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The Impact
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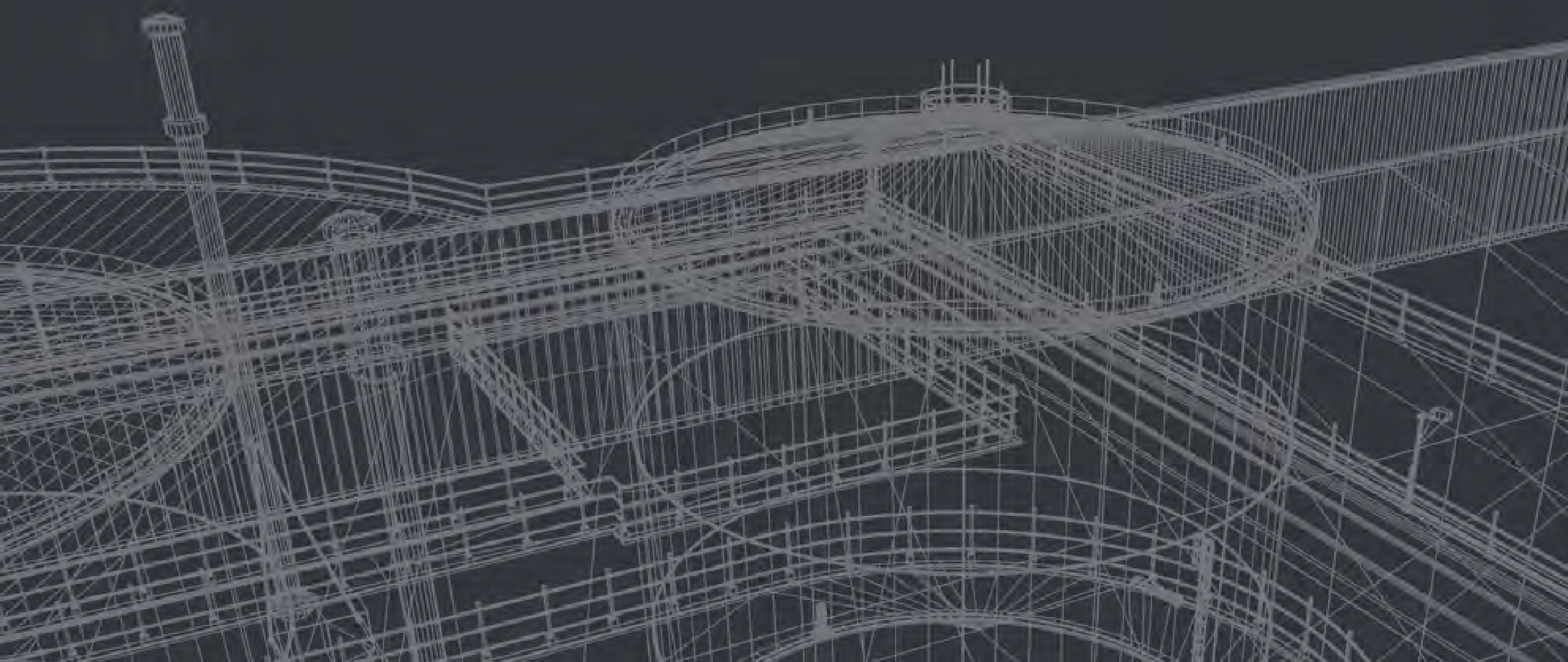

Radiological Effects
of the Nuclear Accidents
in Fukushima on 11 March 2011

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1 Introduction

The Tohoku-Chihou-Taiheiyou-Oki earthquake off the Japanese coast at 2.46 p.m. (local time) on 11 March 2011 was the most severe earthquake in the history of Japan since records began to be kept. The resultant tsunami flooded extensive tracts of the north-eastern coast and reached the Fukushima Dai-ichi (Fukushima I) nuclear plants at 3.27 p.m. with a first wave, and at 3.35 p.m. with a second wave. The earthquake and the subsequent tsunami damaged the Fukushima Dai-ichi plants to such an extent that, on 12 April 2011, the Japanese authorities classified it as a "major accident" according to level 7 of the International Nuclear and Radiological Event Scale (INES).

The Tokyo Electric Power Company (TEPCO) operated six boiling water reactors (BWR) at the Fukushima Dai-ichi site, with a total net power output of 4,547 megawatts (electric) (MW_{el}), a common spent fuel pool and a dry cask storage facility. Together with the neighbouring Fukushima Dai-ni (Fukushima II) site at a distance of 12 km, where four more power plant units with 1'100 MW_{el} each were available, this complex constituted the world's largest nuclear power plant site. At the time of the earthquake, units 1 to 3 were in power operation at Fukushima Dai-ichi. Units 4 to 6 had been shut down for several months due to inspection work. The fuel assemblies from the reactor pressure vessel (RPV) of unit 4 were in place in the unit's own spent fuel pool in the reactor building. The four units of the Dai-ni power plant were in power operation at the time of the earthquake.

In addition to Fukushima I and Fukushima II, additional nuclear power plants (Onagawa 1-3, Tokai and Higashidori) were affected by the earthquake and tsunami, albeit not with serious consequences.

From 2.30 p.m. on 12 March 2011 onwards, there were significant releases of radioactive substances into the environment at the Fukushima Dai-ichi site. These releases had – and to some extent are still having – enormous consequences for the population in the more immediate vicinity. There was a threat that radiation from the drifting radioactive cloud, the absorption of radioactive substances by inhalation and deposits of radioactive substances on the ground would contaminate the population in the surrounding area with greatly increased radiation doses. In order to prevent this, residents had to be evacuated on a large scale. The accident also impacted the living conditions of people resident in the area due to the penetration of activity into the drinking water, the sea and into plants and animals, leading to contamination of the food chain.

On 12 March 2011, in response to the events in Japan, the Swiss Federal Nuclear Safety Inspectorate (ENSI) mobilised its emergency response organisation, which monitored the event continuously and issued ongoing assessments of the situation in the stricken nuclear plants. After the situation had been stablilised, the ENSI emergency response organisation was returned to routine readiness on 24 March 2011. An analysis team was then assigned to continue monitoring developments in Japan and to undertake a comprehensive analysis of the accident at Fukushima Dai-ichi. The detailed progression of the accident /47/, an in-depth analysis of the accident giving special consideration to human and organisational factors /48/, and the knowledge gained from these studies (Lessons Learned) /49/ were each published by ENSI as separate reports.

The present Report describes the state of knowledge regarding the radiological effects of the accident at Fukushima Dai-ichi on the population in the surrounding area and the staff at the power plant site up to October 2011.

Section 2 begins with an explanation of the correlation between the accident on the Fukushima Dai-ichi nuclear power plant site and its assessment according to international criteria. This section goes on to describe and assess the discharge of radioactive material from the reactors in units 1 to 3. The presentation also includes the average ongoing release rates and the treatment of contaminated water present at the plant.

Section 3 presents the dose rates on the nuclear power plant site caused by deposits and distribution of the fission products after the venting procedures and hydrogen explosions. These rates provide the basis for radiation exposure for the assigned staff as described in section 4, and they determined the working conditions for such staff. This section also outlines the difficulties with dosimetric monitoring encountered by the plant operator after the accident, and the countermeasures that were initiated. The status of radiation exposure for employees and other operational staff as currently known to ENSI, and the difficulties in coping with an accident of such proportions, are explained with the help of selected examples.

Section 5 describes the radiation exposure for the population due to the release of radioactive substances in the area surrounding the nuclear power plant. In the first phase after the accident, the main contribution to the dose was supplied by external irradiation from the drifting radioactive cloud and the absorption of radioactive substances via the respiratory tract. In the subsequent ground-level phase, radioactive substances deposited on the ground resulted in a further long-term contribution to the dose due to external irradiation. Radioactive substances that were either directly or indirectly transferred onto and into forage crops and vegeTable les represented another important source for the dose, via the consumption of food (ingestion). Moreover, radioactive substances reached the human food chain from lakes, rivers and the sea, via fish and seafood. Discharges of radioactive substances into surface water (rivers and lakes) contaminated drinking water reservoirs and contributed to the increased radiation exposure via the drinking water supply. This section also sets out the measures implemented by the Japanese government to reduce radiation doses for the population.

Section 6 of this report describes the effects of the accident on Switzerland. The precautionary measures taken by the Federal Office of Public Health (FOPH) as a consequence of the accident and its impact on the Swiss population are outlined. The main measurement results and conclusions for Switzerland are also documented.

Section 7 contains a comparison of the events in Fukushima with those at Chernobyl, examining the various aspects and comparing the effects on the population and the environment, insofar as this is possible with the data available at present.

Section 6 of this report originates from the Federal Office of Public Health (FOPH). The Gesellschaft für Anlagen- und Reaktorsicherheit mbH (GRS) contributed key passages to section 7.

2 INES classification, determination of the volumes released

2.1 Overview

This section explains the classification of the accident at the Fukushima Dai-ichi nuclear power plant site in accordance with the criteria of the International Atomic Energy Agency (IAEA).

The International Nuclear and Radiological Event Scale (INES scale) was developed in 1990 following the accident at Chernobyl, in order to classify and assess events in nuclear plants. The scale extends from level 1 – “anomaly” – to level 7, which represents a “major accident”. Events at levels 1 to 3 are designated as “incidents”; events classified at higher levels are regarded as “accidents”. Events with little or no importance in terms of safety are assigned to level 0.

In order to classify an event, reference is made to an extensive catalogue of criteria which is published in an IAEA manual (cf. /2/).

Level	Brief designation	Aspects		
		Radiological effects outside the plant	Radiological effects inside the plant	Impairment of safety precautions
7	Major Accident	Most serious releases: effects on health and environment in an extensive surrounding area	-	-
6	Serious Accident	Substantial release: full deployment of disaster protection measures	-	-
5	Accident with Wider Consequences	Limited release: deployment of individual disaster protection measures	Severe damage to the reactor core / radiological barriers	-
4	Accident with Local Consequences	Minor release: radiation exposure for the population about the same as natural exposure to radiation	Limited damage to reactor core / radiological barriers Radiation exposure for staff leading to death	-
3	Serious Incident	Very minor release: radiation exposure for the population equal to a fraction of natural radiation exposure	Severe contamination Acute damage to health of staff	“Near accident” Extensive failure of in-depth defence precautions
2	Incident	-	Substantial contamination Inadmissibly high radiation exposure for staff	Incident Limited failure of in-depth defence precautions
1	Anomaly	-	-	Divergence from permissible ranges for safe plant operation
0	-	-	-	No or very minor safety significance

Table 2-1 Assessment aspects for the INES classification according to the international scale

3 | Source: Federal Office for Radiation Protection (BfS) http://www.bfs.de/de/kerntechnik/ereignisse/ines.html

Classification of the Fukushima accident at the highest INES level is based on estimates of the released radioactive substances. Release of the nuclides Iodine-131 and Cesuim-137 (which are critical for classification purposes) increased continuously after the accident and finally exceeded the value above which an accident is classified at level 7 on the INES scale.

In addition to the INES classification of the event, the following section provides a more detailed explanation of the release paths for radioactive substances from the reactor buildings into the environment, and the extent of the releases is quantified. As well as the discharge of gaseous radionuclides and those in particle form into the atmosphere, leakages in the primary containments also resulted in radioactively contaminated water being fed into the adjacent sea.

The actual progression of the accident is presented in detail in a separate ENSI publication (cf. /47/).

2.2 INES classification of the event

2.2.1 Systematic scheme of the INES scale

The international assessment scale for nuclear events (International Nuclear and Radiological Event Scale, INES) comprises levels 1 to 7 for events of major safety significance and level 0 for events with minor or no safety significance. It is therefore possible to classify events at eight levels according to INES (cf. Figure 2-1). The significance of the individual levels is indicated by a number and a brief description.

The levels are characterised by various aspects, as shown in Table 2-1.

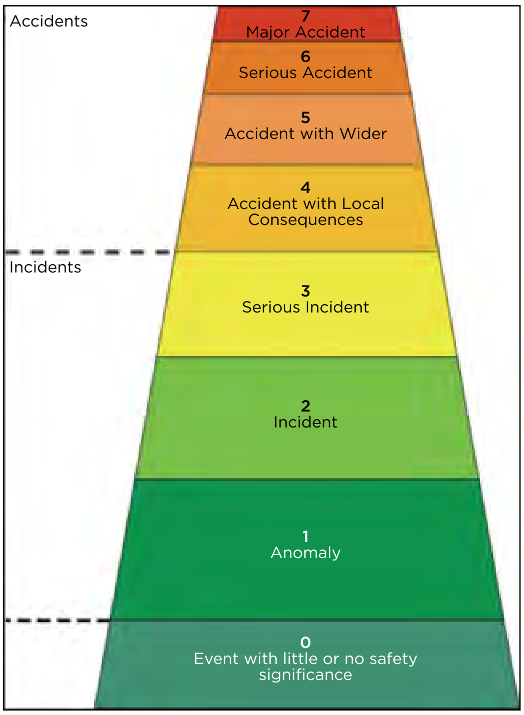


Figure 2-1 The international assessment scale for nuclear events - INES[2]

2 | Source: Bundesamt für Strahlenschutz (BfS) http://www.bfs.de/de/kerntechnik/ereignisse/ines.html

2.2.2 Application of the INES scale to Fukushima Dai-ichi

At 4:36 p.m. on 11 March 2011, the Japanese Nuclear and Industrial Safety Agency (NISA) provisionally classified the event at the Fukushima Dai-ichi site as INES 3. The reason for this was the failure of the supply pumps, entailing the loss of the emergency and residual heat removal systems of units 1 and 2 following the failure of the AC power supply (cf. /1/). The INES classification was made in consideration of the aspect mentioned in Table le 2-1, "Impairment of safety precautions" based on the criterion: "Near accident, extensive failure of in-depth defence precautions".

On 12 March 2011, venting of the primary containment in unit 1 was carried out and a hydrogen explosion occurred in the reactor building. Based on the measurement results from monitoring of the surrounding area, NISA announced the emission of radioactive iodine, cesium and other substances into the surrounding area. At this point in time, NISA calculated the released activity as 0.1% of the core inventory, and it increased the provisional classification of the event to INES 4 for unit 1 (cf. /1/).

On 18 March 2011, once it had to be assumed that there was severe core damage in units 1-3, NISA increased the classification of the event for each of units 1-3 to INES 5; the quantity released was now said to be several per cent of the core inventory (cf. /1/). Classification as INES 5 was made on the basis of the aspect of "Radiological effects inside the plant" mentioned in Table 2-1, and it was now assumed that the criterion of severe core damage and/or severe damage to the radiological barriers was met.

NISA carried out calculations on the quantity released into the atmosphere (cf. /5/). The results obtained, compared with the NSC (Nuclear Safety Commission) values, are shown in Table 2-2 below.

On the basis of cooperation between the Nuclear Safety Commission (NSC) and the Japan Atomic Energy Agency (JAEA), the quantities of radionuclides I-131 and Cs-137 released into the atmosphere at the Fukushima Dai-ichi site were determined independently in the period from 11 March 2011 until 5 April 2011. The amounts released during the aforementioned period are quantified as 1.5E+17 Bq for I-131 and 1.2E+16 Bq for Cs-137 in the NSC publication dated 12 April 2011 /4/.

Nuclide	Assumed quantity released from Fukushima Dai-ichi [Bq]		(Reference value) Quantity released at Chernobyl unit 4 [Bq]
	NISA data	NSC data	
I-131	1.3E+17	1.5E+17	1.8E+18
Cs-137	6.1E+15	1.2E+16	8.5E+16
Cs-137 converted into I-131 equivalent	2.4E+17	4.8E+17	3.4E+18
Total I-131 equivalent	3.7E+17	6.3E+17	5.2E+18

Table 2-2 Comparison of determined quantities released for the INES classification [4]

4 | Source: /5/
5 | The conversion of the Cs-137 values into an I-131 equivalent was carried out by NISA, taking account of INES User's Manual 10.

Figure 2-2 below shows the accumulated releases over the aforementioned period as calculated by NSC (publication dated 12 April 2011), in graphic form (cf. /4/).

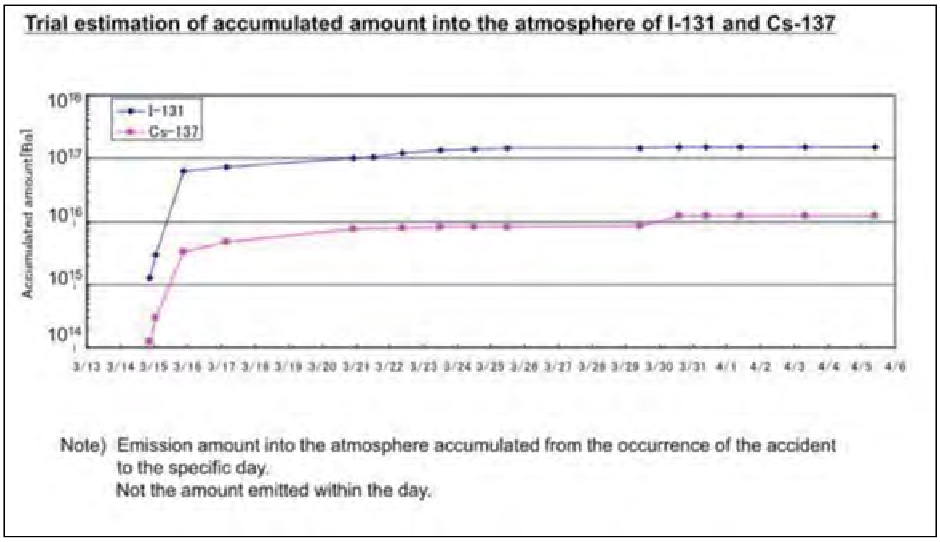


Figure 2-2 Cumulative release of I-131 and Cs-137 according to NSC calculations in the period from 11 March 2011 to 5 April 2011 [6]

On 12 April 2011, NISA made the classification for the entire Fukushima Dai-ichi site. This was undertaken on the basis of the aspect of “Radiological effects outside the plant”, according to the criterion of “Major release of radioactive material with widespread health and environmental effects” in level INES 7. The classification was justified by the calculated quantities of Iodine equivalent released, i.e. 3.7E+17 Bq (NISA) and 6.3E+17 Bq (NSC and JAEA) (cf. /1/). According to the INES Manual (cf. /2/), an event must be classified as INES 7 if the release of radioactive substances into the atmosphere is radiologically equivalent to a release of several 10’000 TBq (1E+16 Bq) of Iodine-131. The calculated releases are described in greater detail in sections 2.3 and 2.4 below.

6 | Source: NSC http://www.nsc.go.jp/NSCenglish/geje/2011%200412%20press.pdf

2.3 Release of radioactive substances into the atmosphere

According to knowledge at present, almost the entire release of radioactive material from the reactors in units 1 to 3 at Fukushima Dai-ichi was due to two processes. On the one hand, unfiltered venting operations of the primary containment caused the release of large quantities of radioactive substances via the air. On the other, hydrogen explosions caused further releases, finally leading to the loss of safety barriers to retain activity.

In detail, the releases were based on the following processes. The loss of the integrity of the fuel assemblies, up to meltdown of the nuclear fuel and subsequent partial transfer into the bottom head dome area of the reactor pressure vessel (RPV), and the partial loss of the integrity of the RPV, were due to the fact that the rector cores were at times not covered with coolant.

Due to the failure of the core cooling and the resultant need to reduce pressure in the RPV via the pressure relief valves, primarily airborne fission products were transferred via the condensation chambers (designed in the shape of a torus in Mark I containments) into the primary containments. Due to the ongoing influx of energy into the primary containments with no removal of heat to the outside, the pressure and quantity of the activity inventory in them rose in each case. As the incident proceeded, emergency measures (containment venting operations) led to high discharges of activity into the surrounding area. It is also suspected that leaks occurred on the lid seal of the primary containment and on wall leadthroughs, due to the increase of heat and pressure in the primary containment as mentioned above. This partial loss of primary containment integrity caused the transport of radionuclides and hydrogen from the primary containment into the reactor building. The subsequent H_2 explosions destroyed the reactor buildings and released larger quantities of radionuclides. From then on, the reactor buildings (which were now open) led to a continuous and diminishing release of radioactive substances (cf. Figure 2-4). Due to the subsequent supply of additional coolant with emergency equipment and also because of internal leakages (e.g. on the Torus, the containment lid or the containment itself) and leaks in buildings, radioactive substances were released into the surrounding area via water.

Inspection of the spent fuel pools in units 2, 3 and 4, including associated nuclide measurements, have so far provided no grounds for assuming major damage to the fuel assemblies (FA) stored there. It is concluded from this that the main releases took place via the containment venting operations or leakages. No statements are yet available regarding the spent fuel pools belonging to units 1, 5 and 6. However, it may be assumed that no releases took place from units 5 and 6, which were less seriously affected by the tsunami and whose reactor buildings remained intact (cf. /11/). Both the fuel assembly wet storage facility and the storage containers in the dry storage facility remained intact and did not contribute to the release of activity into the surrounding area. The dry storage facility, which is located near the turbine hall of unit 5, was damaged by the tsunami (cf. Figure 2-3). As it was not possible to determine any releases of activity by means of measurements /3/, it is assumed that the containers remained intact.

Analyses by NISA in May 2011 indicated release of the core inventory for the Fukushima Dai-ichi site, depending on the reactor unit, of approx. 0.4 – 7% for Iodine-nuclides, approx. 0.4 – 3% for Tellurium nuclides, approx. 0.3 – 6% for the Cesium nuclides and almost the entire inventory of noble gases.

Figure 2-3 Situation in the dry storage facility at the Fukushima Dai-ichi nuclear power plant [7]

7 | Source: Tepco http://www.tepco.co.jp/en/news/110311/images/110909_69.jpg

These values are therefore higher than the first estimates made for the purpose of the INES classification. The releases of fission products into the surrounding area at the start of the events are listed for the individual units in Table 2-3 /1/.

However, the calculated release proportions depend on assumptions, e.g. regarding operating conditions, amounts of water fed into the RPV and regarding possible leakages. The calculated releases may vary within certain bandwidths according to the influencing variables on which they are based. Information about operating data was not fully known at the time the calculations were undertaken, so the behaviour of the plants cannot be described with the necessary accuracy.

Nuclide	Half-life [9]	Quantity released [Bq]			
		Unit 1	Unit 2	Unit 3	Total for units 1-3
Xe-133	5.25 d	3.4E+18	3.5E+18	4.4E+18	1.1E+19
Cs-134	2.06 a	7.1E+14	1.6E+16	8.2E+14	1.8E+16
Cs-137	30.17 a	5.9E+14	1.4E+16	7.1E+14	1.5E+16
Sr-89	50.5 d	8.2E+13	6.8E+14	1.2E+15	2.0E+15
Sr-90	28.64 a	6.1E+12	4.8E+13	8.5E+13	1.4E+14
Ba-140	12.75 d	1.3E+14	1.1E+15	1.9E+15	3.2E+15
Te-127m	109.0 d	2.5E+14	7.7E+14	6.9E+13	1.1E+15
Te-129m	33.6 d	7.2E+14	2.4E+15	2.1E+14	3.3E+15
Te-131m	30.0 h	9.5E+13	5.4E+10	1.8E+12	9.7E+13
Te-132	76.3 h	7.4E+14	4.2E+11	1.4E+13	7.6E+14
Ru-103	39.35 d	2.5E+9	1.8E+9	3.2E+9	7.5E+9
Ru-106	373.6 d	7.4E+8	5.1E+8	8.9E+8	2.1E+9
Zr-95	64.0 d	4.6E+11	1.6E+13	2.2E+11	1.7E+13
Ce-141	32.5 d	4.6E+11	1.7E+13	2.2E+11	1.8E+13
Ce-144	284.8 d	3.1E+11	1.1E+13	1.4E+11	1.1E+13
Np-239	2.355 d	3.7E+12	7.1E+13	1.4E+12	7.6E+13
Pu-238	87.74 a	5.8E+8	1.8E+10	2.5E+8	1.9E+10
Pu-239	2.411E+4 a	8.6E+7	3.1E+9	4.0E+7	3.2E+9
Pu-240	6‘563 a	8.8E+7	3.0E+9	4.0E+7	3.2E+9
Pu241	14.35 a	3.5E+10	1.2E+12	1.6E+10	1.2E+12
Y-91	58.5 d	3.1E+11	2.7E+12	4.4E+11	3.4E+12
Pr-143	13.57 d	3.6E+11	3.2E+12	5.2E+11	4.1E+12
Nd-147	10.98 d	1.5E+11	1.3E+12	2.2E+11	1.6E+12
Cm-242	162.94 d	1.1E+10	7.7E+10	1.4E+10	1.0E+11
I-131	8.02 d	1.2E+16	1.4E+17	7.0E+15	1.6E+17
I-132	2.3 h	4.5E+14	9.6E+11	1.8E+13	4.7E+14
I-133	20.8 h	6.5E+14	1.4E+12	2.6E+13	6.8E+14
I-135	6.61 h	6.1E+14	1.3E+12	2.4E+13	6.3E+14
Sb-127	3.85 d	1.7E+15	4.2E+15	4.5E+14	6.4E+15
Sb-129	4.4 h	1.6E+14	8.9E+10	3.0E+12	1.6E+14
Mo-99	66.0 h	8.1E+7	1.0E+4	6.7E+6	8.8E+7

Table 2-3 Provisional calculation to estimate the airborne release of radioactive substances in the early phase of the accident (taking account of operating data until 16 May 2011) [8]

8 | Source: /1/
9 | Half lives as per /45/

The Ministry of Economy, Trade and Industry (METI) publishes progress reports at regular intervals (cf. /6/), with estimates of the average release rate. As shown in Figure 2-4, the average release rate decreased by several orders of magnitude, i.e. from approx. 8E+14 Bq/h on 15 March to approx. 1E+8 Bq/h in the period from 3 to 13 October 2011. These estimates are based on individual air concentration measurements. In the meantime, precipitation collectors were installed to allow more accurate values.

On 24 August 2011, the NSC announced that the JAEA had carried out new calculations taking account of further radiological measurements in the surrounding area and additional factors at the start of the accident. Taking account of these new conditions, the quantity of radioactivity released between 11 March and 5 April 2011 is calculated as 1.3E+17 Bq for I-131 and 1.1E+16 Bq for Cs-137. The total emission of iodine and aerosols would therefore be approx. 10% less than the value published in April (cf. Table 2-2). There were no significant releases at the Fukushima Dai-ni, Tokai and Onagawa sites.

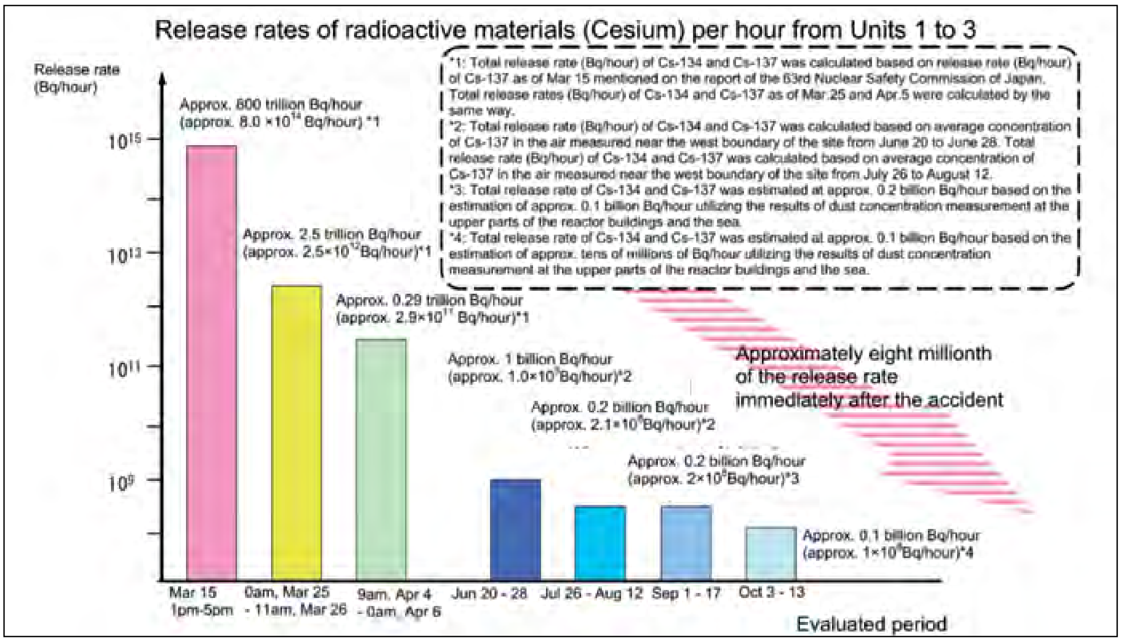


Figure 2-4 2-4 Release rates for units 1-3 at Fukushima Dai-ichi [10]

 Source: METI http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/111017_nps_1pdf1

2.4 Release of radioactive substances via water into the sea

Activity was transported into the primary containments due to the RPV depressurising operations and through the three RPVs which developed leaks due to core meltdown. At least in part, water was able to escape from the primary containments due to leakages. This water accumulated in the lower levels of the reactor buildings. Especially in unit 2, where it is suspected that the Torus is leaking, a large quantity of radioactive water escaped. Another presumed cause of the penetration of activity is the outflow of the mixture of hydrogen, water vapour and nitrogen from the primary containments into the reactor buildings (cf. section 2.3).

After the detonations, and with the reactor buildings open, the spent fuel pools were initially supplied by fire extinguishing cannons and later with concrete pumps. This made it possible to flush radionuclides into the lower levels of the reactor buildings, and rain also caused washouts of the debris distributed over the pool levels by the detonations. From the lower levels of the reactor buildings, the contaminated water flowed into the turbine halls via connecting ducts/channels. The turbine halls, in turn, are connected to the pump houses for the water intakes via cable ducts and concrete shafts (cf. Figure 2-5). The contaminated water reached the sea en route to the water intakes. At the start of September 2011, approx. 90’000 m³ of contaminated water was present in units 1 to 4.

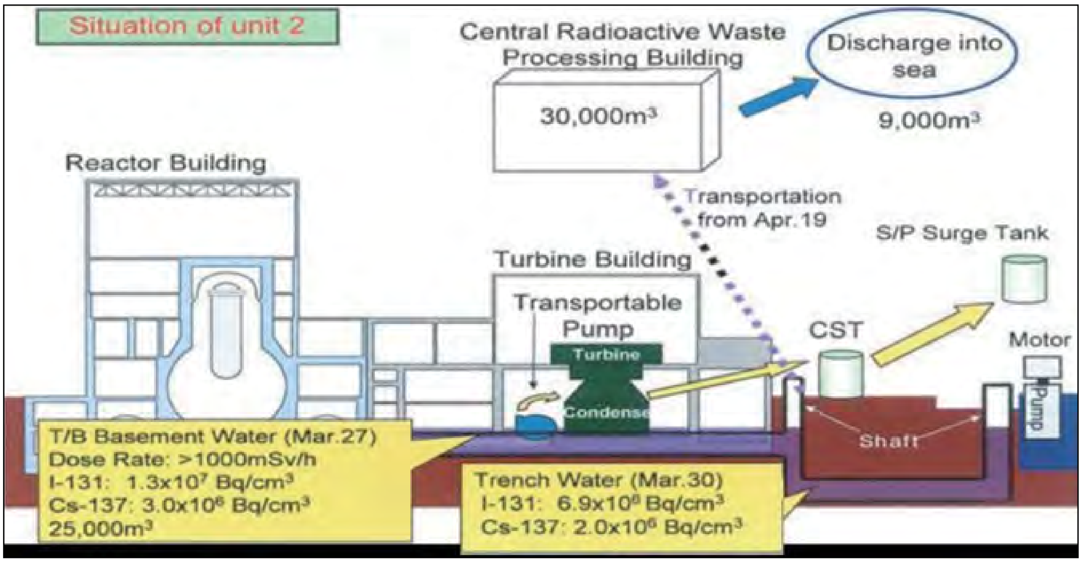


Figure 2-5 Path by which contaminated water spread into unit 2[11]

11 | Source: ICAPP/TEPCO https://www.sfen.fr/ICAPP-11

The analysis results for nuclide concentrations in the accumulated water in the turbine halls at the end of March 2011 are shown in Table 2-4 (cf. /1/). The analysis of the water in the turbine hall of unit 2 showed activity content levels of 1.3E+10 Bq/l for I-131 and 3.0E+9 Bq/l for Cs-137 (cf. /7/). The values exceed those measured in units 1 or 3 by a factor of about 10. The suspected cause is the leaking Torus. The accumulated volume of water by the end of March 2011 was estimated at 25'000 m^3 for unit 2.

A dose rate of >1 Sv/h was measured in the cable shaft near the water intake of unit 2 on 2 April 2011; this was caused by the highly contaminated water with activity values for I-131 of 6.9E+9 Bq/l and for Cs-137 of 2.0E+9 Bq/l. According to NISA's estimates, approx. 520 m^3 of this water, which originated from the turbine hall of unit 2, flowed into the sea via connecting ducts/channels and cable shafts as a result of leakages in the concrete. It was possible to halt this outflow on 6 April 2011.

Unit		Unit 1	Unit 2	Unit 3	Unit 4
Sampling location		Basement, turbine hall	Basement, turbine hall	Basement, turbine hall	Basement, turbine hall
Date		26.03.2011	27.03.2011	24.03.2011 (22.04.2011)	24.03.2011 (21.04.2011)
Nuclide ($T_{1/2}$) Activity [Bq/l]	Mo-99 (66.0 h)	< NWG [12]	< NWG	< NWG (< NWG)	1.0E+3 (< NWG)
	Tc-99m (6.0 h)	< NWG	< NWG	2.0E+6 (< NWG)	6.5E+2 (< NWG)
	Te-129m (33.6 d)	< NWG	< NWG	< NWG (< NWG)	1.3E+4 (< NWG)
	I-131 (8.02 d)	1.5E+8	1.3E+10	1.2E+9 (6.6E+8)	3.6E+5 (4.3E+6)
	I-132 (2.30 h)	< NWG	< NWG	< NWG (< NWG)	1.3E+4 (< NWG)
	Te-132 (76.3 h)	< NWG	< NWG	< NWG (< NWG)	1.4E+4 (< NWG)
	Cs-134 (2.06 a)	1.2E+8	3.1E+8	1.8E+8 (1.5E+9)	3.1E+4 (7.8E+6)
	Cs-136 (13.16 d)	1.1E+7	3.2E+8	2.3E+7 (4.4E+7)	3.7E+3 (2.4E+5)
	Cs-137 (30.17 a)	1.3E+8	3.0E+9	1.8E+8 (1.6E+9)	3.2E+4 (8.1E+6)
	Ba-140 (12.75 d)	< NWG	6.8E+8	5.2E+7 (9.6E+7)	< NWG (6.0E+5)
	La-140 (40‘272 h)	< NWG	3.4E+8	9.1E+6 (9.3E+7)	4.1E+2 (4.8E+5)

Table . 2-4 Nuclide concentrations in contaminated water in the turbine halls [13]

12 | LOD = limit of detection

13 | Source: /1/

In the course of the emergency measures, the decision was taken to discharge approx. 9’070 m^3 of weakly contaminated water from the central waste treatment plant into the sea because the storage capacities were exhausted. In order to create additional storage capacities, weakly active water in unit 2 was pumped from the condenser in the turbine hall into the condensate storage tank and into the Torus compensating reservoir. From 19 April 2011 onwards, part of the highly active wastewater from the turbine hall and the adjacent shafts and ducts/channels of unit 2 could then be pumped into the central waste treatment plant and the condenser. Thanks to the falling water level, the risk of leakages into the sea or the groundwater was reduced.

Another leak was discovered on the channel of unit 3 on 10 May 2011. It was possible to seal this by 11 May 2011. The outflow calculations produced a volume of approx. 250 m^3 with an activity content of 2.0E+13 Bq.

Furthermore, approx. 1’320 m^3 of low active water was pumped into the sea from the concrete shafts of units 5 and 6 between 4 and 9 April 2011. The total activity of this liquid alone that was discharged into the environment was about 1.5E+11 Bq. By way of comparison, the approved annual amount of discharged activity for Fukushima Dai-ichi is 2.2E+11 Bq (cf. /1/).

The total quantity of activity released into the sea as per /1/ is approx. 4.7E+15 Bq.

Since mid-June 2011, the radioactively contaminated water has been cleaned with the help of specially installed decontamination plants, and has been re-used to cool the reactors (more or less in line with the recirculation principle).

2.5 Summary and assessment

After the loss of all safety barriers provided to retain the radioactive substances (fuel matrix, fuel rod cladding, reactor pressure vessel (RPV) with primary circuit, containment with concrete shield and reactor buildings), fission products were released into the environment on a significant scale from reactors 1 to 3.

The releases took place in the course of various accident progressions in units 1 to 3, and in several phases. For these reasons, the classifications as per INES had to be re-assessed as the progression of the event continued, with adaptations to current developments. The Japanese authorities undertook the assessments required for this purpose by applying evaluated computing codes which are in widespread international use (e.g. MELCOR). These require the input of certain boundary conditions such as fuel burnup, retention in the building, etc.

Likewise, the exact quantities of radioactive substances discharged into the sea are not known. The available figures are based on rough estimates by TEPCO, the operating company, because the precise outflow periods and leaked volumes (especially at the start of the accident) cannot be traced. The aim of the deliberate introduction of radioactively contaminated water into the ocean was to mitigate the consequences of the accident and was necessary in the specific situation.

Since the beginning of April 2011, work has been under way to stem the radioactive releases which still continue to a lesser extent. The destruction and contamination of the plant site caused by the hydrogen explosions are a considerable impediment to this work. Moreover, the simultaneous timing of the accidents in units 1 to 3 poses an enormous challenge in terms of staff and work outlay, as well as interactions between the units.

According to the operating company's current rehabilitation plan, it will take approximately three more years to stem the releases completely and to decontaminate the plant site.

3 Ambient dose rates on the power plant site

3.1 Overview

This section documents the ambient dose rates (ADR) measured during and after the accident on the site of the Fukushima Dai-ichi nuclear power plant.

Due to the earthquake and the tsunami, there were partial failures of the stationary ADR measuring probes. With the help of auxiliary provisions and mobile measuring instruments, it was nevertheless possible to maintain measuring operations. In the course of dealing with the accident, measuring operations were expanded and the stationary probes were returned to operation.

At the start of the accident, the ambient dose rates were severely affected by the radioactive releases during the containment venting operations and the hydrogen explosions. Between 11 March 2011 and 27 March 2011, the progression of the accident led to significantly accentuated dose rate peaks. As measures were taken to cope with the accident, the ambient dose rate then dropped constantly from 27 March 2011 onwards, and it is now dominated by the radioactive deposits on the site and the building structures. Pieces of debris or plant components with particularly high dose rates – known as Hot Spots – are present in large numbers in the plants and on the site, making working conditions for the operational staff even more difficult.
zusätzlich.

3.2 Results and development of the ambient dose rate measurements

Extensive values measured by the operators are available for the plant site. Figure 3-1 shows the permanently installed monitoring posts (measurement points) used to register the ambient dose rate (ADR) in blue. In some cases, the function of these monitoring posts was impaired by the earthquake and/or the tsunami. Damage was inflicted on the power supply, the data lines and the computing units in the main building. Partially, the probes were then supplied from mobile batteries and the measured data were evaluated with the help of portable computers.

Due to new ADR measuring points (temporary monitoring posts) installed during the post-accident phase (shown in red), the scope of data changed. Complete data series are not available for all the monitoring posts because of the problems with the power supply.

At the start of the accident, the measured ADR values originated from the releases during venting from the primary containments of the reactors and from the releases due to the H_2 explosions. Based on the chronology, key events can be assigned to the individual dose rate peaks during the progression of the accident. These are indicated in Figure 3-2, which originates from the Gesellschaft für Anlagen- und Reaktorsicherheit mbH (GRS).

Figure 3-1 Locations of ADR monitoring posts on the Fukushima Dai-ichi plant site [14]

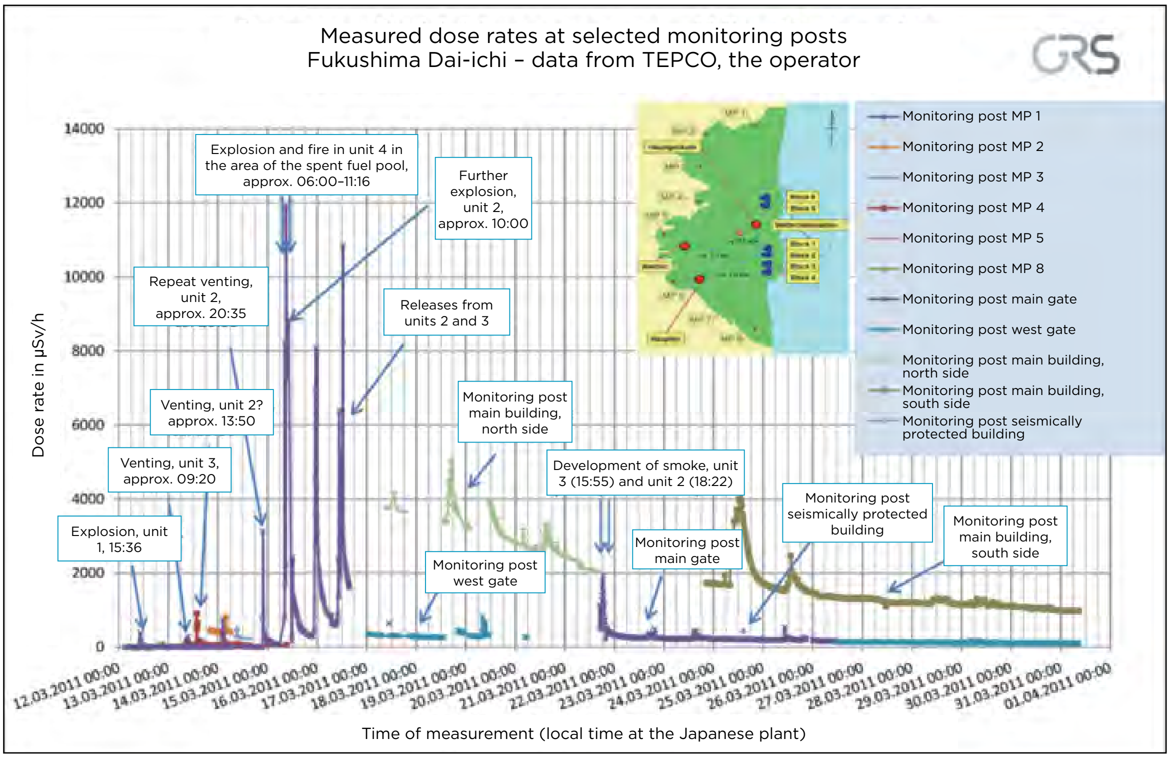


Figure 3-2 Overview of ADR values in the period from 12 to 31 March 2011 [15]

14 | Source: TEPCO http://www.tepco.co.jp/en/nu/fukushima-np/f1/index-e.html
15 | Source: GRS http://fukushima.grs.de/kommunikation-medien/japan-statusmeldung-stand-31-03-2011-1400

The H_2 explosions scattered radioactive debris over extensive areas of the site. In addition, there are numerous Hot Spots (see Figure 3-4) which cannot be easily removed. Moreover, the radioactive substances deposited due to precipitation and other effects lead to increased dose rates on the plant site. The short half life of the iodine nuclides in particular has a favourable effect on the long-term dose rate. Remote-controlled machines are being used to remove contaminated rubble and debris in order to reduce the ambient dose rate. On the other hand, new sources of radiation are created again by the installation of auxiliary equipment to control and reduce the consequences of the accident (e.g. water treatment plants, hoses to pump contaminated water). There are also ongoing releases from the reactors (cf. section 2.2).

The following charts show the ADR values measured by TEPCO with mobile probes (cf. /1/). As measurements were taken at relatively few points on 23 March 2011 – mainly in the area directly surrounding the reactor units (cf. Figure 3-3) – it later became possible to take measurements in most of the areas surrounding the power plant units after the debris had been removed (cf. Figure 3-4).

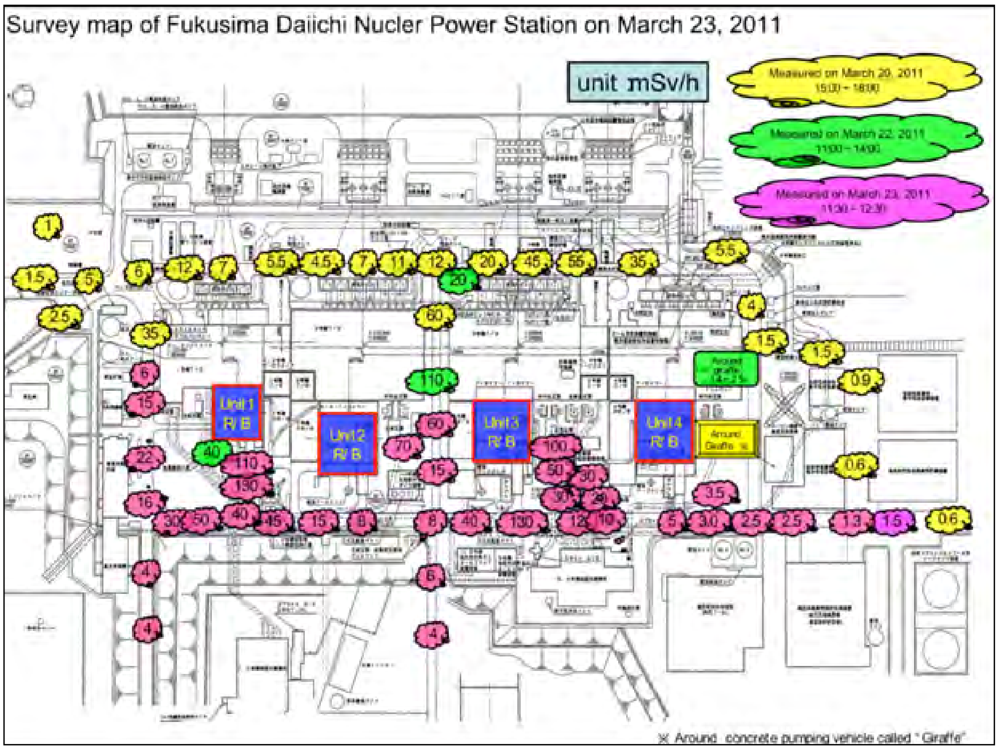


Figure 3-3 ADR values on the Fukushima Dai-ichi site on 23 March 2011 [16]

16 | Source: TEPCO http://www.tepco.co.jp/en/nu/fukushima-np/f1/images/f1-sv-20110323-e.pdf

The reduction in the ADR values in wide areas around the units is clearly recognisable. However, Hot Spots with very high dose rates are repeatedly discovered during the removal of the debris (U1/2 SGTS >10'000 mSv/h) (cf. Figure 3-4).

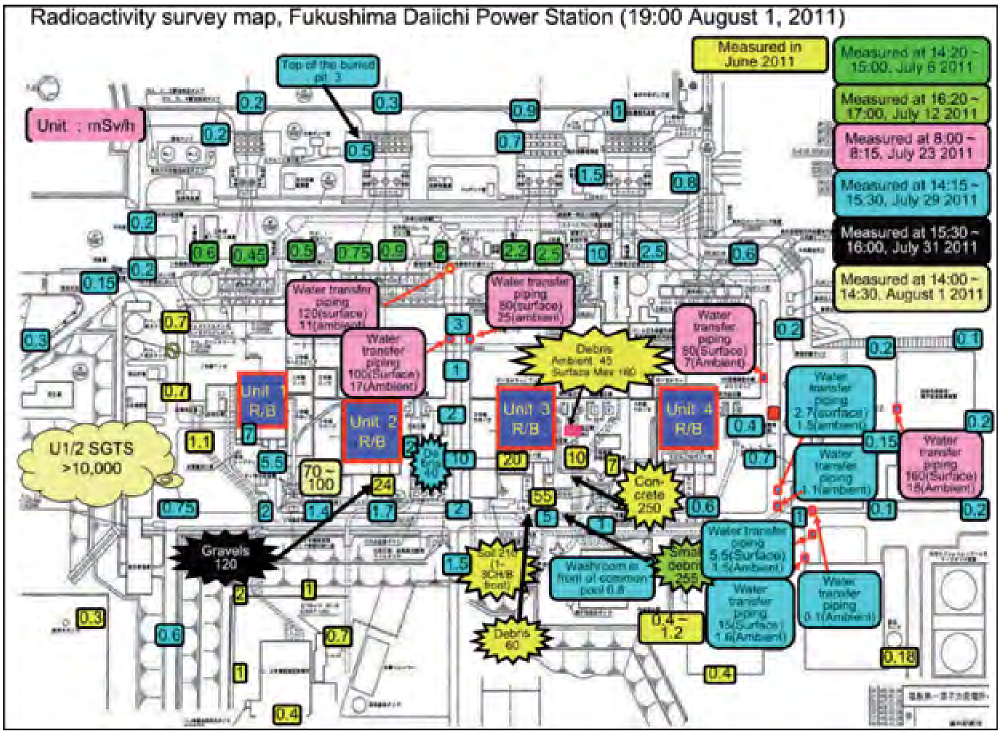


Figure 3-4 ADR values on the Fukushima Dai-ichi site on 1 August 2011 [17]

17 | Source: TEPCO http://www.tepco.co.jp/en/nu/fukushima-np/f1/images/f1-sv-20110802-e.pdf

On 21 May 2011, for example, a dose rate of 1'000 mSv/h was measured in debris near unit 1 (cf. Figure 3-5).

Figure 3-5 Radioactive debris near unit 1 [18]

On 31 July 2011, TEPCO discovered by use of a gamma camera high gamma levels at the bottom of the vent stack shared by units 1 and 2 (cf. Figure 3-6).

Figure 3-6 Base of stack, units 1 and 2, photographed with a gamma camera [19]

On 1 August 2011, measurements were taken at these points with the use of a telescopic detector (cf. Figure 3-7). According to TEPCO, the surface dose rate at the point where the pipes are integrated into the vent stack was >10 Sv/h (cf. /8/). The operator states that this is the highest dose rate yet measured outside the reactor buildings.

The pipes connect the Standby Gas Treatment System (SGTS), also known as the Emergency Gas Treatment System, to the stack.

Figure 3-7 Base of stack between units 1 and 2, measurement with a telescopic detector [20]

18 | Source: TEPCO http://www.tepco.co.jp/en/news/110311/images/110521_7.jpg
19 | Source: TEPCO http://www.tepco.co.jp/en/news/110311/images/110802_2.jpg
20 | Source: TEPCO http://www.tepco.co.jp/en/nu/fukushima-np/images/handouts_110803_01-e.pdf

According to TEPCO, an ambient dose rate >5000 mSv/h was measured on 2 August 2011 on level 2 of the connecting building for the turbine hall (Turbine Building) of unit 1, near the entrance to the so called train room for the emergency gas treatment system (cf. Figure 3-8).

This is the highest ambient dose rate yet measured inside the reactor building. According to /9/, it was detected on pipes that were used to vent unit 1 on 12 March 2011.

3.3 Summary and assessment

There was a major increase in the ambient dose rates inside the reactor units and on the plant site due to the partial lack of water coverage for the reactor cores and the massive releases of radioactive substances from the reactors. Especially at the start of the accident, the workers were confronted with dose rates that no longer permitted work inside the plant, according to the radiation protection rules. Due to the high dose rates, the staff had to leave individual plant areas and (at times) the entire unit on several occasions.

The venting operations for the primary containments and the hydrogen explosions caused widespread distribution of radioactive substances and debris over the plant site. Dose rates, sometimes in the range of several Sv/h, presented enormous obstacles to dealing with the accident and made it necessary to set up restricted zones.

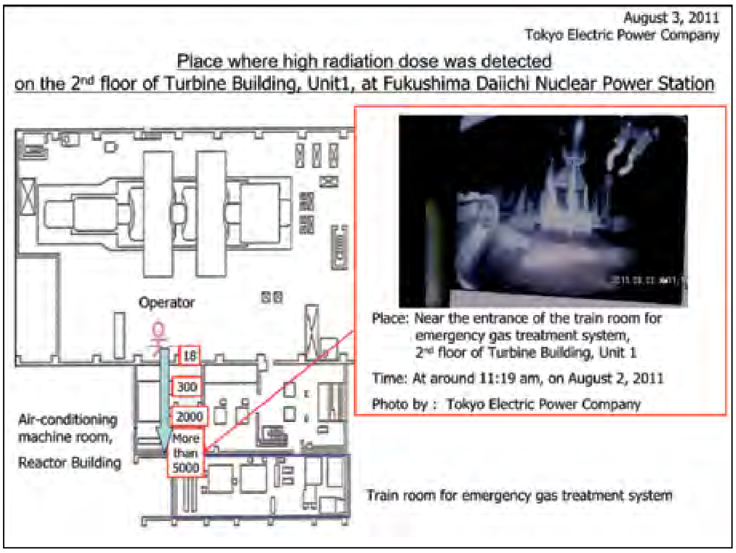


Figure 3-8 ADR values [mSv/h] inside the connecting building for the turbine hall of unit 1 [21]

Even today, the dose rates still impose severe constraints on the clearance work. In some places, the debris can still only be removed remotely.

The ambient dose rate on the plant site has been decreasing steadily since the end of March 2011. This is due to the radioactive decay of the short-lived fission products in particular, the reduced release of radioactive substances from the reactors and the ongoing clearance of debris.

21 | Source: TEPCO http://www.tepco.co.jp/en/nu/fukushima-np/images/handouts_110803_01-e.pdf

4 Radiation exposure and working conditions for staff

4.1 Overview

This chapter presents the radiation exposure which the staff at the Fukushima Dai-ichi nuclear power plant was exposed to from the accident on 11 March 2011 till the beginning of September 2011. All the data listed here is publicly accessible via the Internet.

The earthquake and the tsunami waves (flooding) destroyed not only the structures of the buildings and of the technical systems of the Fukushima Dai-ichi nuclear power plant, but also a large part of the infrastructure for the dosimetry system. The power plant operator and the staff no longer had enough functioning dosimeters at their disposal directly after the tsunami. For this reason, it was impossible to carry out any automatic dosimetry of the staff with Active Personnel Dosimeters (APDs), as normal prior to the earthquake, until about mid-April. Instead, alternative methods were used, such as the calculation of accumulated individual doses by estimating the time spent at the location of action and the ambient dose rate there. Only the leader of each operational group could be equipped with an electronic dosimeter. The radiation dose determined with this dosimeter was assumed as the individual dose for each member of the group. The accumulated doses were read after the assignments, and were entered manually in Excel tables.

Difficulties arose with determining the internal radiation exposure using whole body monitors due to the increased background radiation at the Fukushima Dai-ichi site. The number of persons to be examined was too great, and there was a shortage of whole body monitors.

For the reasons just stated, uncertainty prevails regarding the radiation doses that were actually accumulated. Extensive information about the accumulated individual doses due to external and internal radiation exposure is available on the Internet, but cannot always be interpreted. There seems to be a lack of conclusive data relating to collective doses.

Based on the dose limits stipulated in Japan, the personal dosimetry prior to the accident is compared to that during the response to the accident, and consideration is also given to protective measures and equipment, and to the exceptional working conditions. One of the key points in this chapter is the radiation exposure of people working in the plant during and after the accident, together with reported violations of dose limits. The chapter is completed by information on measures to reduce the doses during work on the plant.

4.2 Dose limits for persons occupationally exposed to radiation in Japan

In Japan, the legally stipulated dose limit for occupationally exposed persons is 50 mSv per year during normal conditions. A maximum of 100 mSv may be accumulated during a five-year period. For women, a maximum limit of 5 mSv during a 3-month period is specified (cf. /39/).

For occupationally exposed persons and who have to carry out emergency work, the effective dose limit is 100 mSv per year. The limit for the dose equivalent for the eye lens is 300 mSv and for the skin 1 Sv per year.

The above mentioned limits are based on the ICRP 1990 Recommendations, Pub. 60 (cf. /35/) and were specified by the Radiation Review Council of the Ministry of Education, Culture, Sport, Science and Technology (MEXT).

In case of a nuclear accident, higher dose limits may be specified if this is necessary in order to deal with incidents. In areas where measures are undertaken to manage a nuclear accident, the effective annual dose can be raised from 100 mSv to 250 mSv from the declaration of the emergency until it is lifted. The emergency was declared on 14 March 2011 and the increase was decided by the Ministry of Health, Labour and Welfare (MHLW) on the next day (cf. /36/). The increase of the limit to 250 mSv was justified on the basis of ICRP 1990 (cf. /35/). The recommendation advises a maximum dose of 500 mSv for persons who participate voluntarily in emergency operations with the aim of preventing worse effects.

The President of the MHLW and the Minister of Education, Culture, Sports, Science and Technology (MEXT) discussed the adjustment of the dose limits in advance with the Radiation Review Council at MEXT and received feedback that such an increase was appropriate.

MHLW has published additional documents for the administrative regulation of radiation exposure for staff who were involved in emergency work at the start and who then carried out different work which entailed exposure to radiation.

4.3 Dosimetric monitoring of plant staff

4.3.1 Status prior to the events of 11 March 2011

Prior to the accident, TEPCO implemented radiation protection measures with the aim of minimising radiation exposure for occupationally exposed persons. At the Fukushima Dai-ichi nuclear power plant, a dosimetry system was in operation to measure radiation exposure during work in the controlled zone; this guaranteed that each person was equipped with an electronic dosimeter (Active Personnel Dosimeter, APD). This system ensures automatic personal allocation of the individual doses and computer-assisted evaluation of the doses.

In addition, the radiation dose of each person was measured as they entered and left the controlled zone. Radiation doses were also recorded individually when donning protective equipment and on reading the APD immediately before entering a controlled zone.

TEPCO regularly carried out measurements to monitor incorporation by the staff, with the help of whole body monitors. These measurements were taken when a person first entered a controlled zone and every three months thereafter.

4.3.2 Changes to dosimetric monitoring subsequent to the accident

4.3.2.1 Measures in the Fukushima Dai-ichi nuclear power plant

When the tsunami waves reached the Fukushima Dai-ichi nuclear power plant and the side of the buildings facing the sea in which the entrances to the controlled zones are located, the dosimetry monitoring system, the reading stations and numerous APDs were flooded and therefore became unusable. According to a report from the Kyodo news agency dated 1 April 2011, 5’000 dosimeters were available to the staff at the Fukushima Dai-ichi nuclear power plant before the accident on 11 March 2011. Only 320 devices were still capable of functioning after the tsunami.

It was no longer possible to equip each individual with an APD directly after the accident. TEPCO therefore decided that instead, each leader of an operational group had to wear a dosimeter. The radiation dose registered by this dosimeter was assumed as the individual dose for each member of the group. After TEPCO was asked by NISA to undertake every necessary effort in order to individually record and monitor the radiation exposure for the staff, TEPCO procured enough dosimeters (from 1 April 2011 onwards) so that every person could again be equipped with a personal dosimeter.

Due to the rising level of radiation and contamination on the power plant site, the staff were ordered to remain in an earthquake-resistant building (Main Anti-Earthquake Building) on the plant site when not engaged in operations. The work assignments were to be prepared, the APDs were to be distributed and the accumulated radiation doses were also to be recorded in this building.

At the outset, staff dosimetry and the recording of radiation doses had to be carried out by hand. The results of the radiation dose measurements had to be typed into Excel tables manually so that they could be stored in a database.

APD's were not worn in the Main Anti-Earthquake Building. For this reason, the external radiation exposure there was determined on the basis of the time spent in the radiation field and the ambient dose rate (ADR); likewise, suitable protective equipment (such as protective masks) was not worn there, although the air contamination in this building exceeded the limits (cf. /37/). This led to incorporations and to violation of the three-month limit for two female workers.

On 14 April 2011, it was possible to commission a new dosimetry system which was almost identical to the previous system (automatic recording of names and radiation doses). Work on the restoration of the regular dose monitoring system was then virtually completed.

As the whole body monitors could not be used in the Fukushima Dai-ichi nuclear power plant due to the increased background radiation, mobile whole body monitors were made available. In addition, the operational staff was taken to other plants for radiation protection checks and incorporation measurements. Due to the large number of persons to be monitored, TEPCO decided to measure individuals with high external radiation doses and those involved in emergency work during March as a priority.

Later the Japanese government in its no. 12 of the Lessons Learned (cf. /11/) called for measures to improve the radiation protection system in case of an accident,. Among other things, there is a recommendation for cooperation by operators subject to instructions from NISA, with the aim of establishing continuous personal dosimetry even in case of accidents. In addition, rules were defined to guide the radiation protection staff regarding the relevant tasks to cope with the emergency. These measures aim to ensure maintenance of radiation protection in case of emergencies. In order to attain this goal, training of staff in accomplishing radiation protection tasks during emergencies should be encouraged.

4.3.2.2 Measures in “J Village”

From 17 March 2011 onwards, the “J Village”, a TEPCO sports facility about 20 km south of the Fukushima Dai-ichi nuclear power plant, was also used to make preparations for operational assignments in the nuclear power plant. Among other activities, protective suits were donned here and decontamination tests were carried out.

A dosimetry system was established in “J Village” for personnel of the Fukushima Dai-ichi nuclear power plant who were exposed to radiation in the course of their work and who were unable to enter the earthquake-resistant building in order to obtain their APDs there. The dosimeters used in “J Village” were of different designs; they were made available at short notice by several organisations. By the daily return to “J Village”, the accumulated radiation doses had to be collected and registered manually. Since the start of June 2011, TEPCO has operated a barcode system for individual identification.

In August 2011, TEPCO transferred the whole body monitors from Fukushima Dai-ichi and Fukushima Dai-ni to “J Village”. A new whole body monitor for “J Village” was also procured.

4.3.2.3 Radiation protection equipment and planning of work

It was difficult to prevent the penetration of radioactive substances into the “Main Anti-Earthquake Building” because the entrance door was not designed to be airtight and the H_2 explosions in units 1 and 3 had caused damage to the door. Moreover, no special protective equipment was installed in order to mitigate the consequences of a nuclear accident. Persons present in this building therefore incorporated radioactive substances. As a countermeasure, a separate ventilation plant with active carbon filters was finally set up in the entrance zone in order to reduce airborne activity in the building. TEPCO considered that no additional measures were necessary.

For work in areas with high dose rates, work plans with appropriate radiation protection measures were drawn up. The staff was also informed about the radiological situation.

4.4 Status of radiation exposure

Assignments at the location of the accident and in its immediate vicinity caused and still causes a significant radiation exposure for all operational staff. The staff consists of external and internal members. In addition to the plant's own staff, third-party personnel from external companies and people from deployment organisations (army, police, fire brigade, etc.) were operational.

4.4.1 Army and police units

The deployment personnel (Self-Defense Forces of Japan) working within the 30 km zone around the Fukushima Dai-ichi nuclear power plant assessed their radiation exposure prior to deployment on the basis of the latest ADR values at the operational location and the planned time of the operation. The protective equipment was selected accordingly. The deployment personnel also used dosimeters to register their accumulated radiation exposure. The limit for the accumulated individual dose is 50 mSv per year, i.e. the same as for persons exposed to radiation during the course of their work.

If an individual dose of 30 mSv is attained during the deployment, the deployment is interrupted so that a buffer is available in order to withdraw from the operational location. For female deployment personnel, on-site deployment is interrupted in a similar manner at 3 mSv (the limit for female deployment personnel is <5 mSv per quarter). The maximum individual dose is specified as 250 mSv for emergencies and life-saving operations. Women are not allowed to take part in assignments of this sort. According to the available information (cf. /1/), no deployment personnel exceeded the aforementioned dose limits.

As of 22 March 2011, 19'703 US air force personnel and marines were deployed in Japan as part of Operation Tomodachi to provide humanitarian aid and to manage the disaster (cf. /38/). No precise information is currently known regarding the number of US military personnel deployed at Dai-ichi, the proven contamination of individuals, the surface contamination measured in the plants and the accumulated radiation doses for the persons involved.

4.4.2 Fire brigades

The maximum individual doses for members of the fire brigade are specified in the fire brigade manual ("Operation Measure Manual of the Fire and Disaster Management Agency"). This manual defines the upper limit for live-saving operations as 100 mSv, with alarm limits of 30 to 50 mSv. A maximum of 100 mSv may be accumulated during a five-year period, with a maximum annual dose of 50 mSv.

In case of an operation within the 20 km radius around the Fukushima Dai-ichi nuclear power plant, the operation-specific dose limits are specified by the fire brigade command centre, taking account of the data mentioned above and with minimisation of radiation doses in mind.

4.4.3 Plant staff and external workforce

By 23 May 2011, about 7'800 persons were involved in the emergency work at the Fukushima Dai-ichi nuclear power plant. Until then, the average individual dose due to external radiation exposure was approx. 7.7 mSv. 30 persons had accumulated individual doses of more than 100 mSv (cf. Figure 4-1).

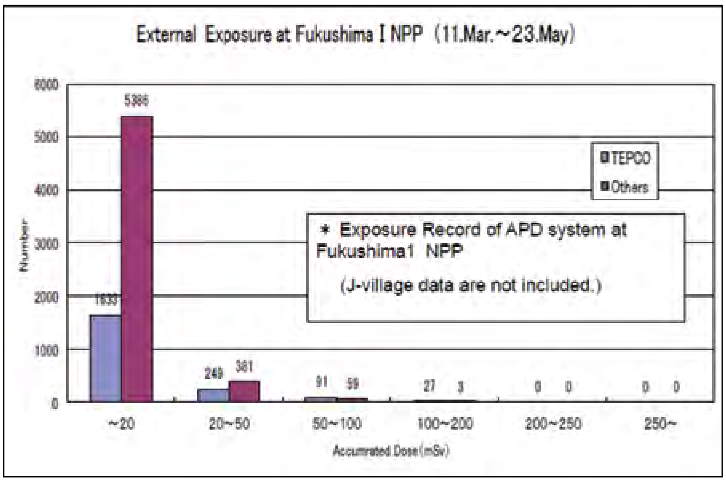


Figure 4-1 Distribution of accumulated radiation doses, 11 March until approx. 23 May 2011 [22]

22 | Source /1/

External and internal radiation exposures taken into account, 3'715 persons had accumulated an average individual dose of 22.4 mSv, according to a report by the Japanese government /1/. In April 2011, 3'463 persons had accumulated an average individual dose of 3.9 mSv and in May 2011, 2'721 persons had accumulated an individual dose of 3.1 mSv on average (cf. Figure 4-2).

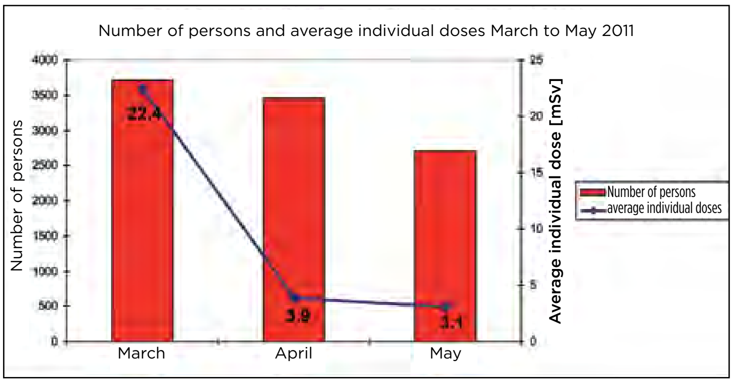


Figure 4-2 Number of persons and average individual doses, March to May 2011

According to the follow-up report by the Japanese government /11/, about 9'900 persons working at the Fukushima Dai-ichi nuclear power plant had been examined for external and internal radiation exposure by 10 August 2011. 103 persons (84 from TEPCO's own staff and 19 third-party staff) have accumulated individual doses of more than 100 mSv. If the external radiation doses for the period from March to July 2011 and the internal radiation doses for the period from March to May 2011 are totalled, the result is an average dose of 10.4 mSv. The maximum individual dose is approx. 672 mSv.

According to information from JAIF (cf. /42/), the dose values of 10 August 2011 were updated by TEPCO. As of 30 September 2011, therefore, out of about 14'800 persons who had been examined up to then, 99 had accumulated an individual dose of more than 100 mSv (100-150 mSv: 77 persons (as of 10 August 2011: 81); 150-200 mSv: 14 persons; 200-250 mSv: 2 persons; >250 mSv: 6 persons). The observed differences (decrease from 103 to 99 persons with a dose of more than 100 mSv) are plausible given the measurement accuracy of personal dosimetry.

4.4.4 Violation of dose limits and potential causes

TEPCO employees have accumulated radiation doses above the limit of 250 mSv. At the time of the H_2 explosions in units 1 and 3, they were mostly carrying out work in the main control rooms (MCR). Because the doors were destroyed, contaminated air was able to reach the main control rooms and, because work was undertaken without protective masks in some cases, led to incorporations.

The following factors may have played key parts for the incorporations of six persons (three operators and three persons from the maintenance staff):

- The accident occurred unexpectedly and quickly, so there was little time to adapt to the necessary radiation protection measures.
- The persons in the control room occasionally removed their masks in order to eat and drink.
- In the case of two persons wearing glasses, it is possible that the masks did not always seal tightly.
- Two persons “lifted” their masks for a short time so that they could work better.
- Four persons were working near the emergency door of the control room, where airborne activity was very high.

On 24 March 2011, two persons sustained heavy contamination on their feet while laying cables in the turbine hall of unit 3, where contaminated water was present at this time. The footwear worn during this work was too low, so the skin on their feet was contaminated by the water. As a consequence, there was a risk of so called “Beta-Burns”. TEPCO immediately implemented decontamination measures, and the affected persons were transported to the Fukushima Medical University Hospital where NISA also carried out checks. A follow-up examination on 11 April 2011 did not establish any acute effects on health. The resultant radiation exposure on the feet of the affected individuals amounted to an equivalent dose for the skin of 2 to 3 Sv.

After an evaluation of the radiation doses, TEPCO confirmed on 27 April 2011 that the radiation dose for one female was over 5 mSv (the limit for occupationally exposed females in order to protect unborn life) for a period of three months (January – March).

On 22 April 2011, it was confirmed that one female had accumulated an effective dose of 17.6 mSv. Of this, an internal radiation dose of 13.6 mSv was caused by inhalation as she removed her protective clothing. On 1 May 2011, it was determined that a second female had an effective dose of 7.5 mSv. Medical examinations of these two women showed that no health risks were present for unborn life (cf. /41/).

4.4.5 Exceptional radiation exposures

Dose rates of up to 700 mSv/h were measured at some places in the reactor building of unit 1 at Fukushima Dai-ichi where repair work had to be carried out. With such a dose rate, the staff may only work on site for about 20 minutes. Staff who measured the dose rates accumulated an individual dose of up to 11 mSv in about 30 minutes.

After the explosion on 15 March 2011, staff entered the reactor building of unit 2 for the first time on 18 May 2011. Four persons in protective clothing, including breathing protection (compressed air cylinders) had the task of investigating the radiological situation and collecting other relevant data. They accumulated radiation doses of between 3 and 4 mSv per person.

On 19 May 2011, staff entered the reactor building of unit 3 for the first time after the explosion of 14 March 2011. Two persons, wearing protective equipment and breathing protection (compressed air cylinders) stayed in the building for about ten minutes in order to take radiation protection measurements. They measured ambient dose rates of up to 170 mSv/h. These two persons accumulated individual doses of between 2 and 3 mSv while taking these measurements.

In the thyroid glands of two persons who were working in the control rooms of units 3 and 4, but also at other locations, 9'760 Bq and 7'699 Bq of iodine-131 (respectively) were measured.

These values are about 10 times as high as those for other persons who were on operational assignments during the accident. In addition, the two persons accumulated external radiation doses of 74 and 89 mSv respectively. It must be assumed that the external and internal radiation doses led to more than 250 mSv per person. Both the affected individuals had no previous health problems. No results from biological dosimetry (blood counts to detect chromosome changes) are available.

One person forgot to place the filter on the full protection mask for about two hours while working on the nuclear power plant site in the open air. The external radiation exposure was 0.5 mSv. TEPCO is investigating whether this could be due to deficient safety measures.

TEPCO is unable to indicate the current whereabouts of 198 persons who worked in the Fukushima nuclear power plant following the accident of 11 March. MHLW asked TEPCO to locate these persons and to examine them for radiation exposure. In a report, TEPCO stated that the 198 persons could not be found, but at the same time confirmed that they were entered in the lists of names of the nuclear power plant for March and April 2011.

TEPCO reports that two persons were unintentionally sprayed with heavily contaminated water from the water treatment system which is used to purify water that accumulates in the reactor buildings. One person accumulated 0.2 mSv and was decontaminated. The second person, who was wearing a raincoat, accumulated 0.1 mSv. TEPCO states that neither of the two persons incorporated any radioactive substances due to this incident.

4.5 Dose reduction measures

4.5.1 Measures to monitor and reduce radiation doses

In their respective supervisory reports, MHLW and NISA (the supervisory authorities) issued several instructions and requests to TEPCO for the purpose of reducing the radiation exposure of persons on the power plant site. The following countermeasures were ordered on 6 June 2011 in order to prevent violations of the limits during activities to deal with the accident:

- If the whole body measurement shows that a person's internal radiation exposure exceeds 100 mSv, further work in the plant is prohibited for the work colleagues of the individual who was examined until the results from whole body measurements are also available.

- Each person with an individual dose above 170 mSv may only undertake work in the Main Anti-Earthquake Building.

It was also determined that several persons had not been correctly reported as having been exposed to radiation in the course of their work. NISA warned TEPCO on account of this error, and requested a review of the procedure for radiation protection monitoring at the Fukushima Dai-ichi nuclear power plant. On the basis of the results, the operator's company had to initiate appropriate countermeasures to exclude the possibility of a repetition.

A report had to be submitted to NISA on this matter. After reviewing the report, NISA issued the following instructions to TEPCO on 25 May 2011:

- Periodic reports must be submitted regarding the procedure for internal and external dose monitoring for the assigned staff, and the implementation of temporary medical checks, as specified in /40/.

- Special emergency work must be notified in advance to the "Labor Standards Inspection Office" so that monitoring of radiation exposure can be supervised.

- A database must be set up in which the radiation doses for persons who took part in emergency work can be tracked over a lengthy period. Onward tracking must also be possible in cases where persons who carried out emergency work change their job. It must also be possible to track the state of health of these persons over the long term.

At both nuclear power plants, Fukushima Dai-ichi and Dai-ni, the radiation doses due to work on dealing with the emergency were added to those arising from normal activities. The dose limit was set at 250 mSv (see section 4.2). This also applies to staff who were not previously registered and employed in the nuclear power plants but who are now assigned to emergency work.

Persons designated as not occupationally exposed persons were working in the Main Anti-Earthquake Building, so a procedure to classify them as occupationally exposed had to be developed subsequently. The persons to be so designated were entered in lists. In the course of the process, these persons were recognised and officially registered, and from then on were monitored for external and internal radiation exposure. Checks with a whole body monitor are still specified if these persons no longer undertake any work as persons exposed to radiation in the course of their work.

The persons working in the Main Anti-Earthquake Building included four female employees designated as not occupationally exposed persons. Two of these women accumulated about 3.4 mSv. In Japan, the limit for not occupationally exposed person in the course of their work is 1 mSv per year. ENSI assumes that these persons were subsequently classified as "occupationally exposed". This reclassification would then mean that there were no further violations of the limit.

Staff is informed about their individual radiation exposure each month. If a guidance value (see below) is exceeded, the following measures are implemented:

- If 100 mSv is exceeded: external radiation exposure > whole body measurement to determine incorporation;
- If 150 mSv is exceeded: external radiation exposure > review of further work;
- If 200 mSv is exceeded: external and internal radiation exposure > no further work may be undertaken in the radiation field.

TEPCO has implemented the following improvements in recent months:

- Dosimetry system: new organisation and more staff to monitor radiation doses;
- Individual identification system, barcodes;
- Whole body measurements, more whole body monitors with better access;
- Use of robots in areas with high dose rates;
- Training of radiation protection staff, training for 4'000 persons is planned.

Active carbon filters have been installed in the ventilation systems of main control rooms. In addition, special areas have been identified where material and equipment must be checked for contamination.

Because dose limits were exceeded for two female employees (see above), all women have been prohibited from working in the Fukushima Dai-ichi nuclear power plant since 23 March 2011 until further notice.

Temporary sleeping accommodation has been provided for about 1'600 persons. This has been used by staff since the end of June. The installation of several waiting rooms and rest rooms with air conditioning was completed between April 2011 and June 2011.

Work was suspended on account of the heat between 2:00 o'clock p.m. and 5:00 o'clock p.m. in July and August 2011.

Doctors are available to the staff round the clock.

4.5.2 Measures in the Main Anti-Earthquake Building

The ambient dose rate on the site of the Fukushima Dai-ichi and Dai-ni nuclear power plants increased due to the release of radioactive substances. As a consequence of the ambient dose rates measured on the Dai-ichi nuclear power plant site, the entire operational site was classified as a controlled zone. At the Fukushima Dai-ichi nuclear power plant, the staff must wear Tyveks (synthetic paper overalls) and gloves as protection against contamination. This should also prevent radioactive substances from being spread into the Main Anti-Earthquake Building. Protective masks must be worn as soon as airborne activity exceeds the reporting thresholds. Depending on the weather conditions and the contamination level, additional protective equipment must be worn.

The Main Anti-Earthquake Building was initially regarded as a non-contaminated zone. This is why no activity measurements were done inside the building before 24 March 2011. On 3 April 2011, the contamination levels for air contamination exceeded the statutory limit (1E+3 Bq/m^3, average value over three months), so the building could no longer be regarded as outside the controlled zone. Since then, radiation protection checks and the wearing of protective equipment have been stipulated. Air extraction systems have been installed in the Main Anti-Earthquake Building and in the sanitary facilities and rest areas. Cleaning work is undertaken on a continuous basis.

Conditions in the Main Anti-Earthquake Building are being continuously improved by additional measures:

- Installation of active carbon filters;
- Installation of lead shielding;
- Setting up a temporary buffer zone to prevent the spread of contamination (security entrance with lock);
- Removal of carpet which is difficult to decontaminate;
- Installation of floors and surfaces that can be decontaminated.

This work is planned on the basis of detailed advance investigations (e.g. regarding the radiological situation). The staff is kept constantly informed regarding safety issues. Radiation exposure is kept as low as possible by closing off areas with increased dose rates. Additional instruction on radiation protection has been provided for the staff. Since the accident, the ambient dose rate (ADR) values on the site and in the Main Anti-Earthquake Building have fallen to about one tenth of the maximum values. So far, no damage to the health of staff has been identified due to the incorporation of radioactive substances.

4.6 Summary and assessment

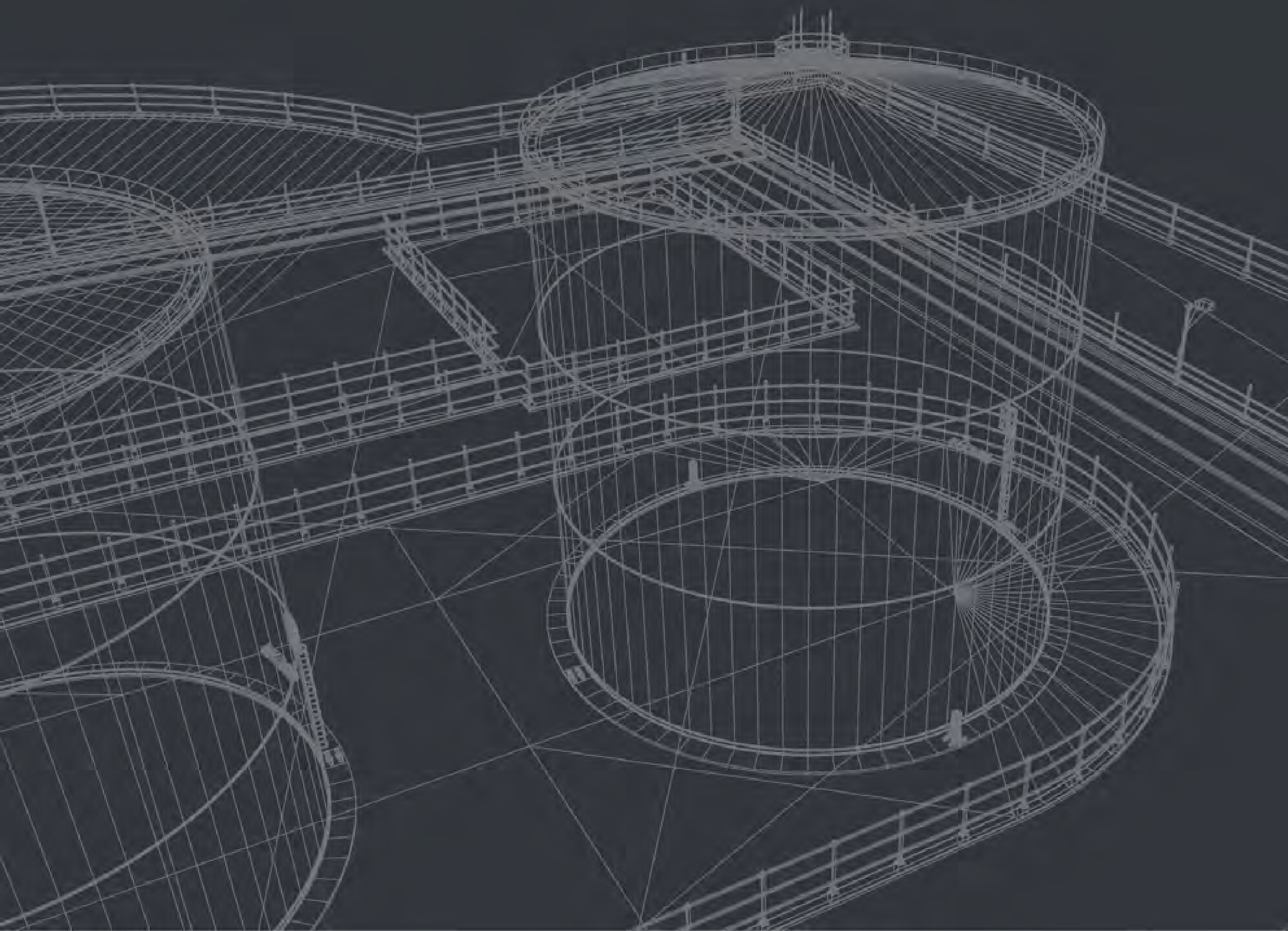
The reports by governmental authorities and by the operator indicate that personal dosimetry did not function as usual in the first hours and days of the accident. More than two thirds of the necessary personal dosimeters were missing. Shortcomings are particularly evident regarding dosimetry for incorporations. It is striking that the triage monitors (hands-/feet-clothing) and whole body monitors were unable to supply reliable measurements on account of the high background radiation at the accident location. Given the severity of the accident, however, the radiation exposure for the plant's own staff and third-party personnel proves to be moderate. There have been no deaths from radiation and no cases of persons with a radiation syndrome. In this context, it would be interesting to note the results of biological dosimetry (blood counts for chromosome changes) for persons with a dose of more than 100 mSv. After the dose limit was set at 250 mSv due to the accident, as is usual both internationally and in Switzerland, six persons with limit violations were identified. This total does not include the two women for whom the applicable limit (for them) of 5 mSv in three months was exceeded.

Since the accident, radiological working conditions in the premises of the plant and on the Fukushima Dai-ichi power plant site differ greatly from the status quo. The measures that were initiated also show that even in the event of such a serious accident, there are still numerous possibilities for reducing doses and for the effective prevention of incorporation and skin contamination, provided that the protective equipment is utilised consistently. In case of an accident involving release of activity, the outlay of staff, materials and equipment for radiation protection is many times higher than during normal operation. This suggests the conclusion that more reserves for accidents than was previously assumed must be kept in readiness in these areas.

Experience gained at Fukushima yields many indications that could also be relevant for the improvement of radiation protection in Switzerland. ENSI has already presented corresponding checkpoints for personal dosimetry and operational radiation protection (cf. /49/). The practical training of persons with radiation protection tasks will have to give more consideration than so far to behaviour in the case of extensive and very high air and surface contamination.

Fukushima

37° 25‘ 26.57“ N, 141° 1‘ 56.87“ E
11.03.2011



5 Radiation exposure of the population in the surrounding area

5.1 Overview

Radioactive substances that are released to the environment in the case of an accident such as the one at Fukushima Daiichi contribute to radiation exposure for the population in the surrounding area via various pathways (cf. Figure 5-1). In the first phase after an accident (known as the cloud phase), it is mostly the external irradiation from the radioactive cloud passing-by and the incorporation of radioactive substances via the respiratory tract (inhalation) that make the main contributions to the dose (cf. sections 5.6 and 5.7). In the subsequent ground phase, radioactive substances deposited on the ground result in a further long-term contribution to the dose by means of external irradiation (cf. section 5.2). The radioactive decay of the substances and their penetration into lower soil levels (which causes shielding of the radiation) causes this dose to decrease continuously over time.

Radioactivity that is either deposited directly on forage crops and vegetables or which penetrates the soil and reaches the plants there via their roots (cf. section 5.3) represents another significant dose source through the consumption of food (ingestion).

Fluid discharges into surface water (rivers, lakes) may contaminate the drinking water reservoirs and consequently cause exposure to radiation via the drinking water supply (cf. section 5.4). In addition, radioactivity from lakes, rivers and the sea reaches the human food chain via fish and seafood (cf. section 5.3 and section 5.5, respectively).

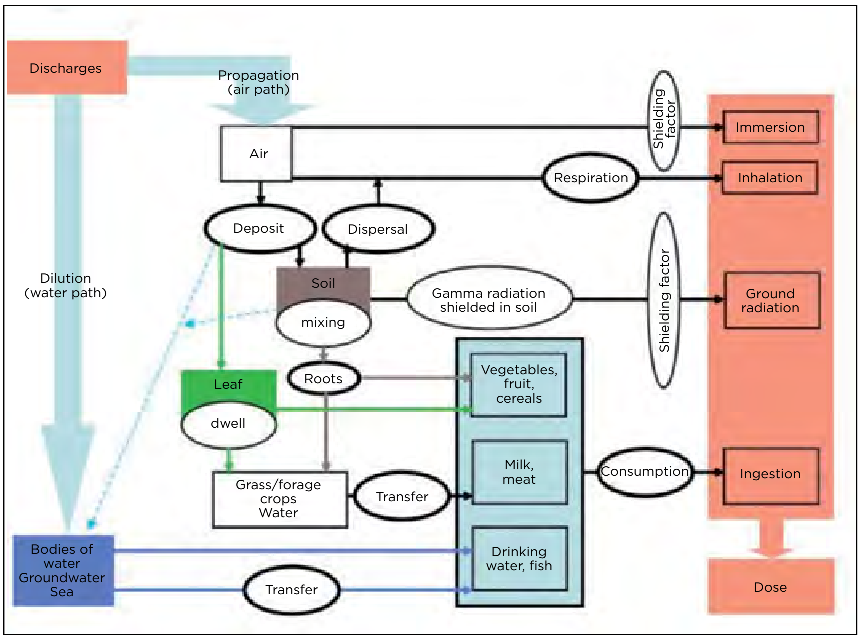


Figure 5-1 Schematic view of the main dose paths that contribute to radiation exposure in the area surrounding a nuclear plant [23]

23 | Source /10/ with the addition of the sea and groundwater paths

5.2 Deposits of radioactive substances on the ground

5.2.1 Weather situation

The main discharges from Fukushima Dai-ichi from 15 March 2011 onwards were largely the consequence of the explosion in unit 2, as Figure 3-2 illustrates. On the evening of 15 March, there were prevailing winds from a south-easterly direction at an altitude of 100 m above the power plant site; and during the night from 15 to 16 March 2011, repeated precipitation (rain or snowfall) was recorded downwind (cf. Figure 5-2, top). As a result, there were substantial deposits of radioactive iodine and cesium isotopes (Cs-134 and Cs-137) in aerosol form in a north-westerly direction, at distances of up to about 50 – 60 km from the site (cf. Figure 5-2, bottom). By comparison, there were significantly smaller deposits of radioactive substances to the north, in the south-western quadrants and in particular along the coast.

In the course of 16 March 2011, the wind veered westerly again so the radioactive discharges from the site were conveyed over the Pacific Ocean.

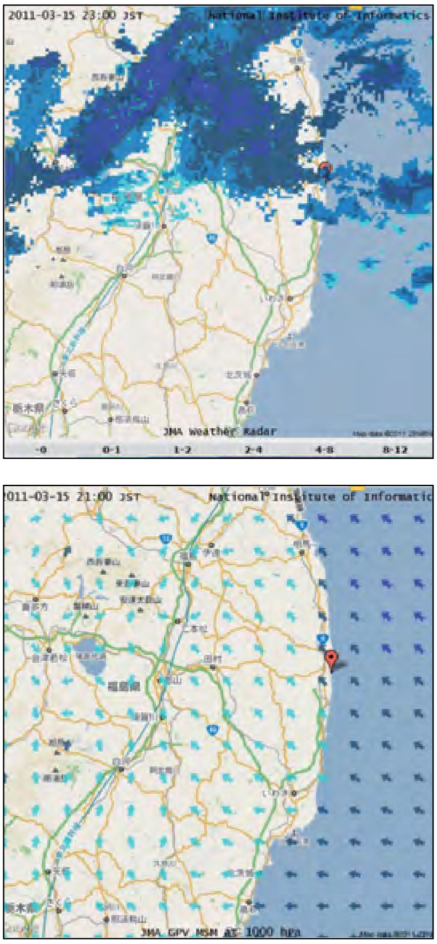


Figure 5-2 Figure 5-2 Weather situation on the evening of 15 March 2011 in the area surrounding the Fukushima Dai-ichi nuclear power plant [24]

In addition to the usual routine programme, various official and private bodies launched an extended environmental measurement programme in the area surrounding the nuclear plant after the release of radioactive substances in order to determine the ambient dose rate (ADR) and the locally deposited activity on the ground and in the soil causing the ADR. This programme was coordinated by MEXT and included regular ADR measurements at various points inside and outside the prohibited zone around the plant. In addition, extensive aeroradiometric measuring flights were carried out in collaboration with the U.S. Department of Energy (DOE) (cf. section 5.2.2). Furthermore, the concentrations of activity in the soil and their progression over time were determined by direct sampling and nuclide-specific evaluations (cf. sections 5.2.3 and 5.2.4).

24 | Source: Japan Meteorological Agency (JMA) http://www.jma.go.jp/jma/en/menu.html

5.2.2 Ambient dose rate due to activity deposits on the ground

The ADR values measured in the area surrounding the Fukushima Dai-ichi nuclear power plant were mainly caused by theIodine isotope I-131 at the outset. This largely decayed in the meantime due to its relatively short half life of 8.02 days, therefore since the end of April 2011, it are primarily the two Cesium isotopes Cs-134 (half life of 2.06 years) and Cs-137 (half life of 30.17 years which give rise to the ADR.

Very soon after the accident, MEXT collaborated with the U.S. DOE to carry out measuring flights to provide cartography for the ambient dose rates. A map indicating the results for 29 April 2011, i.e. about one and a half months after the accident, is shown in Figure 5-3. This figure also contains maximum values for the activity concentration of Cs-137 in the soil and the seawater for several selected points.

The map clearly shows the trail of deposits resulting from the radioactive discharges, which mostly originated from reactor unit 2 on 15 March 2011. In the area shaded in red, the ambient dose rate (caused primarily by Cs-134 and Cs-137 at this time) was over 19 µSv per hour or approx. 200 times the background radiation. A person continuously present in the open air in this zone would

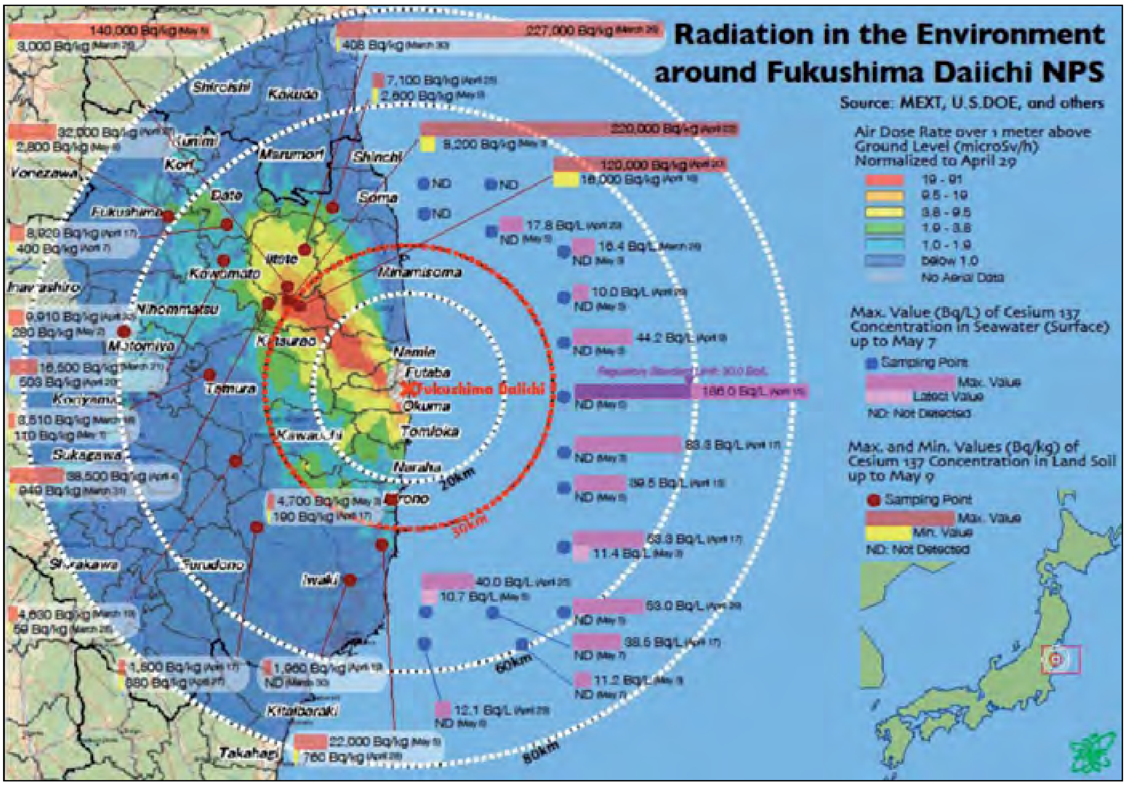


Figure 5-3 Ambient dose rates in the area surrounding Fukushima Dai-ichi on 29 April 2011, selected activity concentrations in soil and seawater [25]

25 | Source: JAIF http://www.jaif.or.jp/english/news_images/pdf/ENGNEWS01_1316677149P.pdf

accumulate a dose of well over 100 mSv due to external irradiation in the course of a year. In the yellow area, this annual dose would still be about 20-50 mSv. The red, orange and yellow zones extend to the north-west for about 40-50 km, i.e. significantly further than the 20 km radius from which the population was evacuated as a first step immediately after the accident. The area in question was subsequently evacuated for this reason (cf. section 5.6) in order to comply with the limit for the yearly dose. Conversely, there are some areas within the 20 km radius (especially along the coast to the north and south of the site) where the external radiation during one year would lead to doses of less than 5 mSv.

The aeroradiometric measurements were extended and refined until the end of July 2011 (cf. Figure 5-4). As was to be expected, the ADR fell marginally as time went on, as can be seen from the slightly smaller size of the areas with specified contamination. This can be explained by the penetration of radioactivity into the soil, leading to a somewhat higher shielding of external ionising radiation. On the other hand, the decrease due to radioactive decay is hardly significant ($T_{1/2}$ of Cs- 137: 30.17 a). At distances of more than 75 km from the power plant site, only isolated instances of increased ADR values can be measured as compared to the background (in Switzerland: typically about 0.1 μSv/h).

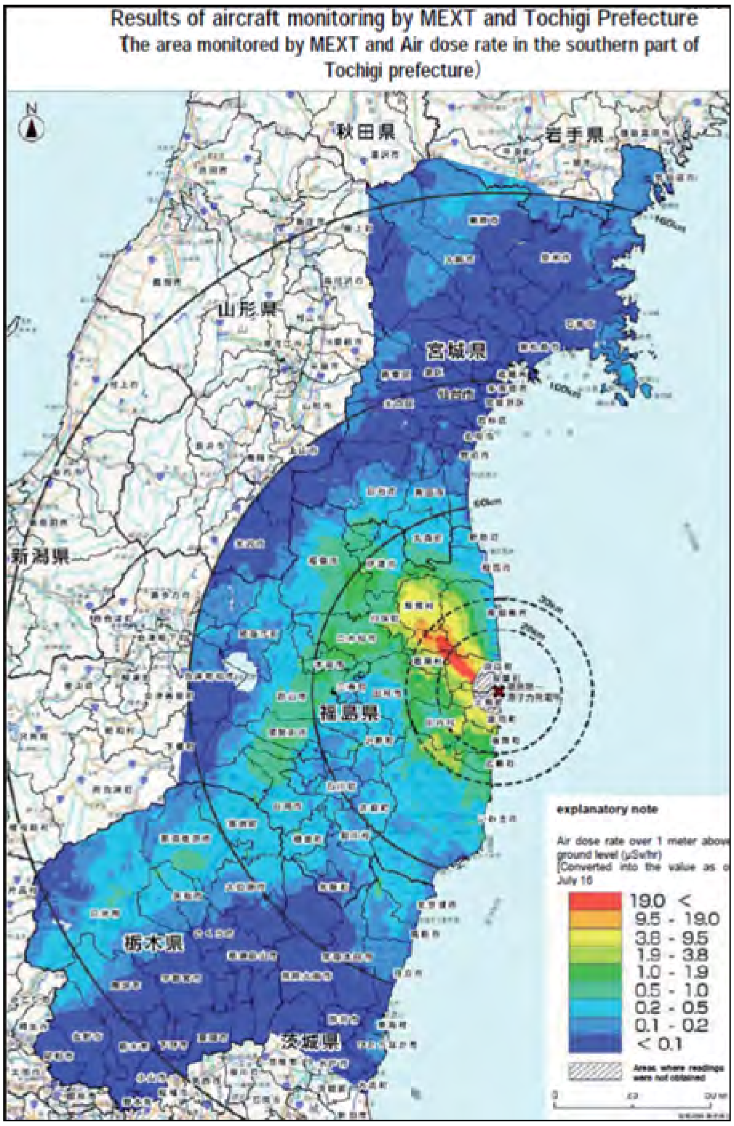


Figure 5-4 Ambient dose rate in the area surrounding Fukushima Daiichi, extended and refined measurement for July 2011 [26]

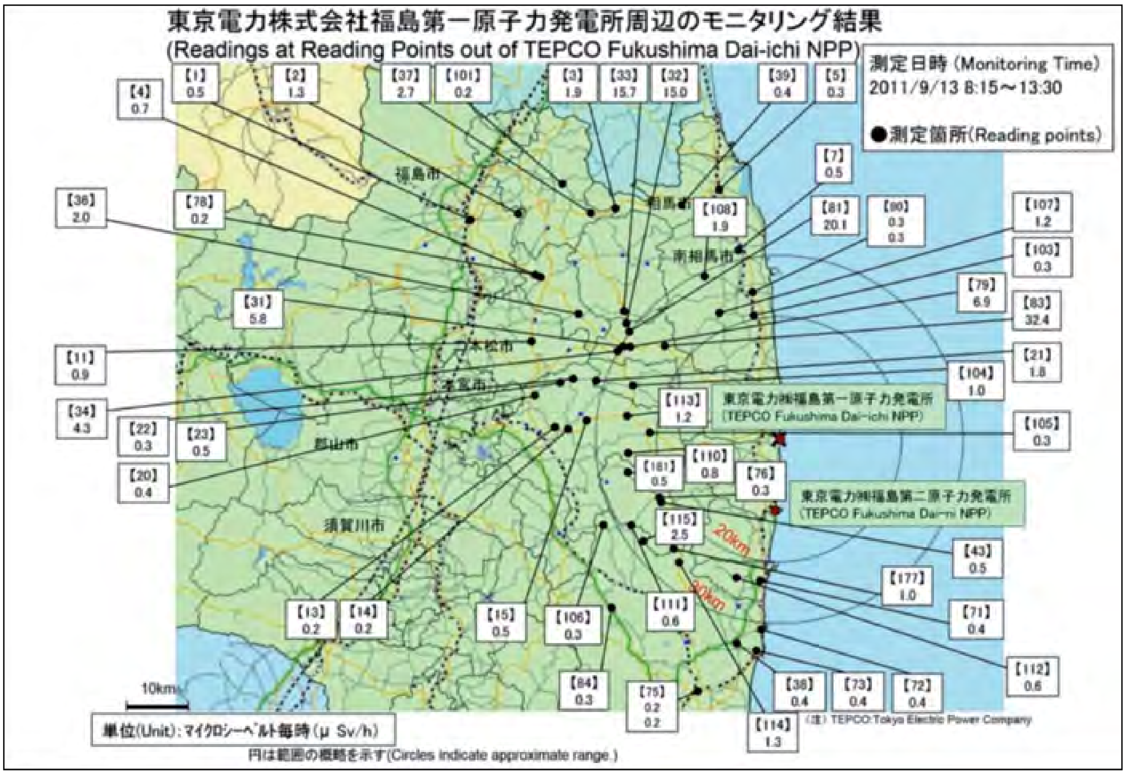


Figure 5-5 Defined monitoring posts for regular determination of the ambient dose rate outside the 20 km prohibited zone (data in μSv/h) [27]

As well as the aeroradiometric measurements – which allow a comprehensive overview of the ADR in the surrounding area , and hence the deposited radioactivity – measurements coordinated by MEXT were taken at a large number of monitoring posts inside and outside the 20 km prohibited zone from about 17 March 2011 onwards. Figure 5-5 provides an overview of the monitoring posts outside the prohibited zone. The values measured on 13 September 2011 are entered in the chart by way of example.

27 | Source: MEXT http://radioactivity.mext.go.jp/en/monitoring_around_FukushimaNPP_monitoring_out_of_20km/2011/09/13511/index.html

The progression of the ADR between 17 March 2011 and the start of September 2011 is shown in Figure 5-6 for all the monitoring posts; Figure 5-7 shows the progression for the five monitoring posts with the highest ambient dose rates values after the accident.

In the first phase, the ADR was dominated by radiation from iodine-131. From mid-April 2011 onwards, however, this iodine, which has a short half life of 8.02 days, had decayed to such an extent that the measured ADR was now caused almost entirely by Cs-134 and Cs-137. As time went on, the ADR only decreased slightly; this decrease was primarily due to the penetration of these nuclides into the soil and the resultant shielding. The model calculation for monitoring post 32 shows the ADR progression that would have been expected taking account of radioactive decay only. It is apparent that the radionuclides must already have penetrated the soil very quickly in the first phase. However, the substantial daily fluctuations suggest that the measurements were not always taken at exactly the same measuring point or under identical measuring conditions (measuring instruments, etc.).

The measurement results at the monitoring posts on the ground correlate very well with the aeroradiometric measurements presented above, within the expected range of accuracy.

Figure 5-8 shows the ADR progression in larger eastern Japanese cities (including Tokyo). Several peaks due to I-131 deposits can be seen clearly; these occurred to the south of the site when the wind turned in this direction in the initial phase of the accident.

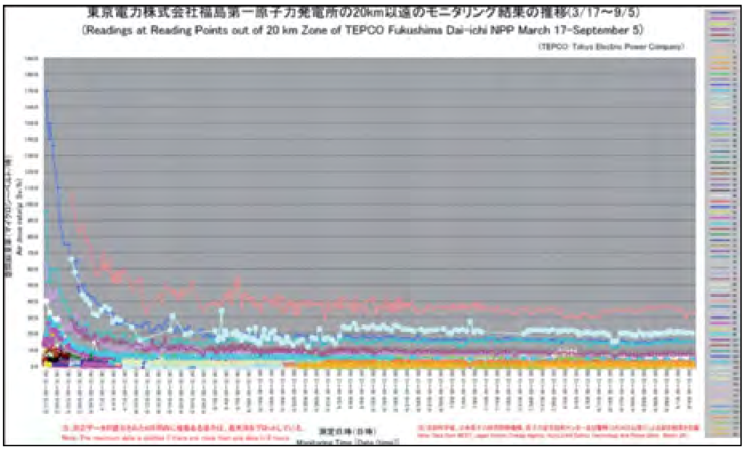


Figure 5-6 Progression of the ambient dose rate at the defined monitoring posts outside the 20 km prohibited zone around Fukushima [28]

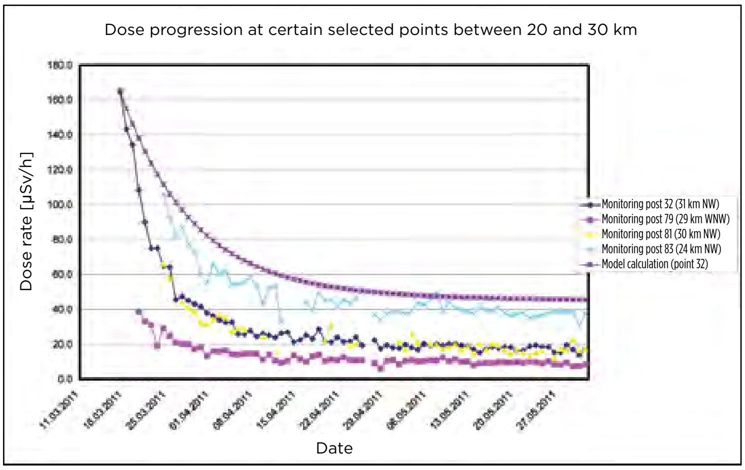


Figure 5-7 Progression at monitoring posts with the highest ambient dose rates directly after the accident

28 | Source: MEXT http://radioactivity.mext.go.jp/en/monitoring_around_FukushimaNPP_monitoring_out_of_20km/2011/09/12475/index.html

One of the effects of these iodine deposits was that in Tokyo, for example, the I-131 limit for infants in drinking water was briefly exceeded (cf. section 5.4). During the course of April, the ADR values normalised again due to the radioactive decay of the I-131. They have now returned to a range of 0.1 µSv/h, as (for example) is typical for the Mittelland region of Switzerland.

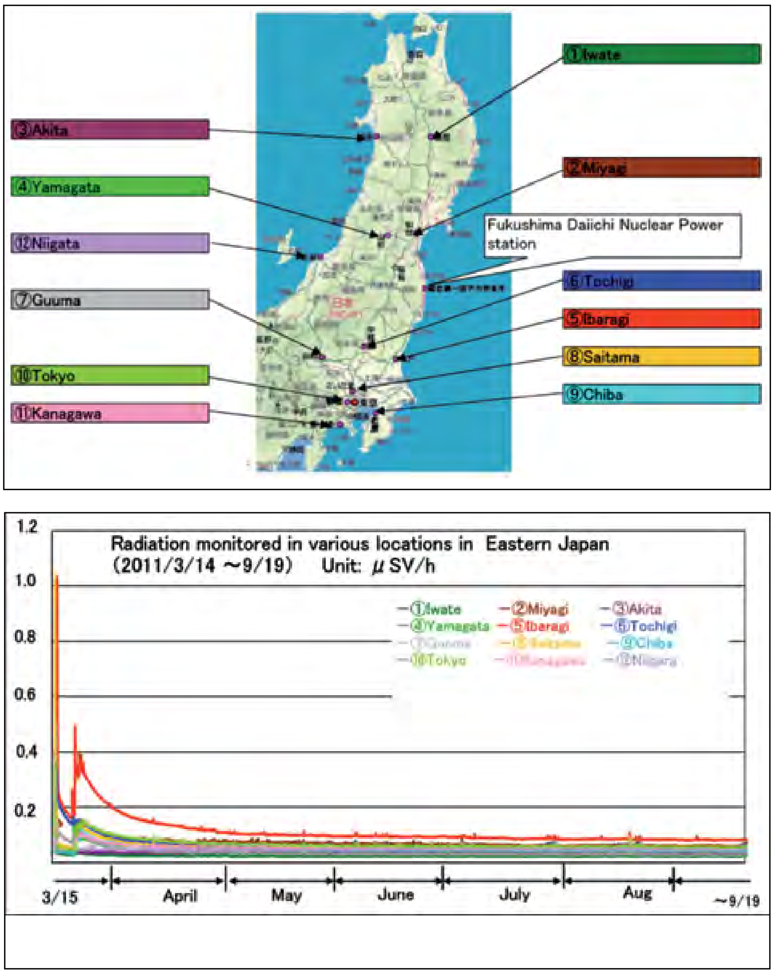


Figure 5-8 Progression of ambient dose rates in major cities in eastern Japan between 15 March and the start of September [29]

29 | Source: JAIF http://www.jaif.or.jp/english/news_images/pdf/ENGNEWS01_1316677149P.pdf

5.2.3 Measurements of soil activity: volatile nuclides, I-131, Cs-134 and Cs-1377

Shortly after the accident, direct measurements of activity concentrations in the soil were taken in the surrounding area, and the dose rate values determined by means of aeroradiometry were also converted into activity concentrations in the surface layer of the soil. The result of this conversion is shown in Figure 5-9.

The trail of deposits in a north-westerly direction is again clearly visible. In the red shaded area, the calculated surface contamination values were over 3 MBq/m². In the area shaded grey-green, the deposited activity concentrations of the two Cs-isotopes were still 30-60 kBq/m², a value that was also measurable in some areas in the south of the canton of Ticino after the reactor accident at Chernobyl in 1986.

Directly after it was deposited on the ground, I-131 was the nuclide for which the highest soil contamination was measured on account of its high volatility and the large concentration in the reactor. At this time, the deposits of Iodine on the ground exceeded those of the two Cs-isotopes by factors of 3 to 20 each (cf. by way of example, the “Soil” rows in Table 5-1). The fluctuating Cs/I conditions on the ground and the significantly divergent conditions on the surfaces of plants can be explained by the different washout and penetration behaviours of Iodine and Cesium. Due to the comparatively short half life of I-131, the two Cs isotopes dominated soil contamination from about April onwards.

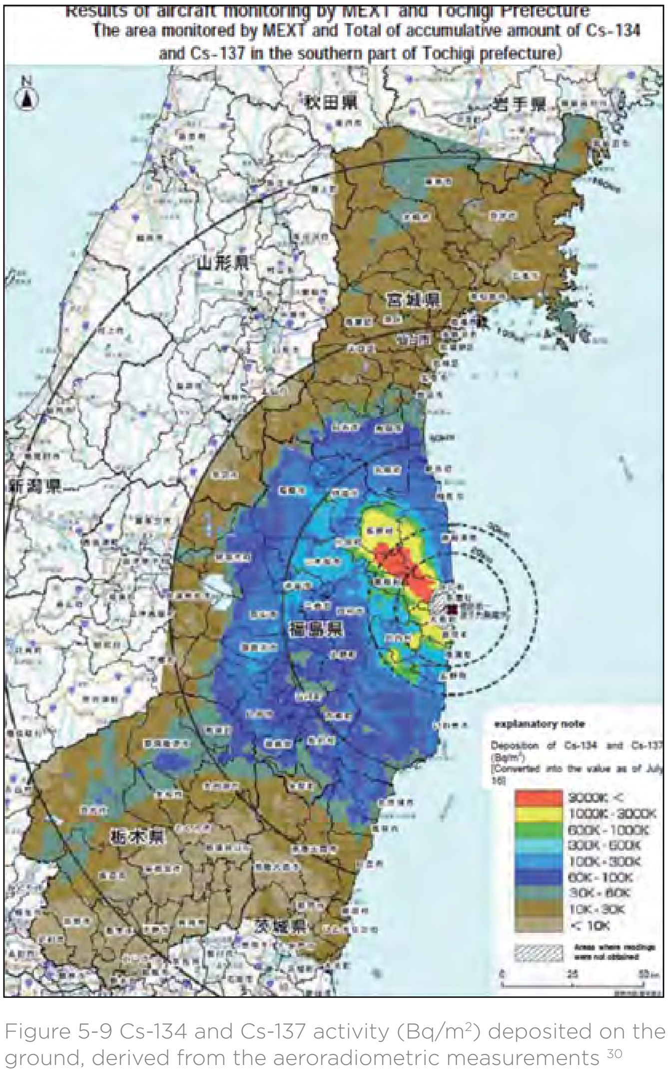


Figure 5-9 Cs-134 and Cs-137 activity (Bq/m²) deposited on the ground, derived from the aeroradiometric measurements [30]

Maximum measurement values for Cs-137 activity concentrations as measured at various points in the soil are shown in Figure 5-3. The highest value was 227’000 Bq/kg, although a direct comparison with the aeroradiometric measurements stated in Bq/ m^2 is very difficult in this case as the depth down to which sampling was carried out is unknown.

From the end of May 2011 onwards, the Japanese Ministry of Agriculture, Forestry and Fisheries (MAFF) launched a campaign entailing gamma-spectroscopic investigation of the activity concentrations of radiocesium in soil used for agricultural purposes at a total of 580 points in the prefecture of Fukushima and the five neighbouring prefectures (Miyagi, Tochigi, Gunma, Ibaraki and Chiba). The results of these measurements are grouped together in Figure 5-10.

As the depth to which the soil was sampled is defined in this case, a direct comparison with the aeroradiometric measurements presented above is possible. The results determined with the two measurement methods correspond very well within the measurement accuracy that can be expected. In the case of cesium, an average transfer factor of 0.05 from soil into the plant is assumed. This means that from a value of 10’000 Bq/kg upwards (red and orange dots in the figure), it must be expected that plant products grown in this soil will exceed the Japanese average limit for Cesium in food of 500 Bq/kg (cf. section 5.3).

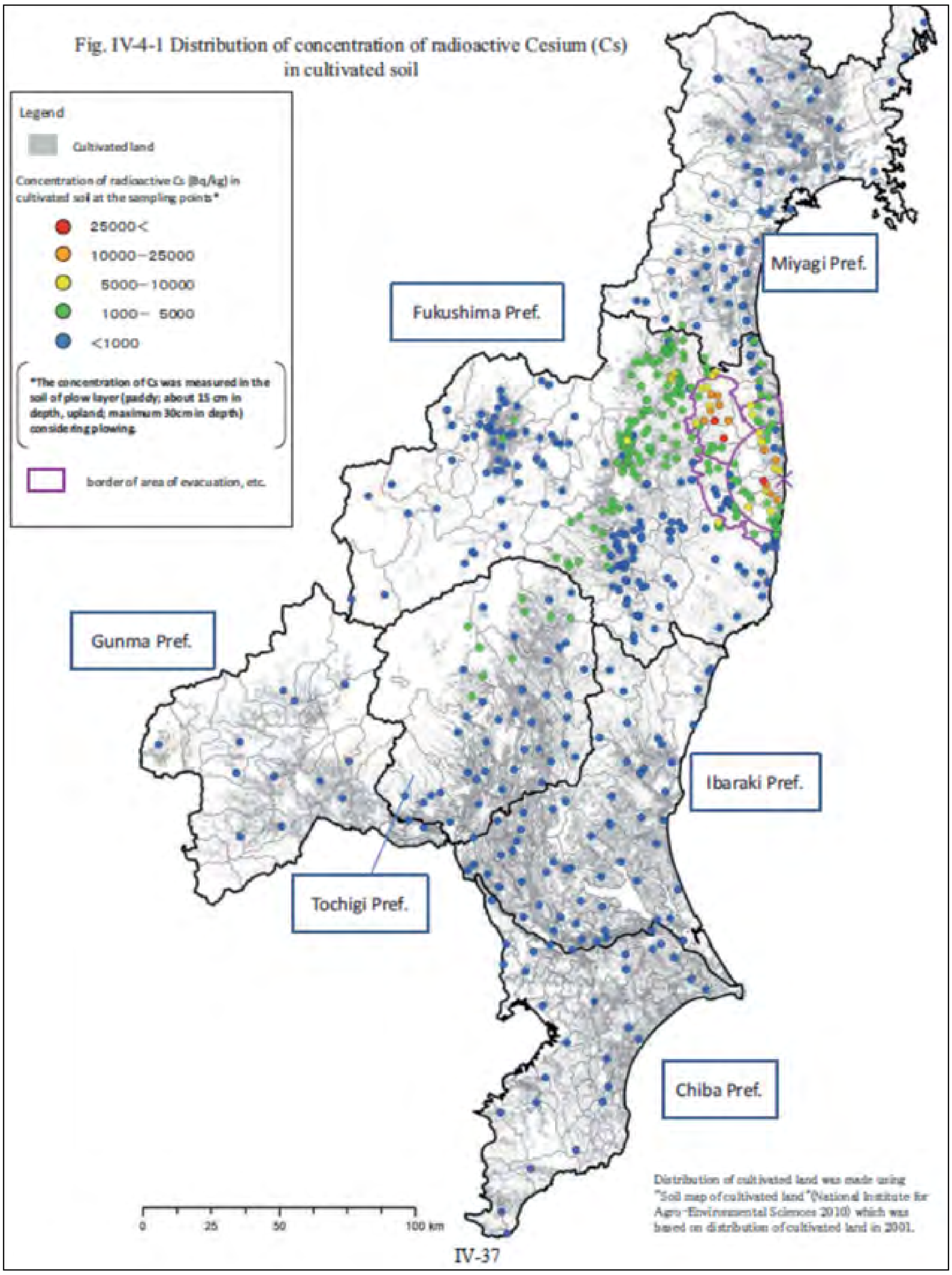


Figure 5-10 Activity concentrations of radiocesium in soil used for agricultural purposes in the area of the plants' roots [31]

5.2.4 Measurements of soil activity: other nuclides (Sr, Pu, U)

In addition to Iodine and Cesium, comparable quantities of other nuclides with long half lives are formed in a reactor during operation (cf. Table 2-3), but they are significantly less volatile by comparison. In this context, of special interest are pure beta emitters such as Sr-89 and Sr-90 or alpha emitters such as Plutonium or Uranium, which can lead to significant radiation exposure if absorbed into the human body via the respiratory tract or through food; however, measurement of these emitters usually involves relatively high outlay. Following the accident, there was particular discussion of a potentially increased release of Plutonium (which nevertheless has very low volatility) because so-called mixed oxide (MOX) fuel assemblies were used in the reactor of unit 3 at Fukushima Dai-ichi. In these fuel assemblies, a small proportion of the fissile Uranium is replaced by Plutonium, resulting in a higher Plutonium share than in the case of pure Uranium fuel assemblies.

Immediately after radioactive substances were deposited, the Japanese authorities took soil samples at various points which they analysed for Iodine, Cesium and Strontium. Figure 5-11 provides an overview of the sampled locations; sampling locations 1 to 3 are situated centrally in the main direction of the dispersal plume.

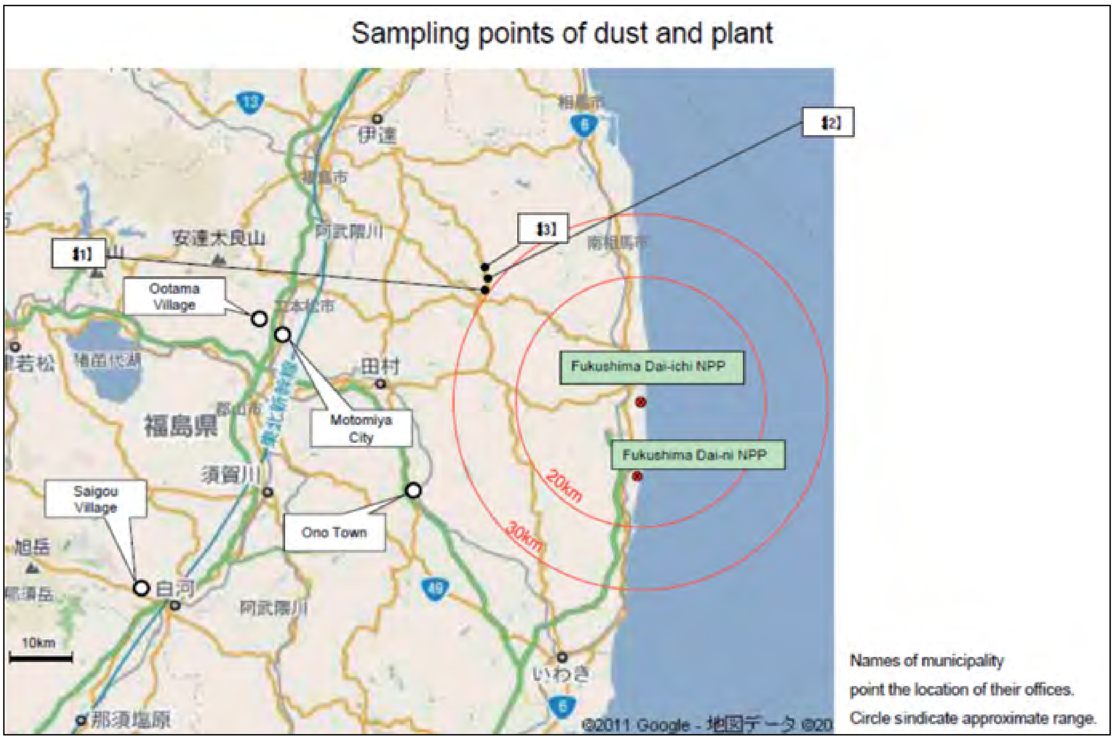


Figure 5-11 Sampling points where activity conditions for further nuclides were investigated immediately after deposits occurred [32]

32 | Source: MEXT http://radioactivity.mext.go.jp/en/1260/2011/03/1305074_0412.pdf

Sample	Sampling location	Date	Activity per nuclide [Bq/kg] (moist soil, plants unprocessed)				
			I-131	Cs-134	Cs-137	Sr-89	Sr-90
Soil	Namie Town	17.03.2011	30'000	2'300	2'300	13	3.3
Soil	Namie Town	16.03.2011	100'000	20'000	19'000	81	9.4
Soil	Iitate Village	16.03.2011	160'000	52'000	51'000	260	32
Plants	Ootama Village	19.03.2011	43'000	89'000	90'000	61	5.9
Plants	Motomiya City	19.03.2011	21'000	57'000	57'000	28	3.7
Plants	Ono Town	19.03.2011	22'000	12'000	12'000	12	1.8
Plants	Nishigou Village	19.03.2011	12'000	25'000	25'000	15	3.8

Table . 5-1 Measurement results for activity concentrations in the soil for radioactive iodine, cesium and strontium about one week after the occurrence of the accident [33]

As shown in Table 5-1, the measured Sr-89 concentrations in the soil are in all cases less by a factor of at least 100 than the values measured at the same point for Cs-134 or Cs-137, and the Sr-90 concentrations are less by a factor of at least 1'000. The Cs/Sr ratio for plants is even greater. This makes it possible to state that the radiation exposure in the area surrounding Fukushima, as compared to those for the two Cs isotopes, are of subordinate importance, even taking into account the less favourable transfer factors and dose factors for Strontium.

In the immediate area surrounding the nuclear power plant, the operating company TEPCO detected traces of Plutonium in the soil in the case of two samples. In both cases, the isotope ratio suggested that this may have originated from one of the damaged reactors.

The concentration of the measured Plutonium there was about 1 – 2 Bq/kg, but, nevertheless, this is of a magnitude that can (for example) be detected in Switzerland as a consequence of atomic weapons tests by nuclear powers.

33 | Source: MEXT http://radioactivity.mext.go.jp/en/1260/2011/03/1305074_0412.pdf

In the wider area surrounding the nuclear power plant, the Plutonium concentration was below the detection limit, even in the main deposit trail. The Uranium measured at the same locations shows a natural isotope ratio between U-235 and U-238 (cf. Table 5-2). If the measured Uranium originated from a reactor, a shift in the ratio in favour of U-235 would be expected due to the enrichment of the fuel.

The radiological effects of Plutonium and Uranium are therefore of minor significance as compared to Cs-134 and Cs-137. Other nuclides were proven to be present in the surrounding area, but they are of considerably less radiological importance than the nuclides already mentioned.

Sampling location	Date	ADR [μSv/h	Activity per nuclide [Bq/kg]		Activity ratio U-235/U-238[36]
			Pu-238	Pu-239 &240	
Near Kodeya, Kuzuo Village	23.03.2011	43.5	< 0.1 (< LOD) [35]	< 0.1 (< LOD)	7.31E-3
East of the Hirusone Tunnel, Namie Town	23.03.2011	46.5	< 0.1 (< LOD)	< 0.1 (< LOD)	7.26E-3
Akougi, Namie Town	22.03.2011	50.1	< 0.1 (< LOD)	< 0.1 (< LOD)	7.23E-3

Table 5-2 Measurement results for activity concentrations in the soil for Plutonium and Uranium about two weeks after the accidentcesium [LOD = Limit Of Detection] [34]

5.3 Contamination of food

In an operation coordinated by the MHLW after the accident, more than 15’000 samples of food were taken throughout Japan up to September; their Iodine and Cesium content was determined and compared with the following limits that apply to food in Japan:

- For Iodine (primarily I-131) in milk and milk products as well as drinking water: 300 Bq/kg for adults and 100 Bq/kg for infants; in vegetables and fish: 2’000 Bq/kg;
- For Cesium (Cs-134 and 137) in milk and milk products as well as drinking water: 200 Bq/kg; in vegetables, fish, meat, eggs and all other food: 500 Bq/kg;
- For Uranium in drinking water, milk and baby food: 20 Bq/kg, for all other food: 100 Bq/kg;
- For transuranium elements in drinking water, milk and baby food 1 Bq/kg, for all other food: 10 Bq/kg.

The applicable activity limits for food according to MHLW are listed in detail in the following Table 5-3.

34 | Source: MEXT http://radioactivity.mext.go.jp/en/1250/2011/04/1305381_0401.pdf
35 | According to MEXT, the values measured for the plutonium isotopes are below the detection limits.
36 | The abundance in the natural occurring element of U-235 and U-238 are 0.7204% and 99.2742% respectively (cf. /45/), and the natural U-235/U-238 ratio is approx. 7.26E-3.

Nuclides	Provisional limit for radioactive substances in foods according to the "Food Sanitation Act" [Bq/kg]	
Radioactive Iodine	Drinking water	300
	Milk and dairy products	
	Vegetables (except root and tuber vegetables)	2'000
	Fishery products	
Radioactive Cesium	Drinking water	200
	Milk and dairy products	
	Vegetables	500
	Cereals	
	Meat, eggs, fish, etc.	
Uranium	Baby food	20
	Drinking water	
	Milk and dairy products	
	Vegetables	100
	Cereals	
	Meat, eggs, fish, etc.	
Alpha emitters, Plutonium and transuranium elements (total concentration of Pu-238, Pu-239, Pu-240, Pu-242, Am-241, Cm-242, Cm-243, Cm-244)	Baby food	1
	Drinking water	
	Milk and dairy products	
	Vegetables	10
	Cereals	
	Meat, eggs, fish, etc.	

Table . 5-3 Activity limits for food in Japan [37]

In Switzerland, the limits for radioactivity in foods are stipulated in significantly more detail in the Ordinance on Foreign Substances and Constituents in Food (FIV) /12/. The present Swiss concept differs somewhat from the Japanese procedure in that the limit is preceded by a lower tolerance value as from which a product is regarded as "diminished in value". For the radionuclides mentioned above, the limits are comparable in terms of magnitude.

By way of example, Table 5-4 shows an excerpt from the data published by MHLW for the prefectures of Fukushima and Ibaraki. For various food groups, the number of measured samples is compared with the number of samples determined to have violated the limit in the seven months between the accident (March 2011) and mid-October 2011.

In Fukushima, approx. 10'500 samples were examined. The limit was exceeded for about 4.5% of them. In the neighbouring prefectures, the percentage of food samples that exceeded the limits were 3% (Tochigi), 2% (Ibaraki, Chiba and Miyagi) and less than 1% (Gunma).

The highest activity value measured was for a sample of spinach taken at Ibaraki on 20 March 2011, with a measured I-131-concentration of significantly more than 50'000 Bq/kg and Cs-134/137 activity of approx. 2'000 Bq/kg. Consumption of one kilogram of such contaminated spinach would lead to an effective dose of 1 mSv for an adult.

37 | Source: MHLW http://www.mhlw.go.jp/english/topics/2011eq/dl/food-110405.pdf

In March 2011, maximum concentrations of about 5'000 Bq/kg for Iodine-131 and approx. 400 Bq/kg for Cs-134/137 were determined in milk and milk products. These amounts of activity are also more or less equivalent to a dose of 1 mSv if an infant were to drink one litre of this milk.

In a seawater fish (sand lance) from the prefecture of Fukushima, I-131 and Cs-134/137 were proven in a concentration of approx. 12'000 Bq/kg in each case as late as mid-April 2011 .

Origin (prefecture)	Food group	Number of samples tested	Samples that exceeded the limit	Examples of affected food samples (number)
Fukushima	Vegetables	5'215	260	Bamboo shoots (55), spinach (39), shiitake cultivated outdoors (40), broccoli (21), ume (11), rapeseed (6), cabbage (6), etc.
	Fish and seafood	1'379	109	Ayu (21), common skate (14), greenling (10), sand lance (6), deep-sea cod (5), etc.
	Milk and milk products	448	18	Unprocessed milk (18)
	Meat and eggs	1'907	61	Beef (56), pork (3), Asiatic black bear (2)
	Cereals	1'502	1	Wheat (1)
	Others	30	2	Tea (1), rape (1)
	Total	10'481	451	
Ibaraki	Vegetables	735	43	Spinach (29), parsley (7), shiitake cultivated outdoors (4), etc.
	Fish and seafood	473	6	Sand lance (5), deep-sea cod (1)
	Milk and milk products	90	5	Unprocessed milk (5)
	Meat and eggs	2'582	4	Pork (4)
	Cereals	469	-	-
	Others	83	13	Tea (13)
	Total	4'432	71	

Table 5-4 Examined food samples and number of limit violations ascertained, using the prefectures of Fukushima and Ibaraki as examples [38]

 Source: MHLW http://www.mhlw.go.jp/english/topics/2011eq/dl/17Oct2011_Sum_up.pdf

Due to the short half life, violations of the Iodine limits in food occurred only until about the end of April 2011. Thereafter, the limit violations were all attributable to high Cs-134 or Cs-137 concentrations. Broken down by product groups, the highest Cs concentrations (Cs- 134 + Cs-137) in foods were as follows:

- Vegetables: 34'000 Bq/kg (spinach, end of March), 13'000 Bq/kg (mushrooms, start of April), 3'000 Bq/kg (tea, mid-May), 4'600 Bq/kg (mushrooms, mid-August), 1'300 Bq/kg (tea, mid-August), 2'400 Bq/kg (citrus fruit, end of August)

- Milk, milk products: 400 Bq/kg (mid-March)

- Fish, seafood: <15'000 Bq/kg (sand lance, April), approx. 1'000 Bq/kg (various, May), approx. 4'500 Bq/kg (ayu, June), approx. 1'800 Bq/kg (ayu, August)

- Meat: up to approx. 4'500 Bq/kg (beef, from July onwards)

The highest concentrations of Cs activity were found for vegetables (leaf vegetables) immediately after the discharge of radioactivity into the environment, in a period of about two months (direct deposits on the leaves). The aforementioned value of 34'000 Bq/kg in spinach would be equivalent to an effective dose for an adult of about 0.5 mSv if one kilogram were to be consumed. In the following phase, the activity concentration in plants was dominated by absorption through the roots – the values therefore decreased significantly as compared to the period directly after the discharge.

Processed and stored plants such as tea constitute a special case. Tea leaves are dried after they are harvested, which entails an additional increase in concentration in respect of the activity present per unit of mass. They are then stored for a very long time before consumption. Especially for long-lived nuclides such as Cs-137, this means that the leaves harvested in the first phase after the accident with activity directly deposited on the leaf can remain in commercial circulation and can therefore reach consumers for quite a long time.

The transfer of radionuclides from forage crops into milk takes place relatively quickly, and fresh milk also goes into commercial circulation soon after production. Consequently, the maximum activity in fresh milk correlates very well with the maximum activity in and on forage crops.

The situation is different for meat (beef). In this case, the rearing and storage period for the meat prior to sale and consumption is rather long. This explains (similarly to the situation with tea leaves) why the maximum activity concentration occurs after a delay of several months in relation to the maximum activity in the forage plant; this statement applies very generally to stored products.

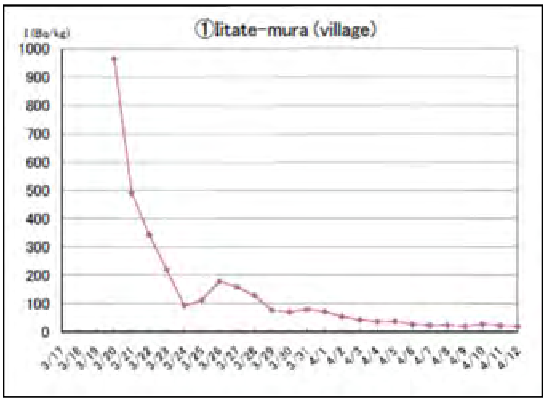
The concentration of activity in fish and seafood correlates with the concentration in the water of lakes and the sea and – to a lesser extent – with the concentration in sediments. In this case too, however, the growth period for fish and seafood, and the resultant delay in catching and processing, leads to a time shift between the maximum concentration in the water and in the fish or seafood.

On the basis of the measurements that were made, MHLW ordered food bans where necessary in order to minimise the dose for the population due to the consumption of contaminated food.

5.4 Contamination of drinking water

Depending on the wind conditions, there were brief violations of the I-131-limit in drinking water for adults or infants in the days following the accident, due to deposits of radioactive substances in surface water in the catchment area of the drinking water supply. Figure 5-12 illustrates this using the examples of two waterworks in the village of Iitate (violation of drinking water limit for adults of 300 Bq/kg) and Tokyo (violation of the guidance value for infants of 100 Bq/kg).

The authorities subsequently urged the population to avoid drinking water taken from surface water sources for a short time. Due to the radioactive decay of iodine-131 and the diminishing discharges and/or deposits, the limits were respected again everywhere from the end of March 2011 onwards.



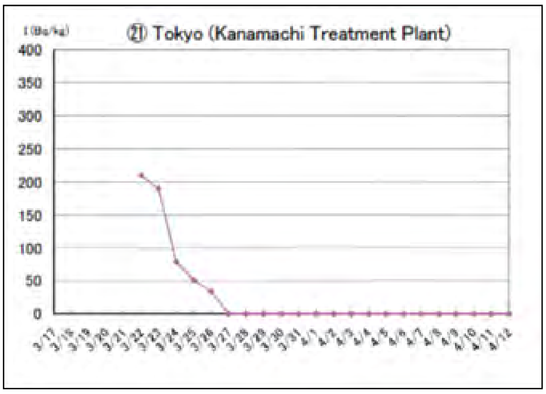


Figure 5-12 Violation of the I-131 activity limit in drinking water after the accident, using the examples of two waterworks in Iitate (prefecture of Fukushima) and Tokyo [39]

Figure 5-13 and Figure 5-14 show the progression of activity in drinking water in various provinces for I-131 and Cs- 134/137: from about mid-April 2011 onwards, the values returned to the level of those measured before the accident, they were therefore significantly below the limits again.

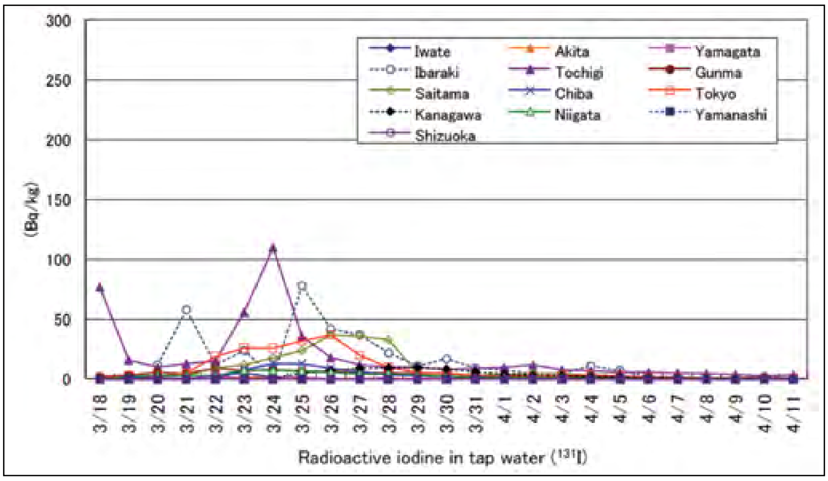


Figure 5-13 Activity concentration for I-131 in the drinking water systems of various prefectures in northern Japan [40]

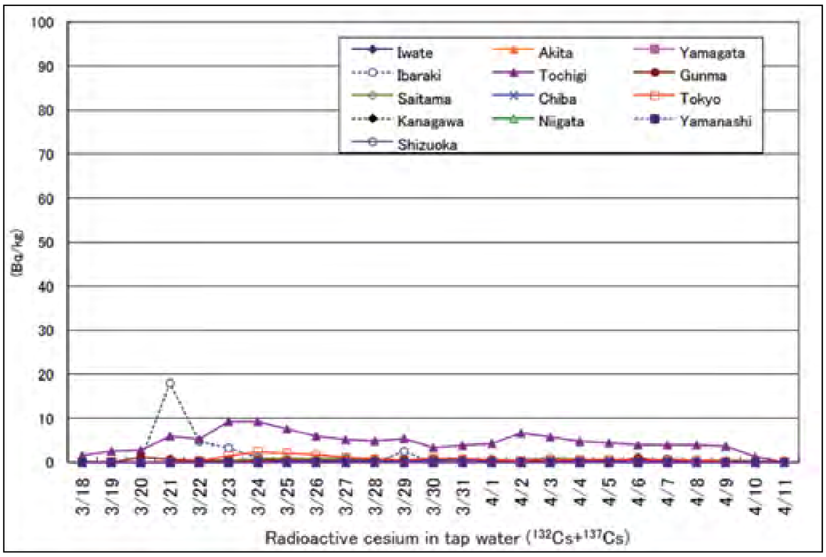


Figure 5-14 Activity concentration for Cs-134/137 in the drinking water systems of various prefectures in northern Japan [41]

40 | Source: MHLW /13/
41 | Source: MHLW /13/

5.5 Contamination of seawater and the seabed

At the start of April 2011, major amounts of severely contaminated water escaped into the sea through an underground shaft and a leak (cf. section 2.4). This discharge was manifested in an increase in the concentration of activity in the seawater at the monitoring posts around the reactors affected by the accident (cf. Figure 5-15 and Figure 5-16)

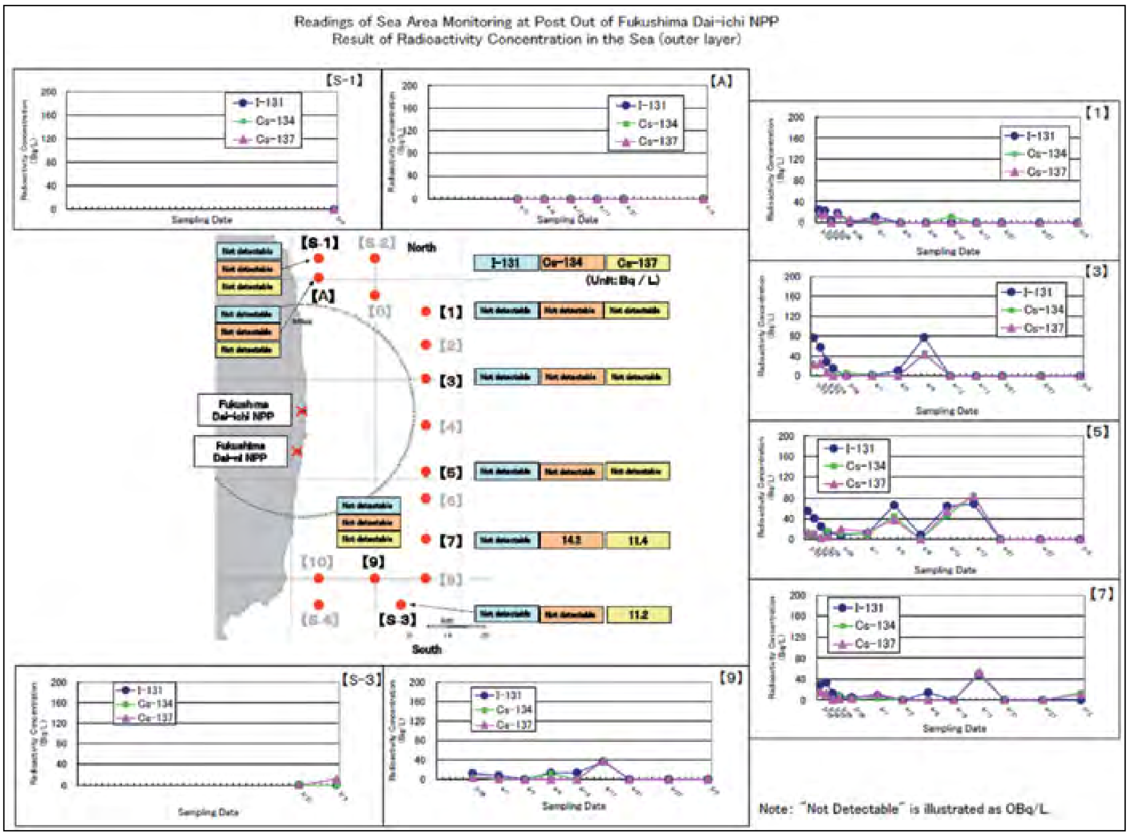


Figure 5-15 Activity concentrations for I-131, Cs-134 and Cs-137 in the seawater around the Fukushima Dai-ichi nuclear power plant on 5 May 2011 [42]

42 | Source: MEXT http://radioactivity.mext.go.jp/en/1340/2011/05/1305678_0505.pdf

and also – albeit after a delay – by higher activity concentrations in fish and seafood (cf. section 5.3). Depending on the ocean currents, the Japanese limits (90 Bq/l for Cs) were almost reached or even exceeded by as much as a factor of 4 at some points (taking account of the total of Cs-134 and Cs-137 activity).

Once major discharges into the sea were successfully halted, the activity values decreased again. Almost without exception, they were again below the detection limit from May 2011 onwards.

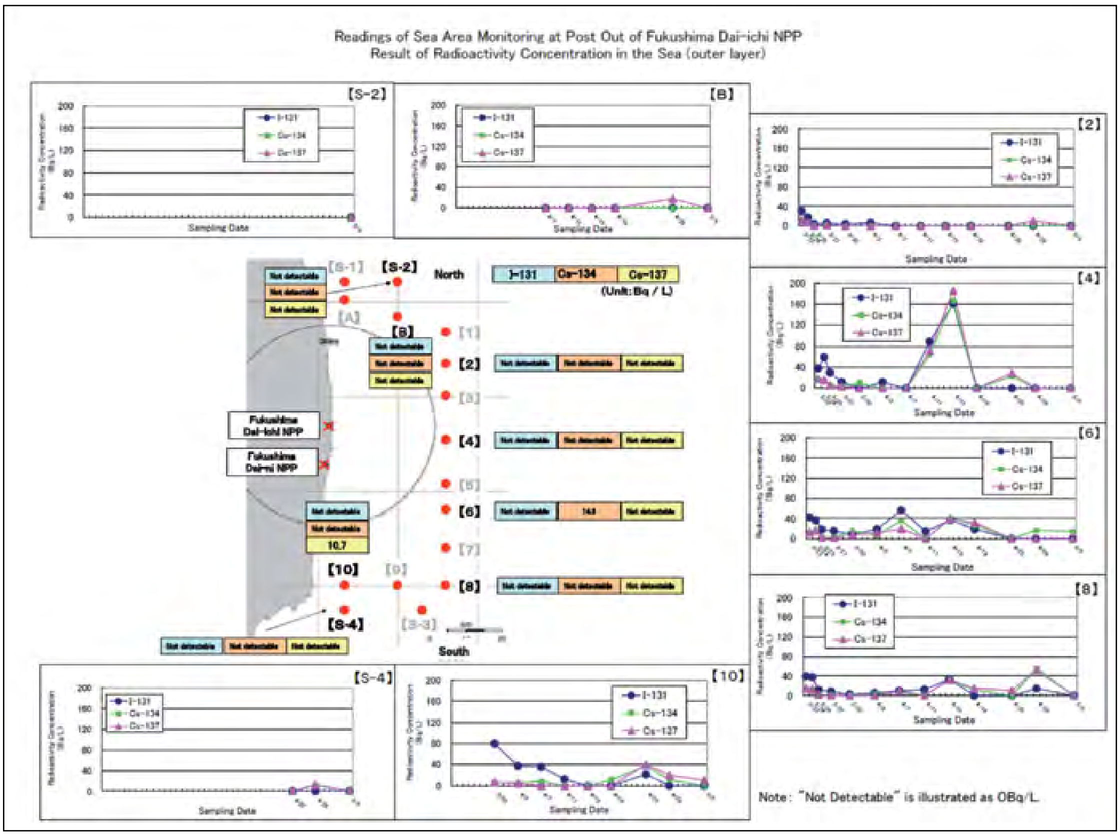


Figure 5-16 Activity concentration of I-131, Cs-134 and Cs-137 in the seawater around the Fukushima Dai-ichi nuclear power plant on 7 May 2011 [43]

43 | Source: MEXT http://radioactivity.mext.go.jp/en/1340/2011/05/1305678_0505.pdf

Waterborne discharges in surface water and in the sea can be deposited on the seabed in a similar manner to the way airborne discharges are deposited on the soil. At the end of July 2011, JAEA took measurements on the coast around Fukushima Dai-ichi (and Dai-ni). The results are grouped together in Figure 5-17. Significantly increased activity concentrations were ascertained at several points, especially to the south and east of the power plant site. These may also represent a source of higher radioactivity concentrations in fish and seafood in the longer term. However, the effects here should be significantly less than in the case of a direct increase in activity in the seawater.

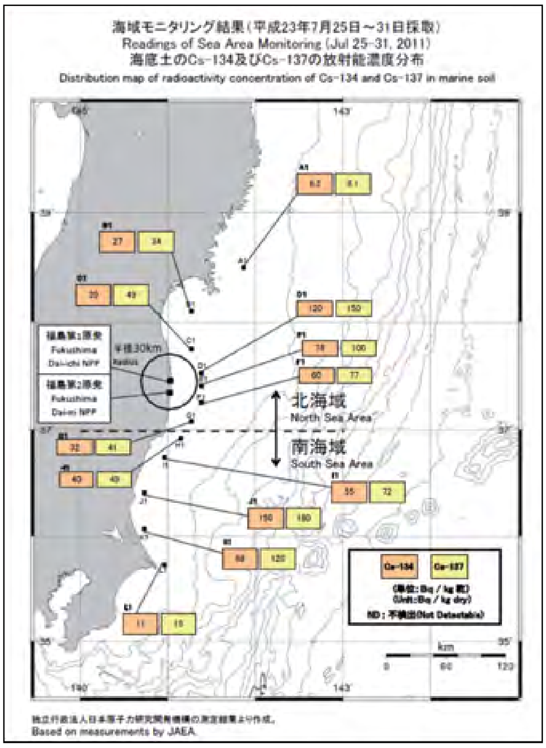


Figure 5-17 Cs deposits on the seabed and in the sediment around the Fukushima Dai-ichi nuclear power plant [44]

The samples from the monitoring posts with the highest Cs values were subsequently examined for possible deposits of Sr-89 and Sr-90, but the measured values were below the detection limits in these cases (cf. Figure 5-18).

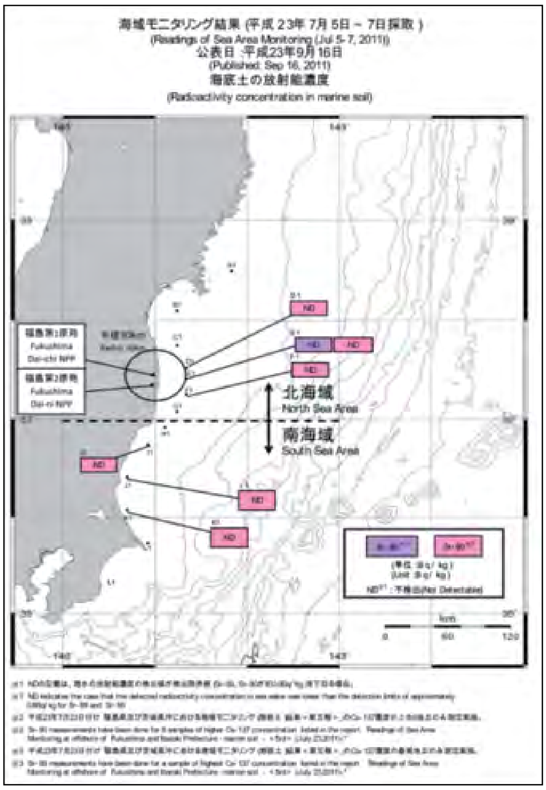


Figure 5-18 Sr deposits on the seabed and in the sediment surrounding the Fukushima Dai-ichi nuclear power plant [45]

44 | Source: MEXT http://radioactivity.mext.go.jp/en/monitoring_around_FukushimaNPP_sea_marine_soil/2011/08/1350_081310.pdf
45 | Source: MEXT http://radioactivity.mext.go.jp/en/monitoring_around_FukushimaNPP_sea_marine_soil/2011/09/1350_091610.pdf

5.6 Measures to reduce radiation exposure

5.6.1 Evacuation of the population in the surrounding area

Evacuation around the Fukushima Dai-ichi power plant site was carried out in the following stages (cf. /1/, /11/ and /14/):

- On 11 March 2011 at 8:50 p.m., the government triggered the preliminary warning for the 2 km zone around the Dai-ichi power plant to be evacuated due to the situation in unit 1.
- On 11 March 2011 at 9:23 p.m., the government ordered people to evacuate the 3 km zone and to remain in their houses in the 3 to 10 km zone due to the aggravation of the situation.
- On 12 March 2011 at 05:44 a.m., the government ordered the evacuation of the 10 km zone around the power plant.
- On 12 March 2011 at 6:25 p.m., as a consequence of the hydrogen explosion in unit 1 and the increase in the ADR on the power plant site, evacuation of the 20 km zone around the power plant was ordered.
- On 15 March 2011 at 11:00 a.m., people were ordered to stay in their houses in the 20 to 30 km zone. At 23:30 hours, completion of the evacuation of the 20 km zone was reported.
- On 25 March 2011, the government advised the population to evacuate the 20 to 30 km zone around the power plant on a voluntary basis.
- On 22 April 2011, due to measurements in the surrounding area outside the 20 km zone around the Dai-ichi power plant, a special evacuation zone was set up (the "Deliberate Evacuation Area"). The 20 km zone itself was declared to be a "Restricted Area". A further zone between 20 and 30 km was defined for any subsequent evacuation that might be necessary ("Evacuation- Prepared Area in Case of Emergency"); this zone would have to be evacuated in case of a further deterioration of the situation.
- In June 2011, individual locations for potential evacuation were identified in other adjacent areas ("Specific Spots Recommended for Evacuation").

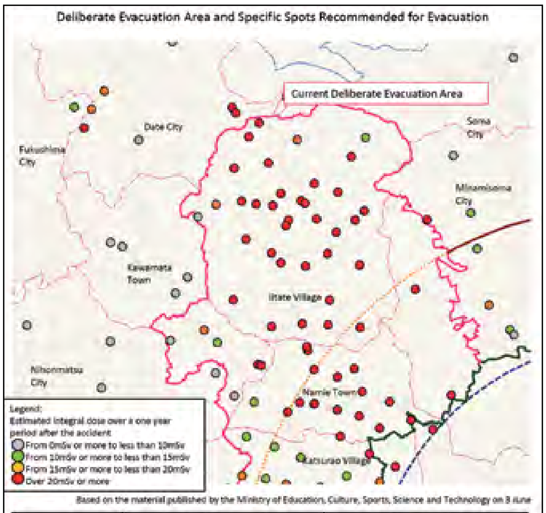
The evacuation around the Fukushima Dai-ni power plant site was carried out in the following stages:

- On 12 March 2011 at 07:45 a.m., the government ordered people to evacuate the 3 km zone and to stay in their houses in the 3 to 10 km zone around the Dai-ni power plant.
- On 12 March 2011 at 5:39 p.m., evacuation of the 10 km zone was ordered.
- On 21 April 2011, the evacuation zone was reduced to 8 km. As a precaution, the population was initially evacuated within a radius of 20 km around Fukushima Dai-ichi (cf. Figure 5-19).

Figure 5-19 Evacuation zones around Fukushima Dai-ichi [46]

The authorities subsequently decided to extend the evacuation zone for specified areas ("Deliberate Evacuation Areas") beyond the 20 km radius in cases where the population would accumulate a dose of more than 20 mSv by March 2012. The affected municipalities are located to the north-west up to a distance of approx. 40 km from the Fukushima Dai-ichi nuclear power plant. The 20 km zone around the Fukushima Dai-ichi power plant that had already been evacuated was converted into a prohibited zone ("Restricted Area"). Residents were recommended to leave the other contaminated areas between 20 and 30 km ("Evacuation-Prepared Areas in Case of Emergency").

At individual places in additional adjacent areas, the authorities recommended compliance with special precautionary measures or departure from the location in question where a yearly dose of over 20 mSv would be accumulated ("Specific Spots Recommended for Evacuation"), (cf. Figure 5-20).



	Deliberate Evacuation Area	Specific Spots Recommended for Evacuation
Applicable Area	Spots with an integral dose over a one year period after the accident exceeding 20mSv are wide spread within the area.	Spots exist in some areas where an integral dose over a one year period after the accident exceeds 20mSv (Exist per residence that is not easy to decontaminate).
Safety Viewpoint	There is a risk of exceeding 20mSv through daily life in general.	The dose decreases by moving away from high dose spots, so a risk of exceeding 20mSv through daily life in general is low.
Governmental Response	Deliberate evacuation (The Government requires across-the-board evacuation.)	Call for attention, provision of information, evacuation assistance, etc. (The Government does not require across-the-board evacuation.)

Figure 5-20 Figure 5-20 Evacuation areas outside the 20 km zone [47]

On 30 September 2011, the stipulation regarding "Evacuation-Prepared Areas in Case of Emergency" (orange zone in Figure 5-19) was lifted again by the Nuclear Emergency Response Headquarters.

46 | Source: METI http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/evacuation_map_a.pdf
47 | Source: METI http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/evacuation_map_b.pdf

5.6.2 Decontamination measures

On 26 August 2011, the Japanese parliament passed a new law on "Special measures for dealing with contamination of the environment by radioactive substances released as a consequence of the Tohoku earthquake". The Japanese Nuclear Emergency Response Headquarters also declared that the decontamination of radioactively contaminated areas was an urgent requirement. The objective of the planned decontamination is to reduce radiation exposure in highly contaminated areas (current dose >20 mSv per year) to less than 20 mSv per year. In the other areas, the value should be less than 1 mSv per year. Top priority in this context is assigned to the decontamination of kindergartens, school premises and other locations where children are present on a daily basis.

Various measures were initiated in order to achieve the defined goals. In the towns of Date and Minamisoma, pilot projects have been running since the end of August 2011 with the aim of demonstrating how residential areas can be decontaminated. In Fukushima and the neighbouring prefectures, information events were staged at municipality level on the following topics, among others: "Basis of decontamination work", "Special measures for dealing with radioactive contamination", "Precautionary measures to be paid attention when decontamination work is carried out by residents" and "The procedure for dealing with waste produced during decontamination".

One particular challenge is also posed by the decontamination of large areas of land and forest used for agricultural purposes. Since May 2011, various feasibility studies on this aspect have been in progress. Suitable decontamination methods have also been developed. On 30 September 2011, the Nuclear Emergency Response Headquarters officially published various methods which it consider as suitable for the decontamination of land and forest areas used for agricultural purposes. It should be noted in this context that virtually no international experience of decontamination work over large areas is available. Other open questions include what is to be done with the radioactive materials produced during decontamination, and how or where they can ultimately be stored.

5.7 Estimation of doses for the population in the surrounding area

5.7.1 Dose in the acute phase

At the outset, a substantial percentage of the radioactive substances were carried out over the Pacific by the prevailing westerly winds. As major releases of radioactive substances only began to be carried simultaneously over land areas from approx. 8:00 p.m. on 14 March 2011 onwards, prompt evacuation of the population (about 70'000 to 80'000 people) was possible within a radius of 20 kilometres. The evacuation was subsequently extended individually to more heavily contaminated areas outside of this zone.

About 78'200 people were living in the 20 kilometre zone and another 62'400 people lived in the zone between 20 and 30 kilometres from the plant (cf. /1/).

Iodine mainly accumulates in the thyroid gland, and children are particularly sensitive. An intake of non-radioactive iodine can cause the thyroid gland to become saturated, so that radioactive iodine no longer accumulates there. Single intakes of non-radioactive iodine were recommended for specific groups of individuals; however, the authorities warned the public against the uncontrolled use of such preparations. Schools were subject to particularly intensive monitoring.

By the end of May 2011, no signs of impairments to health were ascertained in 195’345 people who were examined. No increased iodine radiation doses were found in the thyroid glands of any of the 1’080 children who were examined (cf. /16/). Likewise, no absorption by humans of radioactive strontium was determined up to that time (cf. /15/).

5.7.2 Estimation of the long-term dose

The French Institut de Radioprotection et de Sûreté Nucléaire (IRSN) calculated the expected doses due to external irradiation for one year (cf. Table 5-5) and for 10 and 70 years (cf. Table 5-6) on the basis of deposits measured on the ground (cf. Figure 5-9 and Figure 5-10). The number of persons affected, which is also stated, refers to the area outside the 20 km prohibited zone that was originally evacuated. On the basis of these calculations, all other persons with a forecast dose of more than 20 mSv for the first year were evacuated in addition (cf. Figure 5-20).

Deposits of Cs-134 + Cs-137 (according to MEXT)	>300 kBq/m²	>600 kBq/m²	>1 MBq/m²	>3 MBq/m²	6 – 30 MBq/m²
Dose due to external irradiation in the first year (16.6 mSv/MBq/m²)	>5 mSv	>10 mSv	>16 mSv	>50 mSv	100 – 500 mSv
Number of persons affected (excluding the prohibited zone)	292‘000	43‘000	21‘100	3‘100	2‘200

Table . 5-5 Expected external radiation exposure in relation to soil contamination for a period of one year spent in the location [48]

Deposits of Cs-134 + Cs-137 (according to MEXT)	>300 kBq/m²	>600 kBq/m²	>1 MBq/m²	>3 MBq/m²	6 – 30 MBq/m²
Dose due to external irradiation in the first 10 years (70 mSv/MBq/m²)	>19 mSv	>38 mSv	>63 mSv	>190 mSv	380 – 1‘900 mSv
Lifetime dose due to external irradiation (70 years) (160 mSv/MBq/m²)	>41 mSv	>82 mSv	>136 mSv	>408 mSv	816 – 4‘080 mSv
Number of persons affected (excluding the prohibited zone)	292‘000	43‘000	21‘100	3‘100	2‘200

Table 5-6 Expected external radiation exposure in relation to soil contamination for periods of 10 and 70 years spent at the location [49]

48 | Source: /22/
49 | Source: /22/

This conforms to the recommendations of the International Commission on Radiological Protection, ICRP-103 (cf. /17/) and ICRP-109 (cf. /18/). In the absence of additional measures (e.g. decontamination, shielding, restriction of time spent in the open air, etc.) this would mean that those persons who were not evacuated would accumulate a maximum lifetime dose of about 100 mSv due to external irradiation. This does not take into account any additional contributions to the dose from direct radiation from the cloud at the start of the accident or from the consumption of any contaminated food. Thanks to the promptly implemented evacuation, the personal measurements that were taken and the measures that were initiated for food (monitoring of food contamination and ban on selling it where appropriate), it can nevertheless be assumed that these contributions to the dose are likely to be of little significance.

5.8 Summary and assessment

From 12 March 2011 onwards, releases of radioactive substances occurred as a consequence of the accident at the Fukushima Dai-ichi nuclear power plant. In the first phase (until 15 March 2011), rare gases were discharged mainly during venting of the primary containments of various units, and due to the explosion in the reactor building of unit 1. As the winds were blowing from the land towards the sea during this acute phase and as the Japanese authorities had initiated evacuation measures at an early stage, the doses for the population due to the direct radiation from the cloud were of minor relevance.

From 15 March 2011 onwards large quantities of radioactive iodine and radioactive cesium have been release to the environment in particular due to the hydrogen explosion in unit 2. As the prevailing winds were from the south-east during this day and there was heavy rainfall, the area to the north-west of the power plant was heavily contaminated by deposited radioactive substances up to a distance of about 50 km. In the affected area, this led in some cases to highly increased ambient dose rates from direct radiation, and also to the contamination of foodstuffs produced in these area. Even at present time (November 2011), the ambient dose rates outside of the areas evacuated by the Japanese authorities are still high enough in places to result in an external radiation exposure of 20 mSv in the first year after the event, or of 100 mSv for the lifetime, if a person would stay constantly outdoors. However, the additional dose by the consumption of food (ingestion) is of minor importance for the Japanese population.

Besides the airborne discharge of radioactive substances, leakages in a cable duct led to a significant discharge of radioactivity into the sea at the start of April 2011. The concentration of the activity in the water in thesurroundings of the plant normalised again by the end of April 2011. Nevertheless, isolated samples are even now being found in Japan in fishery products where the limit for Cs-137 is exceeded. In the meantime, the Japanese government has published a plan setting out the options for decontamination measures in order to continue reducing radiation exposure for the population.

6 Effects on the population in Switzerland

(Contribution by the Federal Office of Public Health (FOPH))

6.1 Overview

The accident at the Fukushima Dai-ichi nuclear power plant caused by the extreme earthquake on 11 March 2011 and the associated tsunami led to the release of large amounts of radioactivity in the following days. Air masses with radioactivity from this reactor accident even reached Switzerland at the end of March 2011, albeit in much diluted form.

Radioactivity in the environment and in food is monitored in Switzerland by the Federal Office of Public Health (FOPH). This takes place in collaboration with the cantonal laboratories and other specialised laboratories at federal and cantonal level. After the reactor accident at Fukushima Dai-ichi in March 2011, the ongoing sampling plan was expanded with the addition of extra air filter, grass, vegetables and milk samples. This section documents the main measurement results and conclusions.

The radionuclide concentrations measured in Switzerland were below the detection limits of the automatic alarm measurement networks (NADAM, MADUK and RADAIR), and they were 1'000 to 10'000 times lower than the concentrations measured in Switzerland after Chernobyl.

Primarily, it was possible to determine increased concentrations of Iodine-131 in the air close to ground level with the help of sensitive measuring equipment. Other radioisotopes originating from Fukushima such as Cesium-134 and Cesium-137 were also detected in lower concentrations. I-131 occurred in particulate form and also in gaseous form, in concentrations that were up to five times higher. The maximum total concentration of I-131 (particulate and gaseous) measured close to ground level in Switzerland was about 2'000 µBq/m³. Traces of I-131 carried in the air also reached rainwater, grass and outdoor vegetables (a few Bq per kilogram of fresh/wet weight). Of the milk samples from Switzerland that were measured, only one single sample showed the slightest traces of I-131 (0.1 Bq/kg). The radioactivity from Fukushima that was detected in Switzerland was harmless to the health of the population. Since mid-April 2011, the concentrations of all isotopes from Fukushima in the air in Switzerland have declined (cf. Figure 6-1).

High-volume samplers (HVS) were used to take aerosol samples at five different locations, followed by gamma-spectroscopic analysis in the laboratory. In March and April 2011, the emissions from Fukushima led to significantly increased measurement values, although these were harmless to the health of the population in Switzerland at all times.

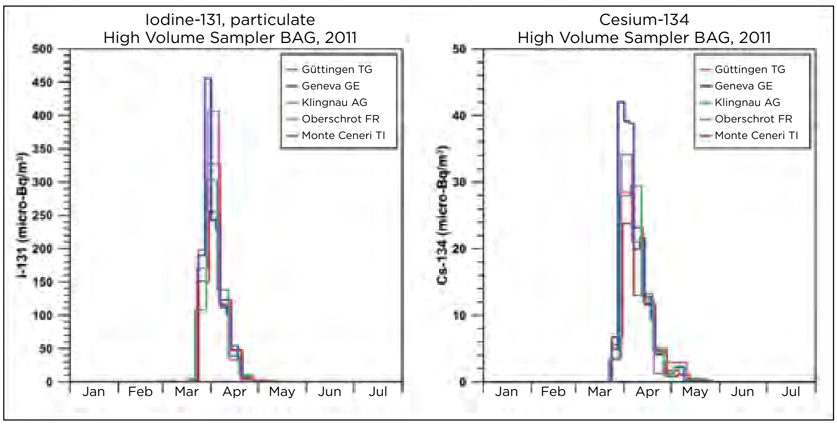


Figure 6-1 Progression of I-131 (left, particulate) and Cs-134 concentrations (right) in Switzerland from the start of January until the end of July 2011 [50]

6.2 Measurements of airborne radioactivity

6.2.1 High-volume samplers (HVS, air filters)

Samples for high-sensitivity measurement of radioactivity in atmospheric dust are taken at five locations in Switzerland using high-volume samplers, as they are known. With the help of a powerful pump, atmospheric dust (aerosols) is collected on a filter for a period of one week. The filter is then analysed by means of gamma-spectroscopy for various radioactive nuclides in the FOPH laboratory in Bern. For all five stations, it was possible to provide clear proof of radioactivity that was released during the reactor accidents at Fukushima and dispersed over extensive areas (cf. Figure 6-1). In particular, there were increased concentrations of I-131 (maximum concentration: 450 µBq/m³) and, to a lesser extent, Cesium isotopes (Cs-137 and Cs-134). The maximum concentrations of Cs-134 were about 10 times lower than those of I-131. The ratio of Cs-137 to Cs-134 was almost 1. Short-lived isotopes such as Tellurium-132 (Te-132), I-132 and Cs-136 were also detected in some samples.

Figure 6-2 compares the progression over time of the I-131 concentrations in Geneva with the values from a measuring station in Japan (Takasaki, Gunma province), a station in the US (west coast, Sacramento, California) and the Schauinsland station near Freiburg in Germany immediately following the accidents at Fukushima (Source: www.bfs.de). The upper dotted red line shows the maximum average daily value that occurred in Germany after the accident at Chernobyl in 1986. The Swiss immission limit (maximum concentration over a lengthy period) is also shown.

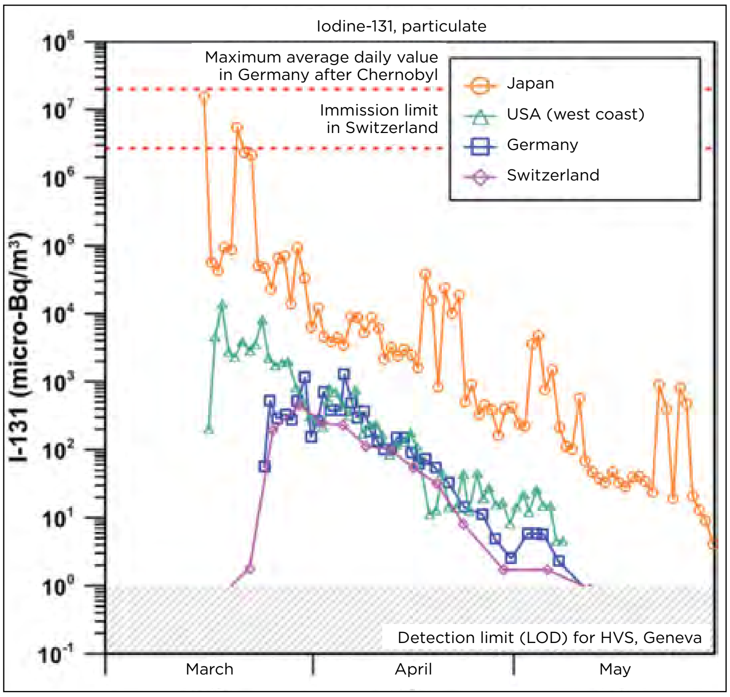


Figure 6-2 Development of the concentration of particulate iodine-131 in the atmosphere [51]

The European measuring stations registered increased radioactivity from about 22 March 2011 onwards. The highest values (up to 6'000 µBq/m³ for particulate I-131) occurred between 28 March and 6 April 2011, predominantly in the northern part of Europe. Towards the end of May 2011, the concentrations in Europe returned to values seen prior to the accident, i.e. generally below the detection limit.

51 | Source: FOPH with reference to www.bfs.de

6.2.2 Gaseous I-131

In Switzerland, gaseous I-131 is measured by four detectors (NaI) which automatically trigger alarms in case of increased values (RADAIR iodine). These detectors are located in the cantons of Geneva, Fribourg, Aargau and Ticino. The quantities of gaseous I-131 that occurred in Switzerland after the accidents in Japan were too small to be registered directly by the Iodine alarm system. On the other hand, some cartridges containing silver/nitrate granulate, which bind gaseous Iodine, were subsequently measured in the laboratory – a process that allows a lower detection limit. For the period from 31 March until 7 April 2011, activity levels for gaseous I-131 of between 1’000 and 1’800 µBq/m^3 were determined at three RADAIR Iodine locations. The concentrations of gaseous I-131 were therefore four to six times higher than those of particulate I-131, a result which corresponds well to measurements in other European countries.

6.2.3 High-altitude in-flight filter measurements (HFF)

High-altitude air samples were collected from two air filters installed on Tiger- F5 jets of the Swiss Air Force.

The results of these HFF measurements are shown in Table 6-1. At the end of March 2011, high-altitude air showed similar I-131 activity (with up to 1'900 µBq/m³) as air near ground level in northern Europe.

The fact that lower values were measured on the ground in Switzerland is probably explained by the weather situation (southerly wind).

The spectrum shown in Figure 6-3 originates from an aerosol sample that was collected on 30 March 2011 by a Tiger-F5 at an altitude of 7'900 m.

Date	Altitude [m]	Specific activity per nuclide [µBq/m³]				
		Be-7	Cs-137	Cs-134	I-131	Co-60
23.03.2011	6'100	5'000±750	<17	<15	140±30	<16
24.03.2011	7'000	4'200±640	<16	<13	<20	<23
25.03.2011	8'070	5'500±830	<20	<19	230±40	<30
25.03.2011	5'030	6'900±900	<11	<9	40±12	<11
30.03.2011	5'200	2'000±330	25±12	<8	280±40	<8
30.03.2011	7'900	10'500±1'500	170±40	170±30	1'900±260	<14
08.04.2011	12'650	31'800±4'000	30±16	<10	21±4	<13

Table 6-1 Results from high-altitude in-flight filter (HFF) measurements [52]

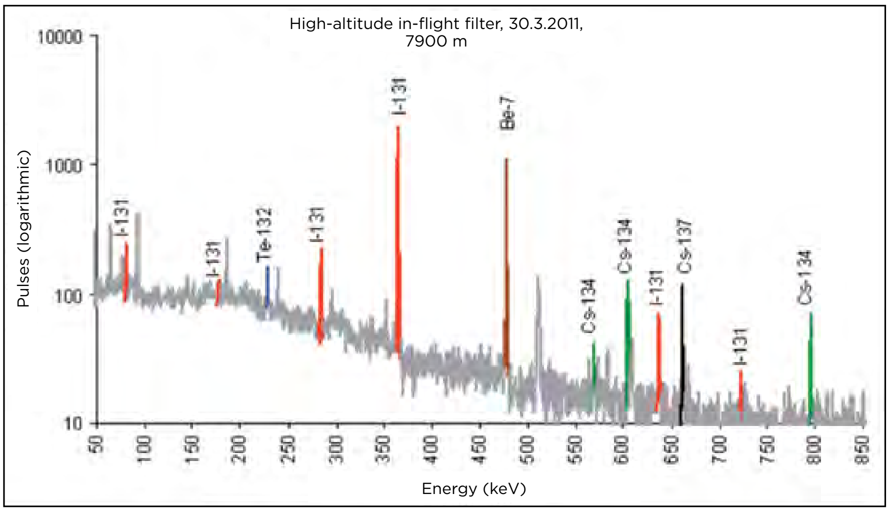


Figure 6-3 Gamma spectrum of an air filter from Switzerland with radioisotopes from the reactor accident at Fukushima [53]

52 | Source: FOPH http://www.bag.admin.ch/themen/strahlung/00045/02372/11747/index.html?lang=de
53 | Source: FOPH

6.3 Food and environmental samples from Switzerland

Air contamination also led to small deposits of radionuclides on the ground. Measurements of radioactivity on grass samples from Switzerland showed values of the order of several Bq/m². The maximum I-131 activity levels in the grass were a few Bq/kg of fresh (wet) weight. The highest values occurred at high altitudes where the quantities of precipitation are proportionately larger. As expected, similar activity levels to those in grass were also found in unwashed leaf vegetables. An approximate factor of 1/3 applies to the transfer of I-131 from grass into milk; i.e. at a constant value of 3 Bq/kg of fresh weight in grass, up to 1 Bq/kg must be expected in milk. Of the milk samples measured after Fukushima, however, only one single sample contained the slightest traces of I-131 (0.1 Bq/kg). Many cows had not yet been fed with fresh grass at the beginning of April. The limit for Iodine-131 in food from Japan is 300 Bq/kg in liquid foods (milk) and 2'000 Bq/kg in all other foods. While I-131 was also detected in rainwater, drinking water was not affected by any radioactive contamination, as expected. Other radioisotopes that definitely originated from Japan included Cs-134, of which minimal traces were detected in some grass samples. Three milk samples and three of lettuce taken in the Lausanne region at the start of April were also examined for radioactive Strontium (Sr-90). No increased values were determined. An overview of the measurements of food and environmental samples taken in Switzerland from mid-March to the end of May is shown in Table 6-2.

Medium	Number of samples	I-131 Maximum	I-131 Median
Air (HVS)	44	456 µBq/m³	48 µBq/m³
Rain	12	1.4 Bq/l	0.2 Bq/l
Vegetables	29	1.2 Bq/kg	< 0.5 Bq/kg
Grass	22	4.6 Bq/kg	0.7 Bq/kg
Milk	61	0.1 Bq/kg	< 0.2 Bq/kg
Drinking water	22	< 0.1 Bq/l	
In-situ	3	< LOD	

Table . 6-2 Overview of environmental and food samples measured following the reactor accidents at Fukushima (15 March to 30 April 2011) [54]

6.4 Summary and assessment

Although it was also possible to detect traces of the radioactivity released at Fukushima Dai-ichi in Switzerland with the help of high-sensitivity processes, there was no danger to the health of the Swiss population at any time.

Contributions to the dose from direct radiation and inhalation were so small as to be negligible.

The radioactivity from Fukushima ingested with food would only have amounted to 0.5 µSv, even if 25 kg of the most heavily contaminated vegetables (leaf vegetables) were consumed. This corresponds to one ten-thousandth of the annual radiation contamination for the population in Switzerland, which is about 5 mSv.

Fukushima

37° 25‘ 26.57“ N, 141° 1‘ 56.87“ E
11.03.2011

7 Comparison of events at Fukushima with those at Chernobyl

(with contributions from the Gesellschaft für Anlagen- und Reaktorsicherheit mbH, GRS)

7.1 Accident progression and release

Chernobyl: In the night from 25 to 26 April 1986, there was an explosion in reactor no. 4 of the Chernobyl nuclear power plant after overcriticality had been reached. This was caused by an uncontrolled power excursion in the reactor core, due among other factors to the physical characteristics of the reactor which was of type RBMK (Russian: Reaktor Bolshoi Moschtschnosti Kanalny = English: high-power channel-type reactor).

The damage to the reactor building was considerably more serious as compared to that caused by the explosions at Fukushima Dai-ichi. For example, the explosion destroyed large parts of the reactor building of unit 4, the turbine hall and the intermediate connecting building. The walls of the reactor hall were partially destroyed and the roof was entirely destroyed. The upper horizontal core plate of the reactor vessel weighing approx. 3’000 t was raised and has since stood at an angle of 15° to the perpendicular. The south-eastern quadrant of the lower core plate and the emergency cooling system in the north-eastern part of the reactor building were entirely destroyed. The reactor shaft, in which the reactor was located, is virtually empty. A large part of the nuclear fuel was hurled into the reactor hall or is present in the form of solidified lava beneath the original position of the reactor.

The explosion of the reactor and the fire in the reactor core that lasted for several days afterwards led to a substantial release of radioactive material into the environment and to the ejection of debris containing fuel from the reactor core into the area surrounding the power plant.

During this intensive release, which continued for about ten days, there were constant changes in weather conditions in the immediate and more distant areas surrounding the site. The radioactive substances released by the explosion and the fire were initially whirled up to an altitude of as much as 1’200 m and were then transported in a north-westerly direction across Belarus as far as Finland and into the central and northern regions of Sweden. On the next day, the wind veered west. The path of the radioactively contaminated air masses passed over Poland, the Czech Republic and Austria to southern Germany, where they arrived between 30 April and 1 May 1986. On the following day, the wind changed to blow towards Greece and Turkey, and then back again towards Scandinavia.

Fukushima Dai-ichi: By contrast, the progression of the ambient dose rate at the Fukushima Dai-ichi site features several separate releases in the period from 11 to about 27 March 2011 (cf. Figure 3-2). During this period, the wind was mainly blowing from westerly directions, so a large part of the releases were blown onto the open Pacific Ocean. On 15 March 2011, however, there was a situation with an airflow from south-easterly directions combined with precipitation, so larger quantities of radioactive substances were deposited in a band running north-west from the site on that day (cf. section 5.2).

Chernobyl: The quantity of radioactive substances released up to 6 May 1986 – disregarding the noble gases (most of which have short half-lives) and the Tritium – was estimated in 1986 as 1.8E+18 Bq, with an uncertainty of ± 50%. Also in 1986, the proportion of nuclear fuel located outside the reactor after the accident was determined as 3.5 3 0.5% of the nuclear fuel mass (190 t). Both estimates have been confirmed by more recent studies. Almost all of the noble gases Krypton and Xenon and the Tritium contained in the core escaped. Major uncertainty continues to prevail regarding the estimate of the released percentages of highly volatile Cesium and Iodine isotopes. A more recent assessment results in a value of 33 ± 10% of the core inventory for the Cesuim-137 release. This corresponds to activity of approx. 2.9E+17 Bq, cf. Table 7-1.

Even greater uncertainty attaches to the determination of the release of Iodine isotopes, which can occur as aerosols as well as in the gaseous state. The relative constancy of the ratio of Iodine-131 and Cesium-137 in the fallout in most European countries makes it possible to set a lower limit on the release of Iodine. A released percentage of at least 50% of the Iodine-131 core inventory should be taken as the most accurate estimate. Taking account of radioactive decay, this corresponds to a release of activity amounting to approx. 3.1E+18 Bq. Strontium-90, with a released percentage of 4% of the total inventory, is representative of the group of not easily volatilised radionuclides. A quota of 3% is assessed for the release of alpha-emitting actinides (which are mostly long-lived), i.e. in particular for Plutonium.

The released percentages in Table 7-1 correspond to the values stated in UNSCEAR 2000 (cf. /19/).

Radionuclide	Half life [days]	Core inventory [Bq]	Estimated proportion released [%]
Kr-85	3'930	3.3E+16	100
Xe-133	5.27	7.3E+18	100
I-131	8.05	3.1E+18	50
Te-132	3.25	3.2E+18	15
Cs-134	750	1.9E+17	33
Cs-137	11'000	2.9E+17	33
Ru-106	368	2.0E+18	3
Sr-89	53	2.3E+18	4
Sr-90	10'200	2.0E+17	4
Pu-238	31'500	1.0E+15	3
Pu-239	8'900'000	8.5E+14	3
Pu-240	2'400'000	1.2E+15	3
Pu-241	4'800	1.7E+17	3
Cm-242	164	2.6E+16	3

Table . 7-1 Percentages of the main radionuclides released in the accident at Chernobyl, as known in 1996 [55]

Fukushima Dai-ichi: In order to determine the total airborne release of radioactive substances at the site, NISA published two estimates on 12 April 2011 /5/. These were made by NISA and the NSC. According to them, the estimated release release of 1.3E+17 Bq of Iodine-131 and 6.1E+15 Bq of Cesium-137 corresponded to about 10% of the quantity of radioactive substances (Iodine equivalent) released due to the accident at Chernobyl. At the start of June 2011, the Japanese government published a report addressed to the IAEA which updated and gave more precise definitions of the estimates for the airborne release of radioactive substances /1/. The result of the calculations, covering a wide spectrum of nuclides, is shown in Table 2-3.

55 | Source: /20/

As compared to the accident at Chernobyl, it is apparent that the releases at Fukushima are dominated by Iodine and Cesium isotopes. In particular, the percentages of not easily volatilised radionuclides such as Strontium (cf. /31/) and/or of long-lived alpha-emitting actinides such as Plutonium (cf. /32/) are estimated as lower by several orders of magnitude.

7.2 Radiological situation on the plant site

Chernobyl: Following the explosion in unit 4, the most urgent priority was to isolate the destroyed reactor from the surrounding environment in order to prevent a further discharge of highly radioactive substances. For this purpose, a concrete and steel structure, known as the “site enclosure” or “sarcophagus”, was erected around the destroyed reactor in the period from May to October 1986. No time was left for detailed planning due to the urgency of the matter.

Fukushima Dai-ichi: Enclosures are to be erected over the reactor buildings of units 1, 3 and 4 so as to prevent further activity from being discharged. The structure in this case is made of steel, covered with reinforced watertight plastic film (cf. Figure 7-1). The construction work on unit 1 at the Fukushima Dai-ichi plant began on 10 August 2011. According to TEPCO, the operating company, work on the enclosure was successfully completed on 28 October 2011. TEPCO goes on to state that a start can be made on building the enclosures for units 3 and 4 in summer 2012 at the earliest, after the debris has been cleared away.

Figure 7-1 Enclosure for unit 1, view from the north [56]

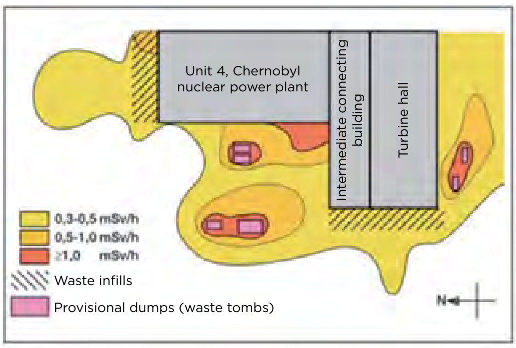
Chernobyl: Of the 190 t of spent nuclear fuel located in unit 4 of the nuclear power plant at the time of the explosion, about 96% is still stored inside the sarcophagus, and about 0.5 to 1% is scattered on the site at distances of up to approx. 500 m from the sarcophagus, mainly in the form of finely dispersed particles but also as pieces of debris from the active zone. Another quota of about 1.5% is located in the form of finely dispersed particles in a zone with a radius of 80 km, although most of it is in the 30 km zone around the power plant. The remaining component of about 1.5% was carried by atmospheric propagation beyond this distance of 80 km (and in some cases much further away) in the form of finely dispersed particles. The total mass of radioactive dust in the sarcophagus is estimated at 1 t, with an activity of 4.3E+15 Bq. The lower rooms of the sarcophagus contain approx. 3’000 m^3 of contaminated extinguishing water and rainwater that has penetrated from outside.

Fukushima Dai-ichi: By means of the provisional feed for a few hours and/or days after the occurrence of the event, the reactors and spent fuel pools were initially supplied exclusively with non-contaminated water from outside (initially seawater and later

56 | Source: TEPCO http://www.tepco.co.jp/en/news/110311/images/110917_02.jpg

fresh water). As a result of this, several hundred cubic metres of highly contaminated water were created each day, especially in the reactor pressure vessel (RPV). Moreover, large quantities of contaminated water accumulated in the buildings' lower storeys, and in trenches and shafts outside the buildings. Due to leaks in the area of the cooling water intakes, highly contaminated water entered the Pacific on several occasions. According to JAIF, up to approx. 100’000 m³ of contaminated water with activity of 720’000 TBq was present on the plant site.

Chernobyl: Figure 7-2 shows the ADR at the Chernobyl site ten years afterwards. The ADR for gamma radiation in the area immediately surrounding the sarcophagus, the degasifier wing and the turbine halls of unit 4 at a height of 1 m above ground level is about 0.3 to 0.5 mSv/h. The dose rate at distances of up to approx. 150 m from the aforementioned buildings is about 0.1 to 0.2 mSv/h. There are about 10 waste tombs for radioactive substances (dumps) with dimensions of up to about 10 x 10m on the site, mainly on the west wall of the sarcophagus. It is suspected that at least three of these waste tombs contain highly active waste and possibly pieces of debris from the active zone. The waste tombs were dug during the decontamination work and when the sarcophagus was being built. The Cesuim-137 concentrations on the nuclear power plant site are approximately between 1’000 and > 10’000 kBq/m²



Cartogram for the ambient dose rate of Cesuim 137 at a height of one meter above ground level

Figure 7-2 Ambient dose rate at Chernobyl unit 4, 1 m above ground level [57]

Fukushima Dai-ichi: The ADR at the “Main building, south side” monitoring post on the plant site is currently about 0.3 mSv/h. In the immediate vicinity and inside units 1 to 4, significantly higher ADR values are measured in some cases. The main deposits detected in soil samples to date are of Iodine-131, Cesuim-137 and Cesuim-134. Due to its short half life of 8.02 days, Iodine-131 no longer contributes to the ambient dose rate, as is also the case on the Chernobyl site.

Chernobyl: In 1986, a medical committee decided on the criteria for evacuation measures in the current 30 km zone around the Chernobyl nuclear power plant. In the first weeks of the evacuation, the main objective was to protect residents (and especially children and pregnant women) living in the area immediately surrounding the nuclear power plant against ionising radiation.

At Chernobyl, the decision criterion applied for evacuation was the measured ambient dose rate. Areas where an additional radiation dose of more than 5 mSv/a /20/ could be expected for members of the population were to be evacuated first. The first evacuation at short notice on 27 April involved 116’000 persons. This was followed on 2 and 3 May 1986 by a second phase of evacuation from the 10 km zone around the stricken reactor, involving about 10’000 persons.

57 | Source: /20/

The 30 km zone around the reactor was also evacuated from 4 and 5 May 1986 onwards. According to a United Nations report, a total of almost 400'000 people (150'000 in Belarus, 150'000 in the Ukraine and 75'000 in the Russian Federation) relocated either on a mandatory basis or of their own accord.

Fukushima Dai-ichi: An evacuation of the population within a 3 km radius around unit 1 was effected on the evening of 11 March 2011. Prior to the cloud phase, the evacuation zone was extended several times within one day until it finally covered a radius of 20 km. On 15 March 2011, the population around this 20 km evacuation zone was recommended to stay inside buildings, within a radius of up to 30 km. On 10 April 2011, it was decided to extend the 20 km evacuation zone so as to include areas where an annual radiation exposure of more than 20 mSv could be expected. A total of approx. 153'000 residents were affected by the evacuation measures /22/.

7.3 Radiological situation in the surrounding area

Chernobyl: Outside of the prohibited zone, areas in Russia, Belarus and the Ukraine with Cesuim-137 activity levels in the top layer of soil of > 37 kBq/m^2 are defined as contaminated and are subject to radiological monitoring, as it is called. According to official information from Belarus, the areas affected 10 years after the event were 46'500 km^2 in Belarus /23/, 57'000 km^2 in Russia /24/ and 41'800 km^2 (including the prohibited zone) in the Ukraine /25/.

Fukushima Dai-ichi: By comparison, areas in Japan with a Cesuim-137 activity level in the top layer of soil of > 30 kBq/m^2 are limited to a few thousand km^2 (cf. Figure 5-19). This results in substantially lower radiation exposure for the population (cf. Table 7-3) and, with suitable decontamination measures, soon makes it possible for many residents to return to their home towns or villages.

Chernobyl: Because the locations of the power plants at Chernobyl and Fukushima are very different, the impacts on the adjacent bodies of water also differ greatly. The Chernobyl nuclear power plant is situated in the interior of the country, on the river Prypyat. The cooling water was taken from the cooling pond located in the south-east of the site (cf. Figure 7-4). This is a significant feature in terms of ecology. With a length of 11.4 km, a width of 2 km and an average depth of 6 to 20 m, its water capacity is approx. 149 million m^3. It was heavily contaminated by the accident. Radioactive particles and "Hot Particles" were introduced into the cooling pond by the radioactive cloud; in addition, approx. 5'000 m^3 of heavily contaminated water was pumped into the cooling pond. The total intake is estimated at approx. 2'200 TBq. Measurements indicate that the contamination nowadays consists mainly of Cesuim-137 and Strontium-90, about 90% of which is bound in the sediment. Each year, between 3.6 and 14 GBq of Strontium-90 flow into the river Prypyat from the cooling pond /27/.

Fukushima Dai-ichi: The power plant is located directly on the coast of the Pacific Ocean. Due to the emergency measures that were implemented to cool the reactors, part of the approximately 100'000 tonnes of highly contaminated water was able to escape uncontrolled into the Pacific (cf. section 2.3). The concentrations of radioactive Iodine and Cesuim isotopes in the seawater rose sharply after this.

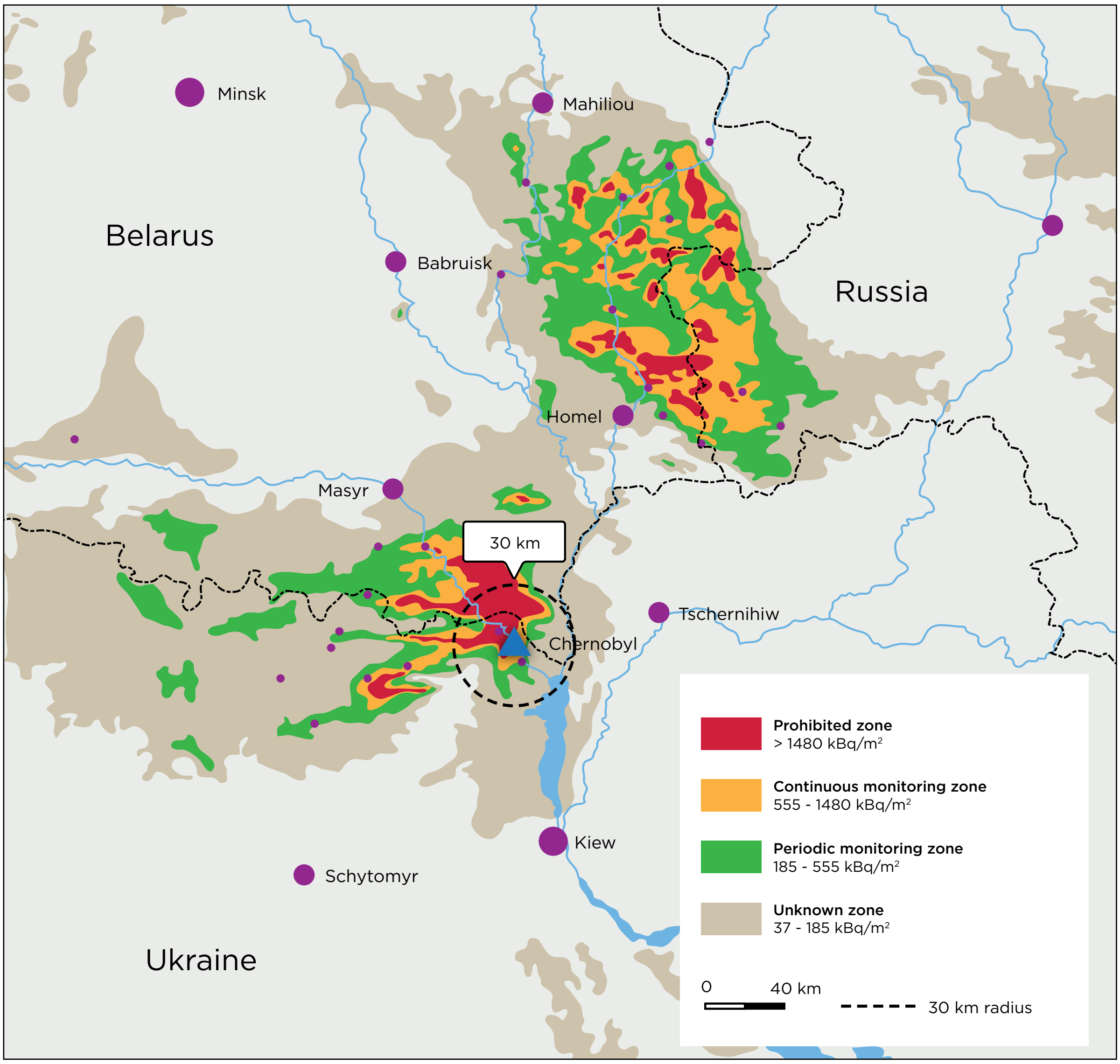


Figure 7-3 Cesium-137 contamination in Ukraine, Belarus and Russia after the reactor accident at Chernobyl [58]

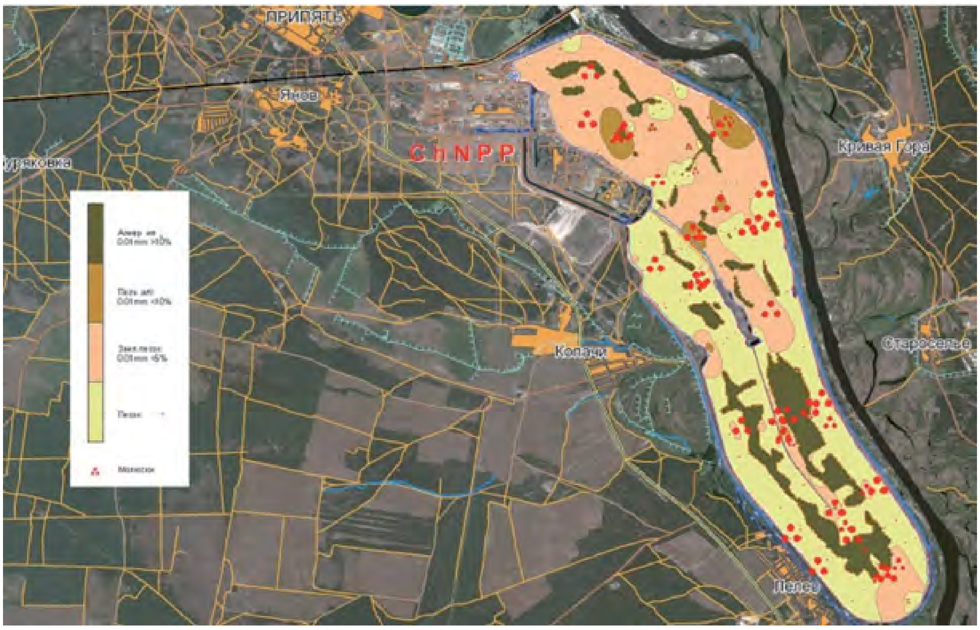


Figure 7-4 Cooling pond at the Chernobyl nuclear power plant with sediments drawn in [59]

58 | Source: University of Texas at Austin, http://www.lib.utexas.edu/maps/commonwealth/chornobyl_radiation96.jpg
59 | Source: /21/

According to estimates by TEPCO, approx. 11'000 tonnes of water with total activity of approx. 5E+15 Bq escaped into the Pacific in the period between 1 April and 11 May 2011, either in a controlled manner by pumping, or in an uncontrolled manner due to leakages (cf. section 2.4). The concentrations of Cesuim-137 measured at the monitoring posts along the coast are shown in Figure 7-5 below. Until about 8 April 2011, a sharp increase in the concentrations of radioactive Iodine and Cesuim isotopes can be observed. Since then, the contamination of the seawater with radioactive substances has gradually diminished, and for those monitoring posts not located in the area immediately surrounding the plant, is below the detection limit.

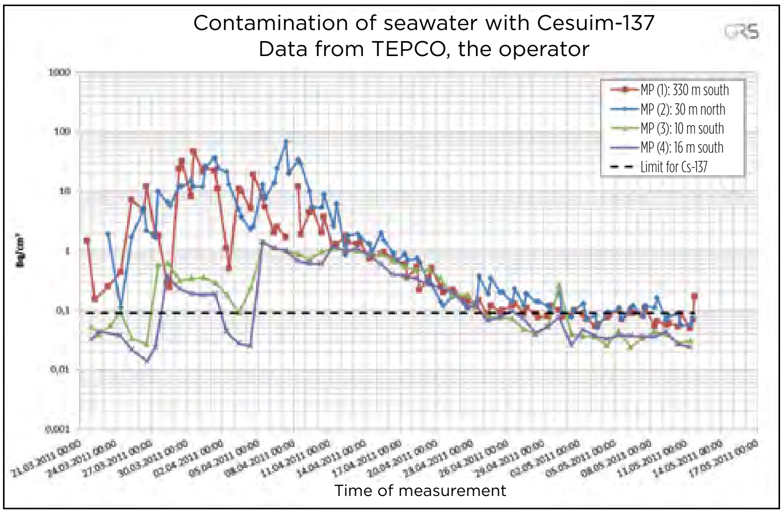


Fig. 7-5 Fukushima Dai-ichi: contamination of seawater with Cesuim-137 [60]

7.4 Radiation exposure for the operational staff and the population

Chernobyl: At Chernobyl, the reactor's operational staff, fire brigade personnel and members of the army such as helicopter pilots were deployed to fight the fire directly and to cover the open reactor core. Some of the individuals in this group received very high radiation doses. About 300 persons were taken to hospital, 134 persons showed symptoms of acute radiation sickness with weakness, vomiting and dizziness, as well as skin burns. Despite intensive medical efforts, sometimes involving bone marrow transplants at specialised clinics in Moscow and Kiev with the help of American doctors, 28 persons died of radiation sickness and of their sustained burn injuries within the first four months after the accident. The body doses were as much as 16 Gy (in this case, 1 Gy corresponds to an effective dose of 1 Sv). By 1998, another 11 persons had died due to received doses of between 1.3 and 5.2 Gy /19/.

Fukushima Dai-ichi: In the case of the reactor accident at Fukushima, on the other hand, no deaths occurred due to radiation sickness. The report by the Japanese government /1/ indicates that up to 23 May, approx. 7'800 persons entered the plant site at Fukushima to carry out work there. On average, these persons received an effective dose of 7.7 mSv, including 30 employees who received doses above 100 mSv. The limit for male power plant staff in emergency situations was increased from 100 to 250 mSv per year (effective dose) on 15 March 2011. According to information from the operator /29/, six persons received a dose of more than 250 mSv (external and internal exposure) in March.

60 | Source: /28/

On 24 March 2011, the feet and legs of two workers came into contact with contaminated water, and they received local skin doses of 2 to 3 Sv.

Chernobyl: Members of the army and civilians from many parts of the Soviet Union were deployed to carry out the decontamination and clearance work in the region of the accident-stricken Chernobyl reactor. The size of this group – known in general as "liquidators" – is difficult to determine, but according to Soviet sources they numbered 600'000 persons. According to the UN Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2000), there has so far been no noticeable increase in the general and cancer-related death rates, or in the rate of leukaemia cases. Comparable data on these aspects from Fukushima are not available as yet.

The radiation exposure for the population due to the reactor accident at Chernobyl is essentially attributable to short-lived Iodine-131 and long-lived Cesuim-137. Up to now, it has not been possible to prove an increase in mortality among the population in the contaminated areas as a consequence of increased exposure to radiation after the accident at Chernobyl. According to the WHO, however, a significant radiation-induced increase in carcinomas of the thyroid gland has been observed among children /30/.

Fukushima Dai-ichi: No noticeable doses have yet been proven among the population in Fukushima. 195'345 persons had been examined by 31 May in the prefecture of Fukushima. During the investigation of thyroid gland doses in Iwaki City, Kawamata Town and Iitate, the screening level of 0.2 mSv/h (corresponding to a thyroid gland dose equivalent of 100 mSv for a one-year-old infant) was not exceeded in any of the 1'080 children aged from 0 to 15 years who were examined /1/.

7.5 Estimation of long-term exposures

Table 7-2 below shows the doses for the population due to external radiation exposure resulting from soil contamination for the first year after the events at Chernobyl. Internal exposures due to inhalation and ingestion are not included in the data (except for Switzerland). Likewise, no account is taken of additional contributions to the dose due to direct cloud radiation at the start of the accident (Fukushima) or due to the consumption of possibly contaminated food.

In contrast to the situation at Chernobyl, residents within a radius of 20 km or 30 km were mostly evacuated in good time before the cloud phase in Japan.

Location	Average effective dose (external) per resident (mSv/year)	Number of residents affected	Comments
Fukushima	5-20	approx. 340'000	Outside of the evacuated zone as far as approx. 70 km to the north-west
Chernobyl	1-14	approx. 75 million	Outside of the evacuated zone, 30 – 1'000 km
	120	approx. 135'000	Inside the evacuated zone, 0-30 km from 26 April to 5 May 1986
Switzerland following Chernobyl	ca. 0.11	7.8 million (as of 2000)	Averaged over the whole of Switzerland + approx. 0.15 mSv internal dose

Table . 7-2 Doses for the population due to external radiation exposure for the first year of presence in relation to soil contamination [61]

61 | Source: /43/, /46/

Chernobyl: Figure 7-6 provides an overview of the propagation of the radioactive cloud from Chernobyl in relation to the progression over time. In most of Switzerland, Cs-137 contamination in the soil of <3 kBq/m² could be proven (e.g. in the Mittelland region: 1.8 kBq/m²), with up to 50 kBq/m² in southern Ticino.

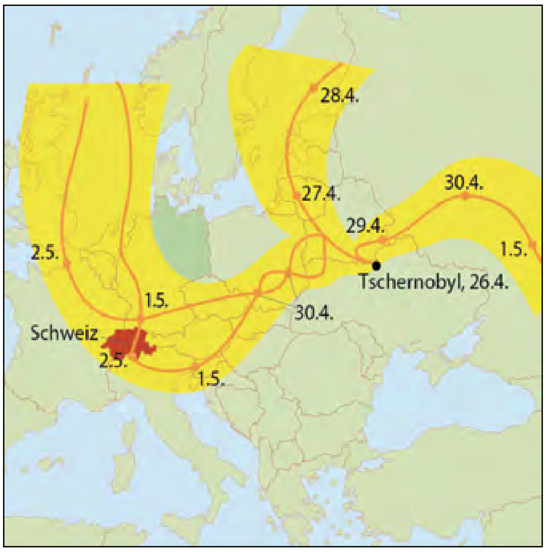


Figure 7-6 Directions of propagation and time progressions for the radioactive cloud from Chernobyl [62]

Fukushima Dai-ichi: Figure 7-7 provides an overview of deposits of Cs-134/137 around Fukushima Dai-ichi and of the expected doses in the first year after the events of March 2011. The evacuation zones are shown in Figure 5-19 and Figure 5-20

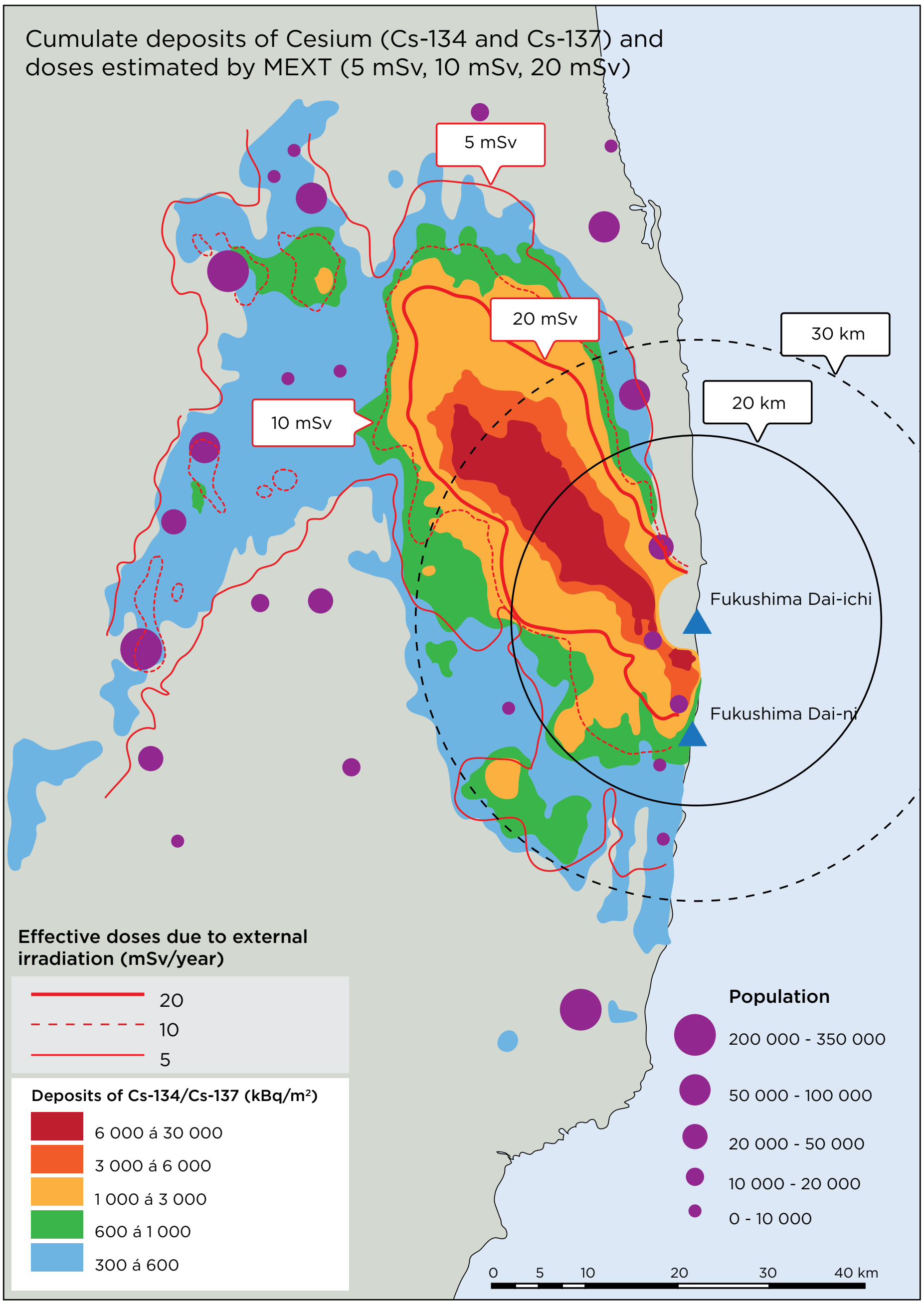


Figure 7-7 Soil contamination (Cs-137 + 134) caused by the Fukushima accident and expected effective doses due to external irradiation in the first year [63]

63 | Source: /22/

The following Table provides an overview of the estimated long-term doses for the population due to the external action of radiation. The dose values for Switzerland and Germany are based solely on the deposits following Chernobyl; as described in section 6.4, the contribution from Fukushima is extremely small and is disregarded in the estimate.

Location	Average effective dose (external) per resident (mSv/year)	Number of residents affected	Comments
Fukushima	approx. 100 in 10 years approx. 160 in 70 years	approx. 340'000	Outside of the evacuated zone as far as approx. 70 km to the north-west
Chernobyl	approx. 190 in 50 years	approx. 75 million	Outside of the evacuated zone, 30 – 1'000 km
Switzerland, estimated according to /44/ and /46/	approx. 0.6 in 50 years approx. 2.2 in 50 years	7.8 million (as of 2000)	In southern Ticino due to rain
Germany /44/	approx. 0.6 in 50 years approx. 2.2 in 50 years		North of the Danube; south of the Danube; due to rain, 30.04

Table . 7-3 Cumulative average effective doses due to external radiation exposure for periods of 10, 50 and 70 years spent at the location

7.6 Summary and assessment

Based on the available information, a comparison of the ecological and radiological consequences of the two reactor accidents at Chernobyl and Fukushima shows that the one at Chernobyl should definitely be assessed as more serious. The explosion and fire inside the reactor at Chernobyl caused the release of about five to ten times more radioactive substances, which were carried in the air for substantially longer distances than in Fukushima where a large part of the release was directed away from inhabited areas and towards the Pacific Ocean. The impact on health of the radiation on the site around the reactor in connection with the implementation of emergency measures was also more drastic at Chernobyl. At Fukushima, however, the work to bring the plant into a permanently stable condition and to establish a closed cooling circuit has not yet been completed, nor is all the relevant information available for Fukushima in order to arrive at a comprehensive assessment of the long-term consequences. According to the data available so far, the effective radiation doses due to the accident in Fukushima will be substantially lower for a (worldwide) population group that is smaller by several orders of magnitude. Moreover, it can already be stated that in Japan itself, the impact of the accident on the population and the surrounding area is considerably less than at Chernobyl. However, a conclusive assessment must be made at a later point in time.

In all these considerations, it should not be forgotten that the Tohoku-Chihou-Taiheiyou-Oki earthquake was not only the cause of the reactor accident at Fukushima, but that it was also responsible for approx. 24’000 dead and missing persons, as well as enormous damage to the economy and the infrastructure with, among other consequences, 792’000 buildings damaged or destroyed (cf. /11/).

8 List of abbreviations

APD	Active Personnel Dosimeter
FOPH	Federal Office of Public Health
FA	Fuel assembly
BfS	(German) Federal Office for Radiation Protection
BMU	(German) Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
DOE	U.S. Department of Energy
EDI	Federal Department of Home Affairs
ENSI	Swiss Federal Nuclear Safety Inspectorate
FIV	Ordinance on Foreign Substances and Constituents in Food
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit mbH [Plant and Reactor Safety Company Ltd]
HFF	High-altitude in-flight filter
HVS	High volume sampler
IAEA	International Atomic Energy Agency
ICAPP	International Congress on Advances in Nuclear Power Plants
ICRP	International Commission on Radiological Protection
INES	International Nuclear and Radiological Event Scale
IRSN	Institut de Radioprotection et de Sûreté Nucléaire [Institute of Radiation Protection and Nuclear Safety]
JAEA	Japan Atomic Energy Agency
JAIF	Japan Atomic Industrial Forum, Inc.
JMA	Japan Meteorological Agency
NPP	Nuclear power plant
MADUK	Automatic network for monitoring the dose rate in the neighbourhood of nuclear power plants
MAFF	Ministry of Agriculture, Forestry and Fisheries
METI	Ministry of Economy, Trade and Industry
MEXT	Ministry of Education, Culture, Sports, Science and Technology
MHLW	Ministry of Health, Labour and Welfare
MOX	Mixed oxide
NADAM	Automatic network for monitoring the ambient dose rate and for giving the corresponding alarm
NISA	Nuclear and Industrial Safety Agency
NPP	Nuclear Power Plant
NPS	Nuclear Power Station

NSC	Nuclear Safety Commission
LOD	Limit of detection
ADR	Ambient dose rate
RADAIR	Réseau Automatique de Détection dans l'Air d'Immissions Radioactives [Automatic In-Air Detection Network for Radioactive Immissions]
RBMK	Reaktor Bolshoi Moschtschnosti Kanalny [High-power channel-type reactor]
RPV	Reactor pressure vessel
SGTS	Standby Gas Treatment System
SSSDB	Sarcophagus Safety Status Database
BWR	Boiling water reactor
$T_{1/2}$	Half life
TEPCO	Tokyo Electric Power Company
UN	United Nations Organisation
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
USA, US	United States of America
WHO	World Health Organisation

9 List of tables and figures

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ENSI-AN-8002
Published 16.12.2011