was determined on the 16th, and the Ministry of Education, Culture, Sports, Science and Technology finalized and announced the “Fulfillment of the monitoring plan for areas 20 km beyond Fukushima Nuclear Power Plant”), but a clear direction was established approximately 10 days after the declaration of a state of emergency. The reasons for the delay in establishing an emergency monitoring system under a state of emergency include the loss of local infrastructure, the loss of OFC function due to the loss of means of communication caused by the earthquake and tsunami, and the continuous aftershocks; however, the reason could also be found in the possibility of human cognitive characteristics (normalcy bias), which prevented an immediate recognition of a state of emergency despite the abnormally high levels of radiation observed in Fukushima area environmental radiation monitoring results and those near the power plant. In the future, it will be necessary to examine the emergency monitoring from such perspectives.

3. Implementation of Radiation Monitoring in Phases

Emergency monitoring is conducted in two phases to clarify its meaning. The radiation monitoring implemented around the 21st was effectively equivalent to phase 1 of the emergency monitoring. There is no indicator for distinguishing phase 1 from phase 2; however, by setting the boundary as the time at which it became possible to stably cool the reactor, the duration of phase 1 can be said to have lasted as long as several months in this case. However, phase 2 of emergency monitoring was implemented even before stable cooling of the reactor was achieved. This indicates the necessity of reviewing the conventional boundary between monitoring in phase 1 and phase 2 from a different perspective based on the progress of the disaster as well as necessary information.

Furthermore, it is not appropriate to limit the target isotopes to be monitored in phase 1 to rare gas, radioiodine, uranium, and plutonium to estimate residents’ dose and the scale of the disaster. In this case, information on radioactive isotopes that are not part of the target isotopes for the early stage of radiation monitoring, i.e., radioactive cesium, is necessary. Furthermore, it is not appropriate to consider residents' dose as an evaluation item in phase 2 due to the indivisible relationship between radiation monitoring and resident dosages. In particular, the accuracy of the dose due to inhalation of radioactive material before the implementation of protective measures largely depends on the radiation information learned during the early stages, so it is necessary to implement emergency monitoring for dose assessment during the early stages. In other words, emergency monitoring can be classified into situations wherein (a) it is difficult to regulate the release of radioactive materials from the facility and (b) the uncertainty of the emission of the radioactive materials is significantly reduced; it is necessary to make plans and to conduct emergency monitoring for each situation to implement protective measures and dose assessments.

4. Effective Use of SPEEDI Information

During the initial stages of an emergency, SPEEDI plays an important role, together with environmental radiation monitoring, in estimating the resident doses and applying proper countermeasures. However, in this earthquake disaster, the ERSS functionality was lost immediately after the earthquake, making quantitative evaluation of the system impossible. Furthermore, there were less records of use of the system as part of the countermeasures during the initial stage. The environmental radiation monitoring guidelines indicate an expectation that SPEEDI should be utilized applying assumed amount of emission source for emergency monitoring and protective measures, even when there is no information about the emission source. The values in the monitoring results near the facility boundaries were extremely high around the noon on March 12. An abrupt change was also indicated in the monitoring results in Minamisoma City in the early evening on the same day. Based on the radiation monitoring results made after the 12th, proper interpretation using SPEEDI on the radiation monitoring results, even ex-post evaluation of the emission would have enhanced the understanding of the dynamic behavior of the radioactive materials over a wide range far from the facility and helped in improving the planning and execution of emergency monitoring plans.

In situations wherein the condition of a disaster can only be estimated through limited radiation monitoring, obtaining information about the emission source is important for understanding the scale and characteristics of the disaster and smoothly and effectively executing not only the immediate countermeasures but also the disaster response in general. There is no indication of consideration given toward estimating the information about the emission source via SPEEDI during the initial stages. The environmental radiation monitoring guidelines do not clearly specify the use of SPEEDI, as mentioned above, but the use of the advanced technology in addition to those in the response manual must be taken into consideration in uncertain emergency situations. Emergency countermeasures must encompass such use. The first dose map based on SPEEDI calculations, which was later announced by the Nuclear Safety Commission, was made with assumed emission rate values based on deductions from the radiation monitoring results. Errors were inevitable in the results, but the estimation results were effective in clarifying the whole picture with regard to the effect of emitted radioactive materials and determining the subsequent protective measures.

V. Conclusions

The following results summarize the examination conducted herein:

(1) There was a time lag between the onset of abnormal phenomena in the nuclear facility and the emission of radioactive materials into the environment. However, from the perspective of disaster prevention, it is important to relate the phenomena inside the reactor to the increase in the air dose rate around the boundaries of the facility during the early stages.

(2) It took a significant amount of time after the declaration of a state of emergency to establish an emergency monitoring system. This delay was caused due to the effect of compound disaster and because of the delay, which may be caused by the normalcy bias—a characteristic in human recognition, during the initial stages of the disaster.

(3) The current environmental radiation monitoring guidelines do not clearly define the duty for evaluating the information about the types of radioactive materials and resident doses during the initial stages. It is necessary to consider the initial stages of a disaster as an emergency radiation exposure situation, as defined by international organizations, and systematically review the actions of obtaining radiation information, dose assessments, and execution of protective measures.

(4) SPEEDI has an important role in understanding the outline of nuclear emergencies in a spatial and temporal manner. When planning for emergency monitoring, it is indispensable to include SPEEDI information to supplement the radiation monitoring information, i.e., the actual measurement information of monitoring points. The SPEEDI system should be sufficiently flexible to utilize, including the estimation of source term.

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