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A Brief Review of Environmental Impacts and Health Effects from the Accidents at the Three Mile Island, Chernobyl and Fukushima Daiichi Nuclear Power Plants

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On 28 March 1979, the most serious accident in the history of USA commercial nuclear power plant operation occurred at the Three Mile Island Nuclear Power Plant. Failure to close a pressure relief valve led to severe damage of uncooled fuel. A series of events then led to core melt and release of fission products. On 26 April 1986, the most severe accident ever to occur in the nuclear industry began at the Chernobyl Nuclear Power Plant. The cause of the accident was a runaway surge in the power level that caused the water coolant to vaporize inside the reactor. This was followed by a steam explosion and fire with release of radioactive materials. On 11 March 2011, a great earthquake and tsunami damaged the Fukushima Daiichi Nuclear Power Plant and caused lose of emergency power supplies for cooling functions. Explosions destroyed the reactor buildings and considerable amounts of radioactive materials were released into the atmosphere and ocean. This paper addresses the cause of the accidents at these three nuclear power plants, the released amount of radioactive materials, and the radioactive contamination and health effects.

Key words: Nuclear power plant accident; Environmental impact; Health effect; Three Mile Island; Chernobyl; Fukushima Daiichi

1. Introduction

A magnitude 9.0 earthquake and subsequent tsunami occurred in the Pacific Ocean off northern Honshu, Japan, on 11 March 2011 which caused severe damage to the Fukushima Daiichi Nuclear Power Plant (F-1NPP). This accident has resulted in a substantial release of radioactive materials to the atmosphere and ocean, and has caused extensive contamination of the environment[1-3]. The accident was provisionally rated as Level 7, the highest level, on the International Nuclear and Radiological Event Scale on 12 April 2011[2]. This level is the same as given the Chernobyl Nuclear Power Plant (CNPP) accident in 1986. In 1979, the most serious accident to have happened in US commercial nuclear power plant operation occurred at the Three Mile Island Nuclear Power Plant (TMINPP) and resulted in releases of radioactive materials.

In this paper, the environmental and health impacts are briefly reviewed for these three accidents, including the cause of the accidents and estimates of the principal radionuclides released during the course of each accident.

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Fig. 1. Three Mile Island Nuclear Power Plant (http://upload.wikimedia.org/wikipedia/commons/b/b9/Three_Mile_Island_%28color%29.jpg).

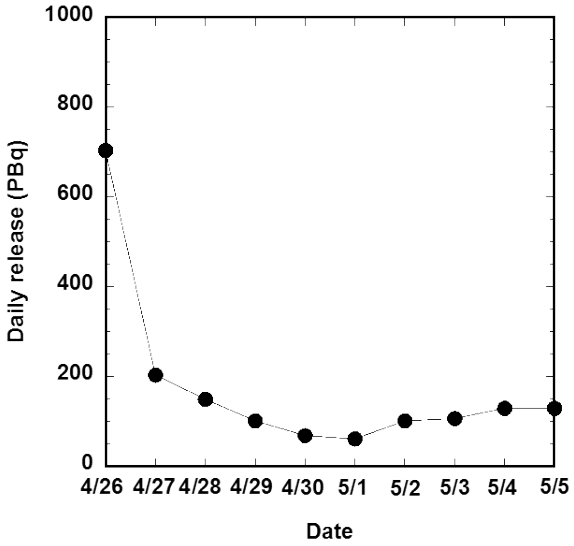

Fig. 2. The estimated daily releases of ^{131}I from the CNPP[9].

2. TMINPP

2.1. The TMI Accident

The TMINPP was constructed on a sandbank of the Susquehanna River, south of Harrisburg, Pennsylvania, USA (Fig. 1) and had two pressurized water reactors. The accident at Unit 2 began about 4 a.m. on 28 March 1979. The cause of the accident was the failure to close a pressure relief valve, which led to severe damage of uncooled fuel. A series of events then led to core melt and release of fission products through a relief valve in the primary water make-up system[4]. About 45% of the core melted and about 19,000 kg of molten core material relocated onto the lower head of the pressure vessel. Despite melting of the fuel, the reactor vessel maintained its integrity and the damaged fuel was contained in it.

2.2. Radioactive contamination of the environment

The accident released large amounts of radioactive materials from failed fuel to the containment, but the environmental releases were relatively small. Most fission products were retained in the reactor core water. The principal radionuclides released to the environment were of xenon and iodine. About 370 PBq of noble gases, mainly ^{133}Xe, and some 550 GBq of ^{131}I were released into the atmosphere[4]. Xenon-133 (half-life: 5.3 days) is chemically non-reactive and does not persist in the environment after it disperses in the atmosphere.

2.3. Health effects

Individual doses averaged 15 μSv within 80 km of the TMINPP, and the maximum effected dose that any member of the public could have received was estimated to have been 850 μSv from external gamma irradiation[5]. It was estimated that the collective effective dose resulting from the radioactivity released to the population living within 80 km of the nuclear power plant was approximately 20 man Sv between 28 March and 15 April[6] or an average value of 30 manSv (with a range of 16 manSv to 53 manSv) for the time period from 28 March through 7 April[7]. The estimated annual collective effective dose to this population from natural background radiation is about 2,400 manSv. The increment of radiation dose to persons living within 80 km due to the accident was somewhat less than one percent of the annual background level[6]. The radiation doses received by the general population as a result of exposure to the radioactivity released during the accident were so small that no detectable additional cases of cancer, developmental abnormalities, or genetic ill-health were predicted to occur as a consequence of this accident[6].

3. CNPP

3.1. The Chernobyl accident

The CNPP was constructed in northern Ukraine, some 20 km south of the border with present-day Belarus and 140 km west of the border with the present-day Russian Federation. The accident at Unit 4 began shortly after midnight on 26 April 1986. It was the most severe ever to have occurred in the nuclear industry. The Chernobyl reactor was a pressurized water reactor using light water as a coolant and graphite as a moderator. The reactor had been operated for many hours in non-design configurations in preparation for an experiment on recovery of the energy in the turbine in the event of an unplanned shutdown[8]. The cause of the accident can be considered as a runaway surge in the power level that caused the water coolant to vaporize inside the reactor. This caused a further increase in the power level,

Table 1. Estimates of the principal radionuclides released during the Chernobyl accident [4]

Radionuclide	Half-life	Activity released (PBq)
Inert gases		
Kr-85	10.72 y	33
Xe-133	5.25 d	6,500
Volatile elements		
Te-129m	33.6 d	240
Te-132	3.26 d	~ 1,150
1-131	8.04 d	~ 1,760
1-133	20.8 h	910
Cs-134	2.06 y	~ 47
Cs-136	3.1 d	36
Cs-137	30.0 y	~ 85
Elements with intermediate volatility		
Sr-89	50.5 d	~ 115
Sr-90	29.12y	~ 10
Ru-103	39 .3 d	>168
Ru-106	368 d	>73
Ba-140	12.7 d	240
Refractory elements (including fuel particles)		
Zr-95	64.0 d	84
Mo-99	2.75 d	>72
Ce-141	32.5 d	84
Ce-144	284 d	~ 50
Np-239	2.35 d	400
Pu-238	87.74 y	0.015
Pu-239	24,065 y	0.013
Pu-240	6,537 y	0.018
Pu-241	14.4 y	~ 2.6
Pu-242	376,000 y	0.00004
Cm-242	18.1 y	~ 0.4

with a resulting steam explosion that destroyed the reactor. After the initial explosion, the graphite in the reactor caught fire and it burned for many days, and releases of radioactive materials continued until 6 May 1986 [8].

3.2. Radioactive contamination of the environment

3.2.1. Release of radioactive materials

The CNPP accident resulted in a substantial release of radioactive materials to the atmosphere and caused extensive contamination of the environment. The release of radioactive materials from the damaged reactor occurred over a 10-day period and they were deposited with greatest density in the regions surrounding the reactor.

The refined estimates of the principal radionuclides released during the course of this accident are given in Table 1[4]. Most of the radionuclides that were released in large amounts have short half-lives and the radionuclides with long half-lives were generally released in small amounts. The releases of ^{131}I, ^{134}Cs and ^{137}Cs were estimated to have been 1,760 PBq, 47 PBq and 85PBq, respectively[4]. Because ^{131}I and ^{137}Cs are responsible for most of the radiation exposure, they are the most important radionuclides. The estimated releases of ^{131}I and ^{137}Cs were about 50% and 30%, respectively, of the core inventory. The estimated daily releases of ^{131}I from the Chernobyl reactor are shown in Figure 2[9]. The release of ^{131}I on 26 April (first day of release) was estimated to be 704 PBq, about 40% of that during the first 10 days after the accident. The estimated releases of ^{132}Te, ^{132}I, ^{133}I, ^{134}I and ^{135}I were 1,040 PBq, 1,040 PBq, 910 PBq, 25 PBq and 250 PBq, respectively, and they were substantially lower than that of ^{131}I. This was due to the fact that most of the short-lived radionuclides decayed in the damaged reactor and were not released[9].

The initial amounts of ^{241}Am were so small that they have not been estimated. The total activity of ^{241}Am will increase with time due to the radioactive decay of ^{241}Pu. The estimated release of ^{241}Pu was 2.6 PBq (Table 1)[4]. The maximum total amounts of ^{241}Am will be 0.077 PBq in the year 2058. This is more than two times larger than the released amounts of $^{239+240}$Pu (0.031 PBq). After 320 years, the total activity of ^{241}Am will be the highest of all the remaining radionuclides[4].

3.2.2. Radioactive contamination

Radioactive contamination was found in every country of the northern hemisphere[10]. A map of ^{137}Cs deposition density throughout Europe as a result of the Chernobyl accident is shown in Figure 3[11]. During the first 10 days after the accident, radioactive gases and particles were initially carried by the wind in westerly and northerly directions, but subsequently, the winds came from all directions, so that all areas surrounding the reactor site received some fallout. The average ^{137}Cs deposition density exceeding 37 kBq/m^2 (1 Ci/km^2) was chosen as a minimum contamination level. This level was approximately ten times higher than the ^{137}Cs deposition density in Europe from global fallout and at this level the human dose during the first year after the accident was approximately 1 mSv. The countries most heavily affected by the accident were Belarus, the Russian Federation and Ukraine. There were also contaminated areas in the three Scandinavian countries (Sweden, Finland and Norway), Austria, Bulgaria, Switzerland, Greece, Slovenia, Italy and Republic of Moldova. The total area with ^{137}Cs deposition density exceeding 555 kBq/m^2 (15 Ci/km^2) in 1986 was 10,300 km^2, including 6,400 km^2 in Belarus, 2,400 km^2 in the Russian Federation and 1,500 km^2 in Ukraine[9].

The three main areas of contamination have been designated the Central, Gomel-Mogilev-Bryansk, and Kaluga-Tula-Orel areas[9]. The ^{137}Cs deposition density exceeded 1,480 kBq/m^2 (40 Ci/km^2) in the 30-km-radius area surrounding the reactor. In some areas of Gomel-Mogilev-Bryansk contamination was comparable to that in the Central area. The ^{137}Cs deposition density was lower in the Kaluga-Tula-Orel area, generally less than 555 kBq/m^2. The area with plutonium levels exceeding 4 kBq/m^2 was located within the 30-km-radius area. The $^{239+240}$Pu deposition density ranged from 0.07 to 0.3 kBq/m^2 in the

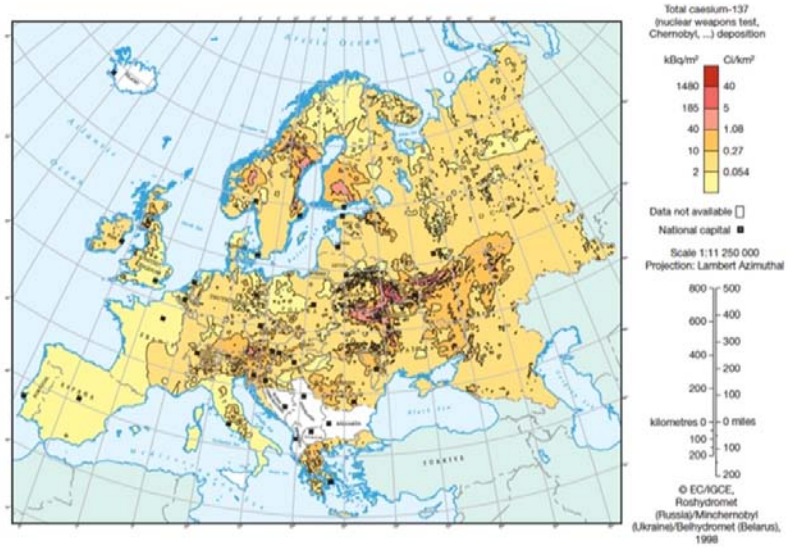

Fig. 3. Surface ground depositions of ^{137}Cs throughout Europe as a result of the Chernobyl accident[11].

Gomel-Mogilev-Bryansk area and from 0.07 to 0.3 kBq/m^2 in the Kaluga-Tula-Orel area[9].

Muramatsu et al.[12] have reported the $^{239+240}$Pu concentrations and ^{240}Pu/^{239}Pu atom ratios in soil samples collected from three forest sites within the 30-km zone. There were no differences in the ^{240}Pu/^{239}Pu atom ratios between the individual samples, although the $^{239+240}$Pu concentration varied widely from 6.3 to 1,430 Bq/kg dry weight. The average ^{240}Pu/^{239}Pu atom ratio in contaminated surface soil samples was 0.408. This atom ratio was much higher than the mean global fallout ratio of 0.18. The high ratio was related to the high burn-up grade of the reactor fuel.

The Chernobyl radioactivity was observed in rain and air samples in Japan[13, 14, 15]. The monthly ^{137}Cs deposition observed at Tsukuba increased to 131 Bq/m^2, which was the same level as that of the highest deposition period in 1963 after the 1961-62 large-scale atmospheric nuclear tests[15]. This pronounced peak of deposition was clearly attributable to the Chernobyl accident because of the observation of short-lived radionuclides (^{131}I, ^{132}I, ^{103}Ru, ^{106}Ru, etc.) and ^{134}Cs[13]. The Chernobyl-derived Pu isotopes, which are characterized by higher activity ratios of ^{238}Pu/$^{239+240}$Pu and ^{241}Pu/$^{239+240}$Pu than those of the nuclear test-derived Pu, also were detected in deposition and airborne dust samples in Japan, and so were volatile radionuclides such as ^{131}I and ^{137}Cs[15]. The Chernobyl ^{90}Sr and Pu isotopes were preferentially scavenged from the atmosphere by wet and dry deposition, over ^{131}I and ^{137}Cs. The behavior difference was due to the particle size difference between the radionuclide-bearing aerosols; the order of decreasing particle size was Pu isotopes > ^{90}Sr > ^{137}Cs. This suggested that large amounts of actinides were deposited near the accident site[15].

The Chernobyl derived ^{134}Cs was detected in the surface seawater of the marginal seas around Japan north of latitude 30°N during the period from July 1986 to September 1986, which reflected the meridional distribution of the Chernobyl derived ^{134}Cs in the surface air over the western North Pacific[16].

3.3. Health effects

The estimates of the average individual and collective doses received by the population groups exposed as a result of the Chernobyl accident have been updated in the UNSCEAR 2008 Report[4]. According to the UNSCEAR 2008, the updated estimates are summarized as follows.

The average effective dose received by the recovery operation workers between 1986 and 1990, mainly due to external irradiation, was estimated to have been 117 mSv. The collective effective dose to the 530,000 recovery operation workers was estimated to have been 61,200 man Sv. There is not enough information to estimate reliably the average thyroid dose to the recovery operation workers.

The average thyroid dose to the evacuees was estimated to have been 490 mGy. For the more than six million residents of the contaminated areas of the former Soviet Union who were not evacuated, the average thyroid dose was 102 mGy. The average thyroid dose to pre-school children was some 2 to 4 times greater than the population average. The high thyroid doses among the general population were due almost entirely to drinking fresh milk containing ^{131}I in the first few weeks following the accident. For the 98 million residents of all of Belarus and Ukraine and 19 oblasts of the Russian Federation, the average thyroid dose was much lower, about 16 mGy. The average thyroid dose to residents of the other European countries was about 1.3 mGy.

The six million residents of the areas of the former Soviet Union deemed contaminated received average effective doses for the period 1986-2005 of about 9 mSv, whereas for the 98 million people considered in Belarus, the Russian Federation and Ukraine, the average effective dose was 1.3 mSv, a third of which was received in 1986.

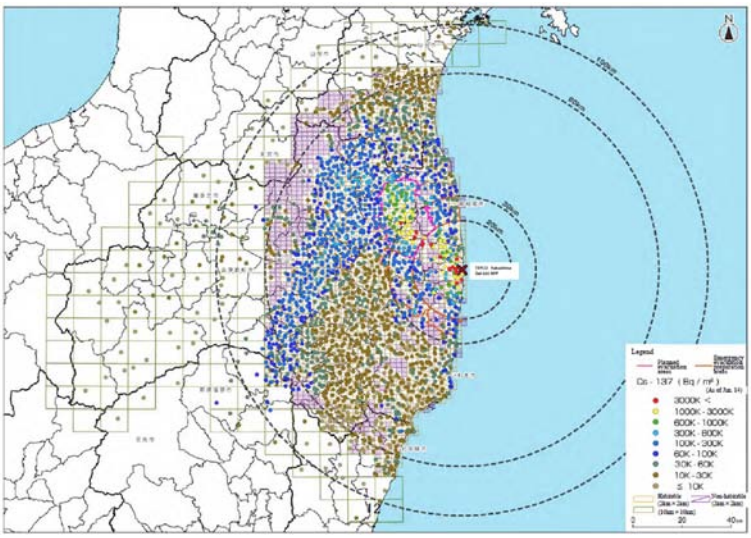

Fig. 4. Soil concentration map compiling the results of ^{137}Cs deposition on land from the F-1NPP accident[3].

Over the 20-year period 1986-2005, about 70% of the population received effective doses below 1 mSv and about 20% received effective doses between 1 and 2 mSv. However, about 150,000 people living in the contaminated areas received an effective dose of more than 50 mSv over the 20-year period.

4. F-1NPP

4.1. The F-1NPP accident

The F-1NPP was constructed in the Futaba District on the Pacific coast in Fukushima Prefecture, Japan. A massive earthquake with a magnitude of 9.0 occurred at 2:46 pm on 11 March 2011, followed by tsunami about 1 hour after the earthquake. The boiling water reactor units in operation automatically shutdown; however, loss of emergency power supplies led to cooling systems failures. Partial core melt of the nuclear fuel and hydrogen explosions occurred and substantial release of radioactive materials to the environment took place.

4.2. Radioactive contamination of the environment

4.2.1. Release of radioactive materials

Large amounts of radioactive nuclides, mainly ^{131}I, ^{134}Cs, ^{137}Cs, were released from the damaged reactors to the atmosphere. The Nuclear Safety Commission of Japan preliminarily estimated the amounts released into the atmosphere to be 150 PBq (1.5×10^{17} Bq) of ^{131}I and 12 PBq (1.2×10^{16} Bq) of ^{137}Cs[1] and the Nuclear Industrial Safety Agency of Japan preliminarily estimated them to be 130 PBq (1.3×10^{17} Bq) of ^{131}I and 6.1 PBq (6.1×10^{15} Bq) of ^{137}Cs[2]. These estimates were updated to be 160 PBq (1.6×10^{17} Bq) of ^{131}I, 18 PBq (1.8×10^{16} Bq) of ^{134}Cs and 15 PBq (1.5×10^{16} Bq) of ^{137}Cs by the Nuclear Industrial Safety Agency of Japan[17] or to be 130 PBq (1.3×10^{17} Bq) of ^{131}I and 11 PBq (1.1×10^{16} Bq) of ^{137}Cs by the Nuclear Safety Commission of Japan[18]. Those amounts accounted for approximately 10% of the 5.2 EBq (5.2×10^{18} Bq) released from the CNPP accident. The Nuclear Industrial Safety Agency of Japan also preliminarily estimated the atmospheric release of 19 GBq (1.9×10^{10} Bq) of ^{238}Pu, 3.2 GBq (3.2×10^{9} Bq) of ^{239}Pu, 3.2 GBq (3.2×10^{9} Bq) of ^{240}Pu and 1.2 TBq (1.2×10^{12} Bq) of ^{241}Pu[18].

4.2.2. Radioactive contamination

The Ministry of Education, Culture, Sports, Science and Technology, Japan, collected soil samples at around 2,200 locations within approximately 100 km from the F-1NPP to analyze the deposited radionuclides by using germanium semiconductor detectors[3, 19]. The soil samples were collected from a 5 cm surface layer at around five points at each location, prior to the rainy season (early summer), before any changes occurred on the soil surface. The soil concentration map compiling the results of ^{137}Cs is shown in Figure 4[3]. Deposition density of ^{137}Cs of more than 1,000 kBq/m^2 was observed in the Namie and Iitate districts[3]. The average ratio of deposition density of ^{131}I to that of ^{137}Cs was around 0.0059 for monitoring points located to the north of the nuclear plant and around 0.024 for monitoring points located south and within a 34 km range to the west from the plant[19]. The distributions of radionuclides in soil samples have also been reported by Kato et al.[20] and Kinoshita et al.[21]. Kinoshita et al.[21] concluded that the radioactive materials transported on 15 March were the major contributors to contamination in Fukushima Prefecture, whereas the radioactive materials transported on 21 March were the major sources in Ibaraki, Tochigi, Saitama and Chiba Prefectures and in Tokyo.

Radioactive materials were also released to the ocean from the plant. The two major pathways existed: direct discharge of radioactive liquid wastes to the ocean and atmospheric fallout of airborne radioactive materials onto the ocean

surface. The levels at the plant site discharge point were exceedingly high, with a peak for ^{137}Cs of 68 MBq/m^3 on 6 April 2011[22]. They noted that a steady, albeit lower, supply of ^{137}Cs continued to be discharged to the ocean at least through the end of July. Buesseler et al.[22] also found that the levels of ^{137}Cs in seawater 30 km from the F-1NPP were some 3 to 4 orders of magnitude higher than existed prior to the F-1NPP accident. Tsumune et al.[23] used a regional ocean model to simulate the ^{137}Cs concentrations resulting from the direct discharge to the ocean off Fukushima Prefecture and found that the total amounts of ^{137}Cs directly released was 3.5 ± 0.7 PBq from 26 March to the end of May. The estimated atmospheric deposits on the ocean surface were about 10 PBq of ^{137}Cs[24].

A car-borne survey for dose rate in air was carried out in March and April 2011[25]. The maximum dose rate in air within the high level contamination area was 36 μGy/h and the estimated maximum cumulative external dose for evacuees who came from Namie Town to evacuation sites was 68 mSv. The mandatory evacuation was justified from the viewpoint of radiation protection.

4.3. Health effects

Assessments of the health effects from radioactive material releases from F-1NPP cannot be made at this time. However, the national and prefectural governments have started monitoring the health of Fukushima prefecture residents and emergency and recovery workers of the plant[26, 27].

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