Chapter 20
Comparison of Radioactivity Release and Contamination from the Fukushima and Chernobyl Nuclear Power Plant Accidents

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Abstract Although both the Fukushima Daiichi Nuclear Power Plant (FNPP) accident in 2011 and the Chernobyl NPP Unit 4 (CNPP) accident in 1986 are classified as Level 7, the worst nuclear incidence on the International Nuclear and Radiological Event Scale by the International Atomic Energy Agency, there are various differences between the two, including the accident process, released radionuclide composition, and meteorological and geological conditions. The amounts of iodine-131 (^{131}I) and cesium-137 (^{137}Cs) released into the atmosphere were about six times smaller after the FNPP accident compared to the CNPP accident. Cesium-137 is the most important radionuclide in considering long-term effects of nuclear accidents. According to Chernobyl laws in Ukraine, Belarus and Russia, depending on the level of ^{137}Cs contamination, the contaminated territories were classified as alienation zone (>1480 kBq m^{-2}), obligatory resettlement zone (555–1480 kBq m^{-2}) and voluntarily resettlement zone (185–555 kBq m^{-2}). The areas of the corresponding zones around FNPP were 272, 459 and 1405 km^2, respectively, which were 11–15 times smaller compared to the CNPP accident. Meanwhile, the number of affected people around FNPP was only three to five times smaller compared to CNPP, reflecting the higher population density for the FNPP accient. Cumulative exposures for the 1st year 1 m above ground (normalized to the initial ^{137}Cs deposition of 1 MBq m^{-2}) were 63 mGy for the FNPP accident, while it was 500 mGy for the CNPP accident because more various radionuclides were emitted in case of the CNPP accident than the FNPP accident. Cumulative exposures at 30 years were evaluated to be 500 mGy and 970 mGy for the FNPP accident and the CNPP accident, respectively.

Keywords Fukushima Daiichi Nuclear Power Plant accident · The Chernobyl accident · Radioactivity release · Radioactive contamination · Cesium-137

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20.1 Introduction

Both the Fukushima Daiichi Nuclear Power Plant (FNPP) accident in 2011 and the Chernobyl NPP Unit 4 (CNPP) accident in 1986 are classified as Level 7, which is the highest level on the International Nuclear and Radiological Event Scale (INES) as defined by the International Atomic Energy Agency (IAEA) [1, 2]. In both accidents, a large amount of radionuclides were released into the environment from the damaged reactors and large areas of land were heavily contaminated to the extent that many people have to be evacuated for a long period [3–5]. Although it is clear that each accident had a big impact on society, they were different in various aspects, including the accident process, composition of radioactive contamination and geological conditions [6, 7].

FNPP was the first nuclear power plant built by the Tokyo Electric Power Company (TEPCO) and its first unit (Unit 1: 460 MWe) began operation in 1971. By 2011, FNPP had six boiling water reactor (BWR) units (Units 2–5: 780 MWe; Unit 6: 1100 MWe) developed by General Electric (GE, USA). Units 4, 5 and 6 were out of operation at the time of the earthquake (14:46 March 11, 2011) due to annual maintenance work, while Units 1, 2 and 3 were operating at full power [8, 9].

The epicenter of the Great East Japan Earthquake was approximately 180 km away from FNPP. At 14:47, the three operating reactors were automatically shut down due to a large seismic acceleration, and emergency diesel generators (EDGs) were then activated to provide necessary electricity to the station. The tsunami waves, at over 10 m high, arrived at FNPP around 15:36 and flooded the basement of the turbine buildings where EDGs were located. EDG failure resulted in power loss for the pumps providing coolant water to remove decay heat from the reactor cores, which was the real emergency that led to the FNPP accident.

Several emergency cooling systems that do not require electric power were installed at each BWR in the event of a power outage. These cooling systems included isolation condenser (IC) systems, reactor core isolation cooling (RCIC) systems and high-pressure coolant injection (HPCI) systems. Unit 1 was equipped with IC and HPCI, while Units 2 and 3 were equipped with RCIC and HPCI. These emergency cooling systems were not designed to work for a long period, and consequently three FNPP reactors operating at the time of the tsunami became damaged one by one. The sequence of reactor damage is summarized below [10]:

- Unit 1: After EDG power failure, both IC and HPCI systems lost function. Without emergency cooling, the reactor core began meltdown, and fuel melted through the reactor pressure vessel (RPV) in the evening of March 11. At 02:30 March 12, the drywell (DW) inner pressure was measured to be 840 kPa, about twice the maximum design pressure of 427 kPa. To avoid rupture of DW, the operator tried to vent the pressure, successfully releasing pressure to the acceptable level at 14:30. At 15:36 March 12, however, a hydrogen explosion occurred at the roof of the reactor building, which was strong enough to destroy the roof and the wall on the highest floor of the reactor building.

- Unit 3: After power loss, RCIC remained functional until 11:36 March 12, and then HPCI was automatically actuated. In the early morning on March 13, the Unit 3 operator decided to switch the cooling system from HPCI to the line using fire engine water prepared outside the building. However, the cooling systems were not switched quickly, which left the reactor without a cooling supply for about 7 h. The meltdown and melt-through process of Unit 3 began in the morning on March 13 and subsequently worsened. A hydrogen explosion occurred at 11:01 March 14.
- Unit 2: After power loss, RCIC remained functional until 13:25 March 14. The Unit 2 operator attempted a change of cooling system to fire engines, but was unable to switch systems quickly, leaving the reactor without a cooling supply for about 2 h. The meltdown and melt-through process of Unit 2 began in the evening on March 14. A high DW pressure was observed that night, and an attempted venting operation was unsuccessful. In the morning on March 15, a sudden drop of DW pressure was observed, which suggested containment rupture and massive release of radioactivity into the atmosphere.

In this paper, we compare the radiological consequences between the FNPP accident and the CNPP accident with respect to the amount of radioactivity released into the atmosphere and the radioactive contamination on land.

20.2 Radioactivity Release

A gradual increase in radiation levels was observed at the entrance gate of FNPP beginning 04:00 March 12. Radioactivity release from the Unit 1 reactor building began early in the morning of March 12. The first large release occurred as a result of the Unit 1 vent operation at 14:30 March 12, followed by the hydrogen explosion at 15:36. Unit 3 began to release radioactivity in the morning on March 13. Serious radioactivity release from Unit 2 occurred from the evening of March 14 to the morning of March 15. Significant radioactivity release into the atmosphere continued up to the end of March.

The amount of radionuclides released into the environment is the basic information required to consider the scale of nuclear accidents. To date, two methods have been applied to estimate the amount of radionuclides released by the FNPP accident. The first method is a computer simulation of the accident process. This method requires many assumptions about the parameters used in the simulation, which increases uncertainty in the results [11, 12]. The second method is based on an inversion technique that combines environmental measurements and a simulation of atmospheric transport of released radionuclides [13–16]. The time trend of radioactivity release of four main radionuclides xenon-133 (^{133}Xe), ^{131}I, tellurium-132 (^{132}Te) and ^{137}Cs obtained by the second method is shown in Fig. 20.1. The data for ^{133}Xe are taken from the UNSCEAR report [4], while the data for other radionuclides are taken from the recent work by Katata et al. [16]. The cumulative distribution of radionuclide release is plotted in Fig. 20.2. Xenon-133 release was completed by

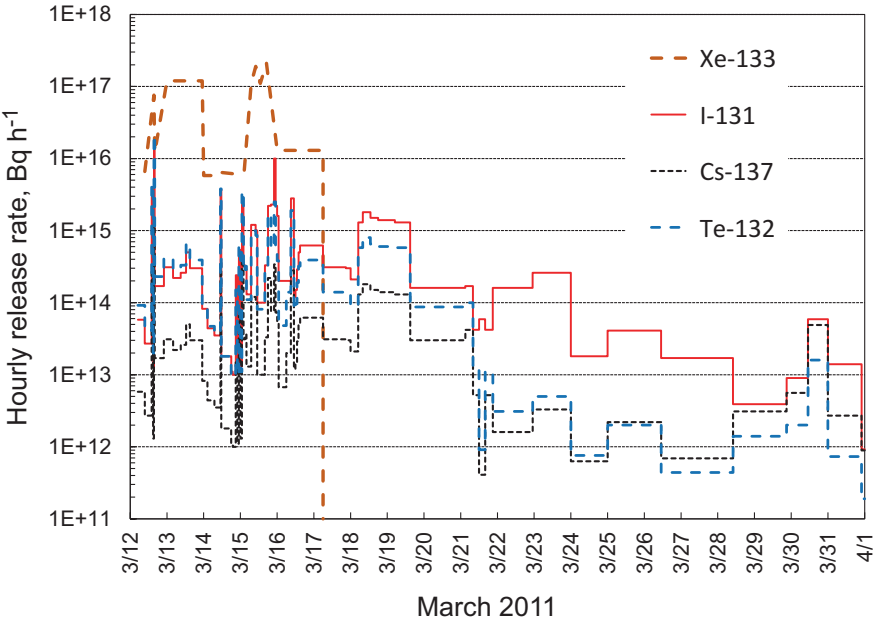

Fig. 20.1 Hourly radioactivity release from the FNPP accident into the atmosphere during March 2011

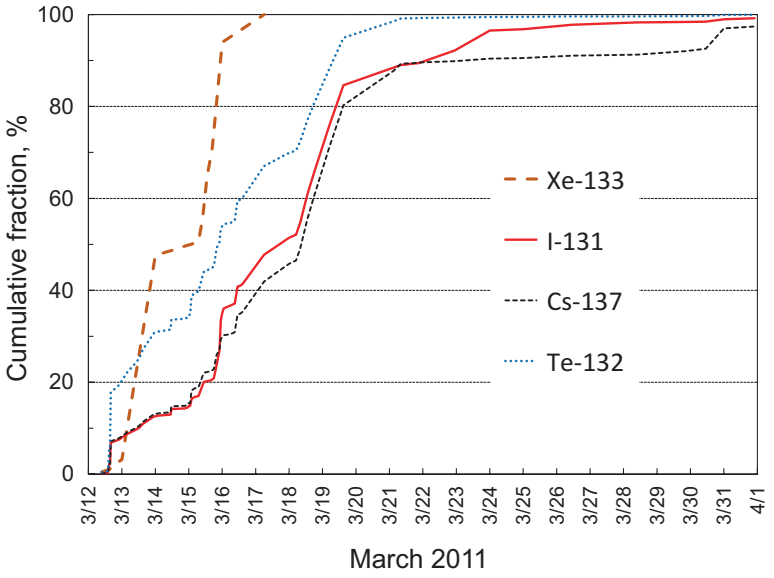

Fig. 20.2 Cumulative distribution of radionuclide release of the FNPP accident

Table 20.1 Comparison of the amounts of main radionuclides released into the atmosphere by the FNPP and CNPP accidents

Radionuclide	FNPP[a]		CNPP[b]	
	Released radioactivity, PBq	Fraction of core inventory[c], %	Released radioactivity [17], PBq	Fraction of core inventory[d], %
^{133}Xe	10,500 [4]	87	6500	100
^{131}I	300 [16]	5	1760	55
^{132}Te	310 [16]	3.6	1150	43
^{134}Cs	15 [16]	2.1	47	26
^{137}Cs	15 [16]	2.1	85	30
^{90}Sr	0.14 [12]	0.03	10	5
^{95}Zr	0.017 [12]	2×10^{-4}	84	1.5
^{103}Ru	7.5×10^{-6} [12]	9×10^{-8}	168	3.5
^{106}Ru	2.1×10^{-6} [12]	9×10^{-8}	73	3.5
^{140}Ba	3.2 [12]	0.03	240	5
^{141}Ce	0.018 [12]	2×10^{-4}	84	1.5
^{239}Np	0.076 [12]	7×10^{-5}	400	1.5
^{239}Pu	3.2×10^{-6} [12]	1×10^{-4}	0.013	1.5

[a]Decay-corrected at 14:46 on March 11, 2011
[b]Decay-corrected on April 26, 1986
[c]Inventory values from Nishihara et al. [18]
[d]Inventory values from the Ukraine report [19]

March 17. As shown in Fig. 20.2, about 80% of the release of two important radionuclides, ^{131}I and ^{137}Cs, occurred between March 15 and March 21. Radioactive materials released by two hydrogen explosions on March 12 and March 14 did not make a significant contribution to the total release.

Estimated total amounts of various radionuclides released into the atmosphere by the FNPP accident are compared with those released by the CNPP accident in Table 20.1. Xenon-133 release was greater for the FNPP accident than the CNPP accident. The released activity ratio of FNPP to CNPP for ^{131}I and ^{137}Cs is about one-sixth. Compared with the CNPP accident, very small amounts of other radionuclides such as strontium-90 (^{90}Sr), zirconium-95 (^{95}Zr), ruthenium-103 (^{103}Ru), etc. were released by the FNPP accident. These differences can be explained by the element characteristics and accident processes. Xenon-133, a rare gas radionuclide, easily escaped into the environment in both the accidents. The difference in ^{133}Xe release simply reflects the reactor power of FNPP (Units 1, 2 and 3: total 2 GW electricity) and CNPP (Unit 4: 1 GW). Because the CNPP accident was a power surge accident, the explosion occurred within the reactor core and destroyed the reactor and the building at the same time. This led to direct exposure of the damaged reactor core to the atmosphere, as well as dispersion of nuclear fuels around the damaged Unit 4 building. Meanwhile, the explosions in the FNPP accident did not happen in the reactor cores. The meltdown and melt-through of reactor cores occurred inside the containment structures without direct exposure to the atmosphere. Therefore, mainly gaseous and volatile radionuclides were released into the atmosphere in case of the FNPP accident.

20.3 Radioactive Contamination

The area of ^{137}Cs-contaminated land is the most important factor in determining the long-term effects of nuclear accidents. The first effort to make a ^{137}Cs deposition map around FNPP was carried out by a team from the US National Nuclear Security Administration (NNSA) that arrived at the Yokota air base near Tokyo in the early morning on March 16, 2011. Beginning March 17, the team conducted an aerial measuring system (AMS) survey of radioactive contamination in the area around FNPP [20]. The results of the survey were published in their website in the autumn of 2011 [21]. Dr. Sawano, an expert on the Geographic Information System (GIS) technique, found the AMS survey results for FNPP by chance and edited the ^{137}Cs deposition map as shown in Fig. 20.3 [22]. His comparison of the ^{137}Cs-contaminated area and population size for the FNPP accident and the CNPP accident is shown in Table 20.2 [23].

As seen in Table 20.2, the ^{137}Cs-contaminated area was 11–15 times larger for the CNPP accident than the FNPP accident, while the affected population living in contaminated zones defined by Chernobyl laws was only 3–5 times larger for the CNPP accident than that for the FNPP accident, reflecting a higher population density in

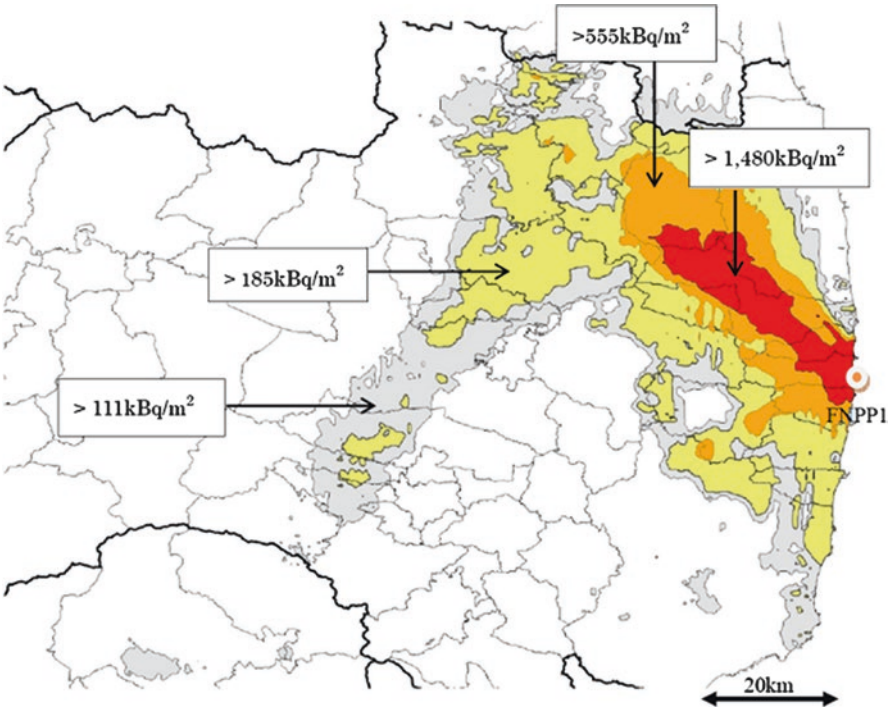

Fig. 20.3 Cesium-137 deposition map for the FNPP accident derived from DOE/NNSA AMS data following the Chernobyl classification scheme

Table 20.2 Comparison of contaminated land area and population for the FNPP and the CNPP accidents

	Zone classification in CNPP by ^{137}Cs contamination level[a]					
	(First zone)		(Second zone)		(Third zone)	
	>1480 kBq m^{-2}		555–1480 kBq m^{-2}		185–555 kBq m^{-2}	
	Area, km^2	Population, persons	Area, km^2	Population, persons	Area, km^2	Population, persons
FNPP	272	30,159	495	52,157	1405	261,076
CNPP	3100	149,000[b]	7200	235,000	19,120	689,000
CNPP/FNPP ratio	11.4	4.9	14.5	4.5	13.6	2.6

[a]According to the Chernobyl laws in Ukraine, Belarus and Russia, first zone, second zone and third zone correspond to areas of alienation, obligatory resettlement and voluntarily resettlement, respectively [23]
[b]This number includes 116,000 persons who were evacuated from the 30 km zone just after the accident in 1986

Table 20.3 Relative deposition ratios of radionuclides (^{137}Cs = 1), contributing γ-ray exposure 1 m above ground [6, 7]

Radionuclide	Half-life	Exposure rate conversion factor (nGy h^{-1})/(kBq m^{-2})	Relative deposition ratio to ^{137}Cs	
			FNPP	CNPP
^{95}Zr	65.5 days	2.82	–	20
^{95}Nb	35.0 days	2.92	–	20
^{103}Ru	39.3 days	1.85	–	16
^{131}I	8.04 days	1.49	11.5	18
^{132}Te	3.25 days	0.79	8	28
^{132}I	(2.30 h)[a]	8.61	8	28
^{134}Cs	2.07 years	5.97	1	0.4
^{137}Cs	30.1 years	2.18	1	1
^{140}Ba	12.8 days	0.57	–	22
^{140}La	(1.68 days)[a]	7.83	–	11
^{239}Np	2.36 days	0.60	–	120

[a]These radionuclides are treated at radioactive equilibrium with parent radionuclides

the latter. Another difference is that the east side of FNPP is surrounded by the Pacific Ocean, and the wind direction over the Japanese islands is predominantly to the east. Therefore, radionuclides were more likely to deposit in the Pacific Ocean than on land.

Gamma-ray exposure rates above the contaminated ground were calculated assuming the radionuclide composition both for the FNPP and the CNPP accidents. The deposited amounts of radionuclides contributing γ-ray exposure were shown in Table 20.3 as values of relative deposition ratio to ^{137}Cs [6, 7]. Deposition was assumed to occur at a time on April 26, 1986, the day of the accident for CNPP and on March 15, 2011, the day when the most severe contamination occurred for FNPP. Figure 20.4a shows the temporal change in the γ-ray exposure rate 1 m above

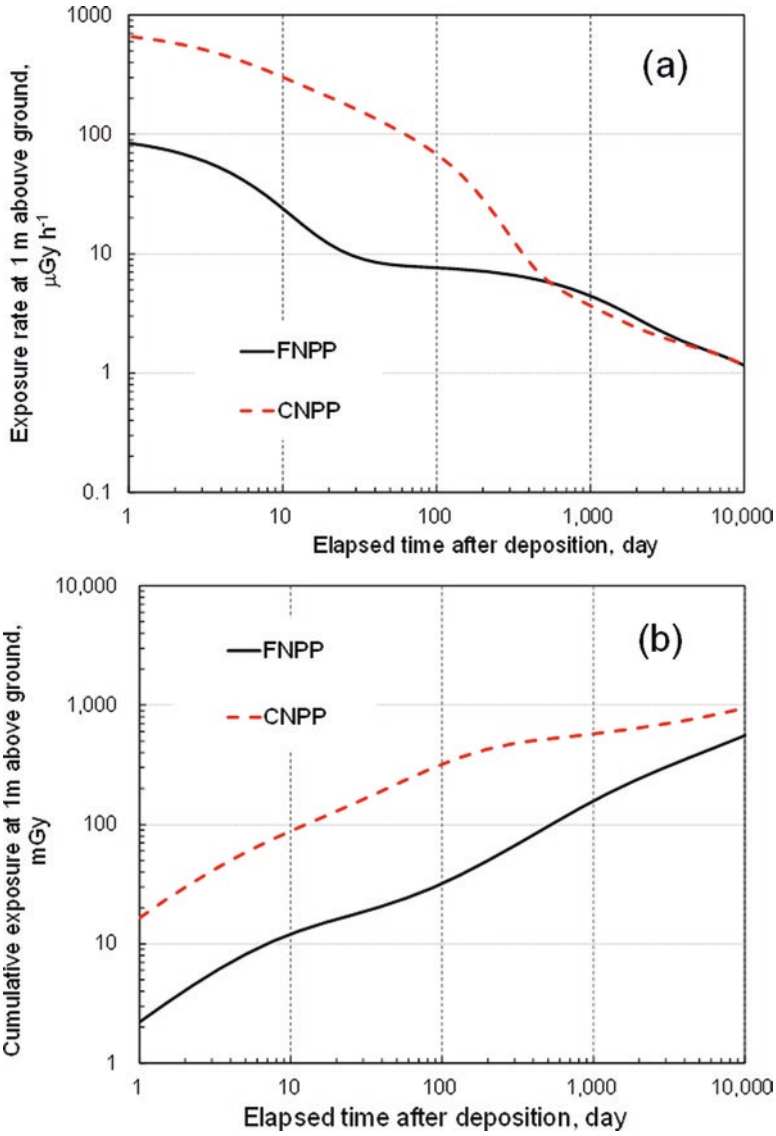

Fig. 20.4 (**a**) Radiation exposure rate, μGy h^{-1} and (**b**) cumulative exposure, mGy, at 1 m above ground normalized to the initial ^{137}Cs deposition of 1 MBq m^{-2}

ground normalized to the initial ^{137}Cs deposition of 1 MBq m^{-2} for both the FNPP and the CNPP accidents. The initial exposure rate 1 day after deposition was 80 μGy h^{-1} for the FNPP accident, while it was 700 μGy h^{-1} for the CNPP accident (nine times larger). Given the radionuclide compositions in Table 20.2, such radionuclides as ^{95}Zr, ^{103}Ru, ^{140}Ba and ^{239}Np have a substantial contribution to radiation exposure during the 1st year after the CNPP accident. Two months after deposition,

radiocesiums ^{134}Cs and ^{137}Cs accounted for 99% of the radiation exposure rate in the FNPP accident, while the contribution of radiocesiums in the CNPP accident was only 4% of the exposure rate at the same time [6]. Interestingly, the FNPP exposure rate exceeded CNPP approximately 1.5 years after deposition and was almost the same after 10 years (Fig. 20.4a). This exposure rate trend is created by differences in the deposition ratio of ^{134}Cs (half-life: 2.07 years) to ^{137}Cs (half-life: 30.1 years) for the FNPP accident (^{134}Cs:^{137}Cs = 1:1) and the CNPP accident (^{134}Cs:^{137}Cs = 0.5:1).

Cumulative exposures 1 m above ground normalized to the initial ^{137}Cs deposition of 1 MBq m^{-2} were plotted both for the FNPP and the CNPP accidents (Fig. 20.4b). Cumulative exposures after the 1st year were 63 mGy and 500 mGy for the FNPP and the CNPP accident, respectively. Cumulative exposures at 30 years are 500 mGy and 970 mGy for the FNPP and the CNPP accident, respectively. The contribution of radiocesiums to the cumulative exposure for the 1st year was 83% for FNPP and 7.4% for CNPP, and at 30 years it is 98% for FNPP and 84% for CNPP. Therefore, different compositions of ground contamination between the FNPP accident and the CNPP accident led to different patterns of radiation exposure, primarily during the 1st year.

20.4 Conclusion

Although both the FNPP accident and the CNPP accident are classified as Level 7, the worst nuclear incidence classification of the INES by IAEA, there are various differences between the accidents. These differences include the accident process, released radionuclide composition and meteorological and geological conditions. Cesium-137 is the most important radionuclide to consider due to its long-term effects. The amount of ^{137}Cs released by the FNPP accident is estimated to be about six times smaller compared to the CNPP accident. The ^{137}Cs-contaminated land area is 11–15 times smaller for the FNPP accident compared to the CNPP accident. Cumulative radiation exposure for 1 year above ground at the same level of ^{137}Cs contamination is about eight times smaller for the FNPP accident compared to the CNPP accident, while it decreases to about two times for 30 years, reflecting the different radionuclide composition of ground deposition.

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