January 7, 2014
Tokyo Electric Power Company

Method for internal dose estimation of workers at the Fukushima Daiichi nuclear power station

TEPCO established a method of the dose estimation on August 2 2011 and up-loaded a report of the dose estimation of workers on the website on July 5 2013 [1]. In the present document, the main part of the report has been translated into English by advice of experts at National Institute of Radiological Sciences (NIRS). This document describes the method for dose estimation of workers in charge of emergency or recovery operations from March 11 to June 30 in 2011 at the Fukushima Daiichi nuclear power station (FDNPS). Most of the workers could not be monitored soon after the accident because of the limitation on the number of whole-body counters available, resulting in the missing of the detection of short-lived nuclides. Main considerations in the method are as follows: (1) how to estimate the internal dose from Iodine-131 (^{131}I) that was not detected in late measurements of the workers and (2) how to evaluate multiple intake events during the period of the operation. The workers whose internal doses were estimated to be over 20 mSv as committed effective dose were further investigated at the Japan Atomic Energy Agency (JAEA).

1. Direct measurements

Whole-body measurements for the workers were performed using two types of whole-body counters (WBCs). The first one was chair-geometry WBC equipped with a plastic scintillation detector. This WBC had been used for routine individual internal dose monitoring at TEPCO's nuclear power stations before the accident. The second one was standing-geometry WBC equipped with two large NaI(Tl) scintillation detectors (FASTSCAN, Canberra Inc., US). This WBC belonged to JAEA and was operated at the Onahama coal center or TEPCO's branch offices. Hereinafter, these two types of WBCs are refereed as WBC(PL) and WBC(NaI).

Additional measurements of ^{131}I in the thyroid were performed using a NaI(Tl) scintillation survey meter. The results of measurements were used for internal dose estimations of the workers who entered the FDNPS site before early May in 2011 and were measured with WBC(PL)s. This was because it was difficult to determine the body content of ^{131}I by WBC(PL)s. Details on the direct measurements are described as follows.

1-1 Whole-body measurements with WBC(PL) (until the end of June)

Whole-body measurements with WBC(PL)s were performed to estimate internal doses from ^{134}Cs and ^{137}Cs. All net signals from WBC(PL)s were regarded as those from ^{137}Cs conservatively. (Refer to Note). When surface contamination was suspected, Whole-body measurements with WBC(PL)s were performed after the surface contamination level was reduced. WBC(PL)s were calibrated using an anthropometric phantom and a coin shaped solid radiation source of ^{137}Cs. Evaluation procedures for committed effective dose (CED) from ^{134}Cs and ^{137}Cs were described as follows.

(1) Net counts from a WBC(PL) are converted to the body content in ^{137}Cs equivalent using the calibration factor obtained from the phantom.

(2) The intake is calculated using the total body retention rate at the elapsed days from the assumed intake date.

(3) The CED is calculated by multiplying the intake by the effective dose coefficient of ^{137}Cs.

(4) The CED obtained from thyroid measurements (^{131}I) with a NaI(Tl) survey meter is added to the CED from ^{134}Cs and ^{137}Cs.

Note: It is impossible to determine the body contents of ^{134}Cs and ^{137}Cs separately by WBC(PL)s. Thus, all net signals from WBC(PL) were regarded as those from ^{137}Cs. For example, if A (Bq) of ^{134}Cs exists in the body, the body content in ^{137}Cs equivalent is evaluated to be about 2A (Bq), taking into account the difference in total emission rates between ^{134}Cs and ^{137}Cs. Internal dose from ^{134}Cs is then calculated as 1.34E-05*A mSv (=2A*6.7E-06 mSv), being larger 9.6E-06*A mSv that is an evaluated CED value based on the body content of ^{134}Cs. Thus, the whole-body measurements with WBC(PL)s give overestimations for CEDs from ^{134}Cs and ^{137}Cs.

1-2 Whole-body measurements with WBC(PL) (from July in 2011 onward)

Thyroid measurements with a NaI(Tl) survey meter were not performed later than July in 2011 because ^{131}I in the thyroid could not be detected. Therefore, the CED from ^{131}I was estimated based on either environmental data or human data of the subjects with positive detection of ^{131}I (described later).

WBC(PL)s installed at J-Village (the forward base for workers in charge of recovery work) were basically used for the screening in which a screening level (SL) (20,000 cpm as a net count) that corresponds to 0.5 mSv in CED was set. The subjects with results lower than SL were reported as “below recording level”. The subjects with results exceeding SL were further measured with WBC(NaI)s to obtain individual CED values.

Note: The screening level was set at the corresponded to 0.5 mSv in monthly whole-body measurements. SL was introduced by the following equation.

SL=0.5 mSv/6.7E-06 mSv/Bq * 0.36 / 1.3 Bq/cpm = 20,666 cpm

0.36: whole-body retention rate for ^{137}Cs on 30th days after intake

1.3 Bq/cpm: a typical calibration factor for WBC(PL)s

1-3 Thyroid measurements with NaI(Tl) survey meter

Thyroid measurements with a NaI(Tl) survey meter were employed to directly obtain the content of ^{131}I in the thyroid. These measurements were performed until early May in 2011. Evaluations based on this method were performed only for workers who entered the FDNPS from March to early May in 2011. The content of ^{131}I in the thyroid for these workers was not detected after this period.

Note: The NaI(Tl) survey meter is a non-spectrometric device, which is normally used for measuring ambient dose rates. The probe of the survey meter is placed on the front surface of the neck. The content of ^{131}I in the thyroid is obtained by multiplying a net reading (μSv/h) by a conversion factor (Bq/μSv/h) that is evaluated using a suitable phantom.

1-4 Whole-body measurements with WBC(NaI)

WBC(NaI)s are capable of quantitative determinations of the body content for each detected nuclide. If the contamination on the body surface were found on hair or the head, decontaminated by non-contaminated water was performed before the measurements. Iodine-131 was quantified as the total body content rather than the thyroid content because WBC(NaI)s were calibrated assuming a uniform distribution of the nuclides throughout the entire body; this was because the calibration was made using a Transfer phantom with the whole-body geometry source (see Canberra's homepage). The relationship in the determined ^{131}I activity between thyroid and whole-body measurements is described elsewhere [2], expecting that the ^{131}I activity from WBC(NaI)s was overestimated by about a factor of three in terms of the thyroid content. However, no correction was made in the measurements with WBC(NaI)s.

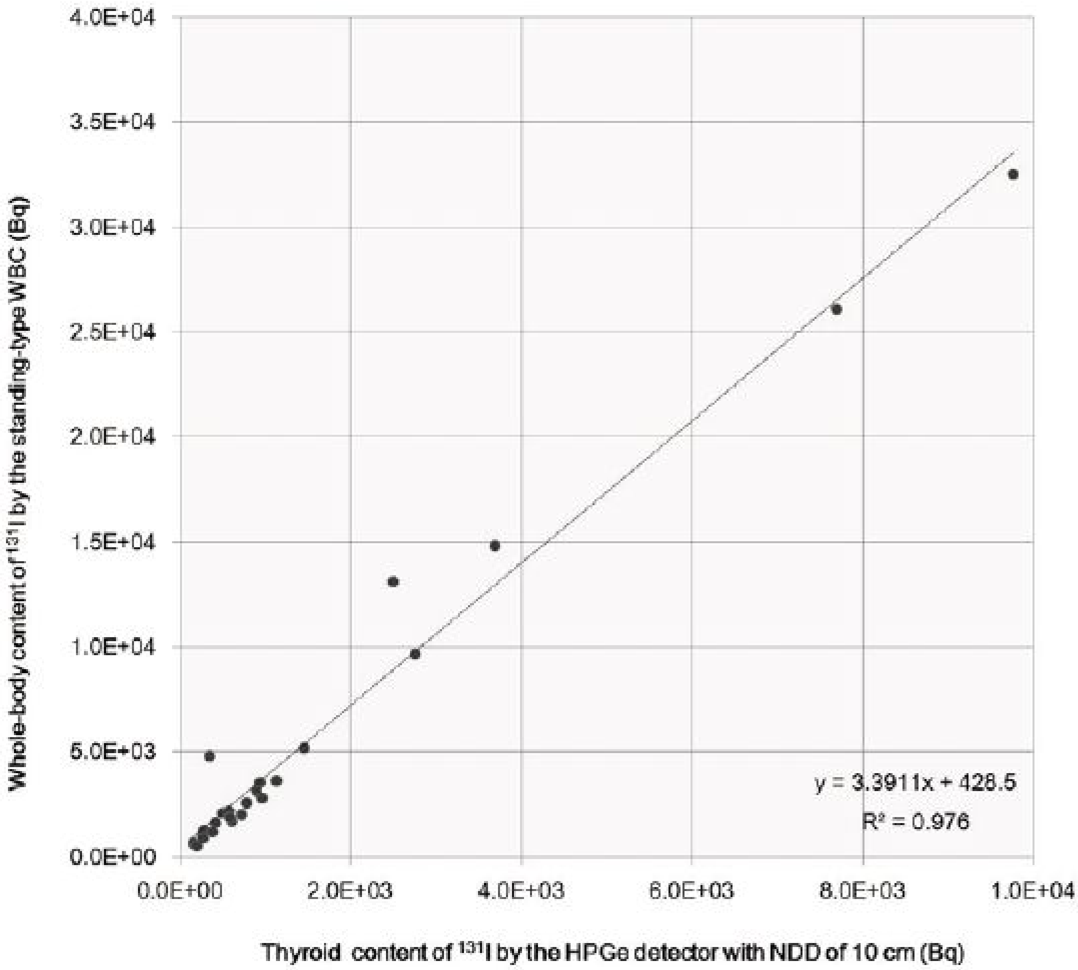

Figure 1 Comparison between the thyroid content measured using the HPGe detector and whole-body content measured using the standing-type WBC (total-body calibration) for ^{131}I [2].

1-5 Precise measurements at other institutions

The subjects were further investigated at JAEA when their internal doses exceeded 20 mSv in TEPCO's dose estimation. For those, behavior surveys were also performed in order to establish a realistic intake scenario. Some details on the measurements at JAEA are described elsewhere [2, 3]. The internal dose estimations were made by TEPCO based on the direct measurement results provided from JAEA.

Seven workers with their tentative dose estimations exceeding 250 mSv (including the external dose) were investigated at National Institute of Radiological Sciences (NIRS) [4]. The internal dose estimations for the seven workers were made by TEPCO based on the direct measurement results provided from NIRS.

2. Internal dose calculation

The items needed for the internal dose calculations are summarized in **Table 1**.

Table 1 Items in the internal dose calculations

Item	Description
1. Nuclides to be evaluated (chemical form)	^{131}I (vapor form) $^{132}Te/^{132}I$ (vapor form) ^{134}Cs (Type F compounds) ¶^{134}Cs was not evaluated in WBC(PL). ^{137}Cs (Type F compounds)
2. Committed effective dose coefficient	Reference: ICRP Publication 68 etc. ^{131}I (vapor form): 2.0E-05 mSv/Bq ^{134}Cs (Type F compounds) : 6.7E-06 mSv/Bq ^{137}Cs (Type F compounds): 9.6E-06 mSv/Bq
3. Retention rate	Data taken from MONDAL3 code developed by NIRS [5] and IDEC code [6]
4. Intake scenario	An acute intake scenario was assumed. The intake day was assumed as follows. ● If the starting day of operation at FDNPS is in March or April in 2011, the intake day was assumed to be the starting day (or March 12 for the subjects who started operations before March 11). ● The mid-point date of operation was regarded as the intake day for the subjects with their operations in May in 2011 or onward.

3. Methods to estimate the ^{131}I intake in case of no detection

Iodine-131 was rarely detected in the late measurements of the workers. The airborne sampling at the FDNPS site showed almost no detection of ^{131}I in July, 2011 or later (**Figure 2**). Thus, ^{131}I was excluded in the internal dose estimation when the (assumed) intake date was in July, 2011 or later.

The methods to estimate the ^{131}I intake for the subjects with no detection and the intake date from March 12 to the end of June in 2011 are described as follows.

(A) Method based on airborne radioactivity concentration ratio of $^{131}I/^{137}Cs$

The airborne radioactive concentration ratio of ^{131}I to ^{137}Cs was calculated from the airborne sampling data at the FDNPS site. Due to an insufficient number of the data, the moving average ratio (over the successive five days) on the intake date was used for the internal dose calculations (**Table 2**); namely, the intake of ^{131}I was calculated by multiplying the intake of ^{137}Cs from the whole-body measurements by the above ratio. The moving average ratio before March 19 was set at 121.7 (average from March 19 to March 24) because of a lack of data.

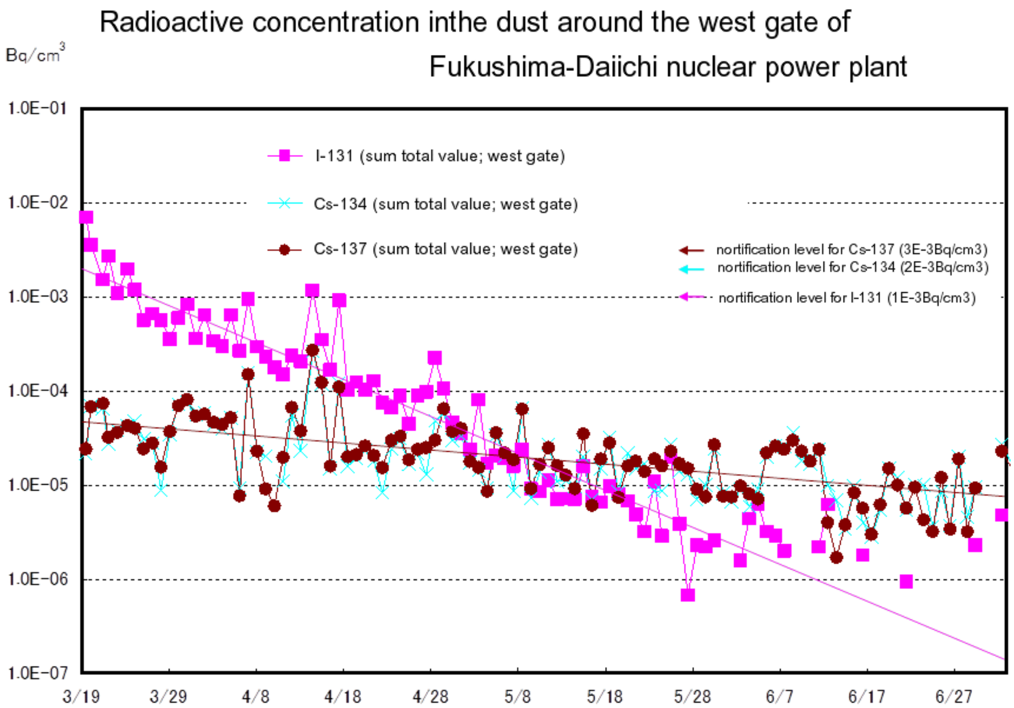

Figure 2 Radioactivity concentration of each nuclide in the airborne sampling at the FDNPS site. MDA values of each nuclide (^{131}I, ^{134}Cs, and ^{137}Cs) are in the order of 10^{-6} - 10^{-5} Bq/cm^3.

(B) Method based on the detection limit of ^{131}I

The minimum detectable activity (MDA) value for ^{131}I (as the total body content) was obtained for each whole-body measurement and was used to calculate the intake of ^{131}I assuming that the body content corresponding to the MDA value remained in the body.

Methods (A) or (B) were applied to the subjects who were measured with WBC(NaI)s. The final dose estimate was determined based on the lower of the two models' estimates. **Figure 3** illustrates the conceptual diagram of Methods (A) and (B).

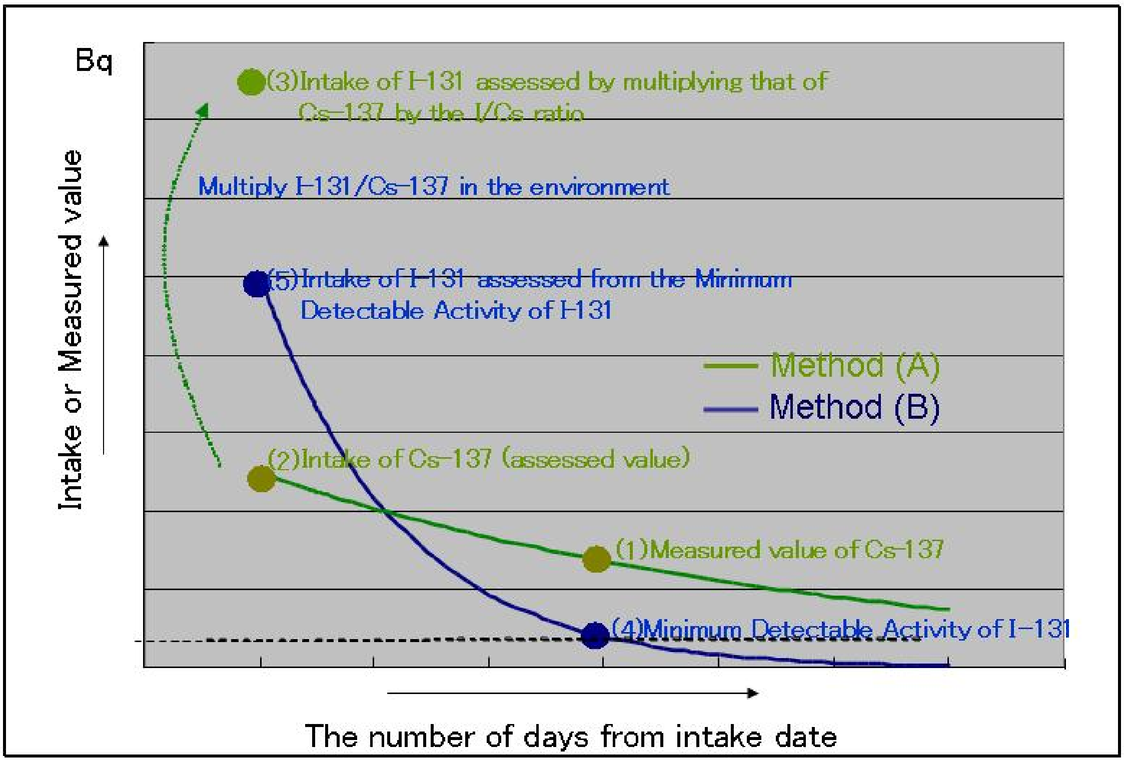

Figure 3 The conceptual diagram of Methods (A) and (B).

Method (A): Intake of ^{137}Cs is calculated based on the measured whole-body content with the retention rate ((1) → (2)) Intake of ^{131}I is then estimated using the airborne concentration ratio* of ^{131}I to ^{137}Cs ((2) → (3)). Method (B): Intake of ^{131}I is estimated from the MDA value of ^{131}I in whole-body measurements ((4) → (5)). * Refer to **Table 2**.

Table 2 Airborne radioactivity concentration ratio of ^{131}I to ^{137}Cs

	I-131			Cs-137			I-131／Cs-137		Intake location
	Gaseous	Particle	Total	Gaseous	Particle	Total	Curent day	5-day running average	
11/Mar/2011								121.7	Data collected on 3/19
12/Mar/2011								121.7	
13/Mar/2011								121.7	
14/Mar/2011								121.7	
15/Mar/2011								121.7	
16/Mar/2011								121.7	
17/Mar/2011								121.7	
18/Mar/2011								121.7	
19/Mar/2011	5.90E-03	1.10E-03	7.00E-03	-	2.40E-05	2.40E-05	291.7	121.7	North side of main administration building
20/Mar/2011	2.30E-03	1.30E-03	3.60E-03	3.90E-05	2.90E-05	6.80E-05	52.9	112.1	
21/Mar/2011	1.50E-03	9.20E-06	1.51E-03	3.60E-05	3.80E-05	7.40E-05	20.4	95.8	
22/Mar/2011	2.20E-03	4.70E-04	2.67E-03	1.30E-05	1.90E-05	3.20E-05	83.4	46.8	Main gate
23/Mar/2011	6.70E-04	4.30E-04	1.10E-03	2.30E-05	1.30E-05	3.60E-05	30.6	42.2	
24/Mar/2011	1.50E-03	5.00E-04	2.00E-03	3.10E-05	1.20E-05	4.30E-05	46.5	42.6	
25/Mar/2011	8.80E-04	3.20E-04	1.20E-03	2.40E-05	1.60E-05	4.00E-05	30.0	30.6	
26/Mar/2011	3.00E-04	2.60E-04	5.60E-04	8.80E-06	1.60E-05	2.48E-05	22.6	31.8	
27/Mar/2011	4.50E-04	2.10E-04	6.60E-04	1.40E-05	1.40E-05	2.80E-05	23.6	24.5	
28/Mar/2011	3.60E-04	2.10E-04	5.70E-04	8.10E-06	7.50E-06	1.56E-05	36.5	20.2	West gate
29/Mar/2011	2.40E-04	1.20E-04	3.60E-04	2.30E-05	1.40E-05	3.70E-05	9.7	17.7	
30/Mar/2011	4.10E-04	1.90E-04	6.00E-04	4.00E-05	3.00E-05	7.00E-05	8.6	14.4	
31/Mar/2011	6.40E-04	1.90E-04	8.30E-04	4.50E-05	3.60E-05	8.10E-05	10.2	9.3	
1/Apr/2011	2.50E-04	1.10E-04	3.60E-04	3.40E-05	2.00E-05	5.40E-05	6.7	8.8	
2/Apr/2011	4.30E-04	2.10E-04	6.40E-04	3.70E-05	2.00E-05	5.70E-05	11.2	8.4	
3/Apr/2011	2.30E-04	1.10E-04	3.40E-04	3.10E-05	1.60E-05	4.70E-05	7.2	8.9	
4/Apr/2011	2.00E-04	1.00E-04	3.00E-04	2.80E-05	1.60E-05	4.40E-05	6.8	13.3	
5/Apr/2011	4.20E-04	2.20E-04	6.40E-04	2.10E-05	3.10E-05	5.20E-05	12.3	12.3	
6/Apr/2011	2.00E-04	6.70E-05	2.67E-04	-	9.30E-06	9.30E-06	28.7	13.4	
7/Apr/2011	7.80E-04	1.70E-04	9.50E-04	-	1.50E-04	1.50E-04	6.3	17.1	
8/Apr/2011	2.10E-04	8.70E-05	2.97E-04	1.40E-05	9.00E-06	2.30E-05	12.9	20.6	
9/Apr/2011	1.50E-04	8.00E-05	2.30E-04	-	9.10E-06	9.10E-06	25.3	16.4	
10/Apr/2011	1.30E-04	4.90E-05	1.79E-04	-	6.00E-06	6.00E-06	29.8	15.8	
11/Apr/2011	1.10E-04	4.00E-05	1.50E-04	1.40E-05	5.80E-06	1.98E-05	7.6	14.4	
12/Apr/2011	1.30E-04	1.10E-04	2.40E-04	2.90E-05	3.80E-05	6.70E-05	3.6	10.2	
13/Apr/2011	9.70E-05	1.10E-04	2.07E-04	1.10E-05	2.60E-05	3.70E-05	5.6	4.8	
14/Apr/2011	7.60E-04	4.20E-04	1.18E-03	8.10E-05	1.90E-04	2.71E-04	4.4	5.4	
15/Apr/2011	2.20E-04	1.30E-04	3.50E-04	8.10E-05	4.20E-05	1.23E-04	2.8	6.3	
16/Apr/2011	1.10E-04	5.80E-05	1.68E-04	1.60E-05	-	1.60E-05	10.5	6.2	
17/Apr/2011	5.70E-04	3.50E-04	9.20E-04	-	1.10E-04	1.10E-04	8.4	6.6	
18/Apr/2011	7.10E-05	3.20E-05	1.03E-04	1.40E-05	6.00E-06	2.00E-05	5.2	6.8	
19/Apr/2011	5.00E-05	7.50E-05	1.25E-04	1.40E-05	7.00E-06	2.10E-05	6.0	5.9	
20/Apr/2011	7.00E-05	3.30E-05	1.03E-04	1.70E-05	9.10E-06	2.61E-05	3.9	5.2	
21/Apr/2011	7.60E-05	5.20E-05	1.28E-04	1.30E-05	7.60E-06	2.06E-05	6.2	4.6	
22/Apr/2011	3.70E-05	3.80E-05	7.50E-05	9.00E-06	6.30E-06	1.53E-05	4.9	4.0	
23/Apr/2011	4.00E-05	2.70E-05	6.70E-05	1.50E-05	1.50E-05	3.00E-05	2.2	3.7	
24/Apr/2011	4.80E-05	4.20E-05	9.00E-05	1.70E-05	1.60E-05	3.30E-05	2.7	3.2	
25/Apr/2011	3.10E-05	1.40E-05	4.50E-05	1.00E-05	8.60E-06	1.86E-05	2.4	3.0	
26/Apr/2011	5.00E-05	4.00E-05	9.00E-05	1.40E-05	1.00E-05	2.40E-05	3.8	4.1	
27/Apr/2011	5.10E-05	4.70E-05	9.80E-05	1.20E-05	1.30E-05	2.50E-05	3.9	3.9	
28/Apr/2011	1.60E-04	6.60E-05	2.26E-04	-	3.00E-05	3.00E-05	7.5	3.6	
29/Apr/2011	6.30E-05	4.40E-05	1.07E-04	4.50E-05	2.00E-05	6.50E-05	1.6	3.0	
30/Apr/2011	3.30E-05	1.30E-05	4.60E-05	2.50E-05	1.20E-05	3.70E-05	1.2	2.5	

	I-131			Cs-137			I-131／Cs-137		Intake location
	Gaseous	Particle	Total	Gaseous	Particle	Total	Curent day	5-day running average	
1/May/2011	2.3E-05	1.2E-05	3.5E-05	1.7E-05	2.3E-05	4.0E-05	0.9	2.1	West gate
2/May/2011	1.5E-05	8.9E-06	2.4E-05	1.0E-05	7.9E-06	1.8E-05	1.3	2.1	
3/May/2011	4.0E-05	4.1E-05	8.1E-05	7.2E-06	8.2E-06	1.5E-05	5.3	2.0	
4/May/2011	8.7E-06	8.3E-06	1.7E-05	8.6E-06		8.6E-06	2.0	2.0	
5/May/2011	1.2E-05	8.6E-06	2.1E-05	2.1E-05	1.5E-05	3.6E-05	0.6	1.9	
6/May/2011	1.0E-05	9.1E-06	1.9E-05	1.2E-05	1.0E-05	2.2E-05	0.9	0.9	
7/May/2011	9.0E-06	7.0E-06	1.6E-05	1.2E-05	6.6E-06	1.9E-05	0.9	0.7	
8/May/2011	1.3E-05	1.1E-05	2.4E-05	2.9E-05	3.5E-05	6.4E-05	0.4	0.7	
9/May/2011	5.1E-06	4.1E-06	9.2E-06	9.2E-06		9.2E-06	1.0	0.6	
10/May/2011	4.8E-06	3.7E-06	8.5E-06	8.3E-06	8.2E-06	1.7E-05	0.5	0.6	
11/May/2011	7.3E-06	3.9E-06	1.1E-05	1.1E-05	1.4E-05	2.5E-05	0.4	0.6	
12/May/2011	4.7E-06	2.4E-06	7.1E-06	1.0E-05	6.1E-06	1.6E-05	0.4	0.5	
13/May/2011	4.9E-06	2.3E-06	7.2E-06	7.9E-06	4.9E-06	1.3E-05	0.6	0.5	
14/May/2011			7.1E-06			9.2E-06	0.8	0.7	
15/May/2011			1.6E-05			3.5E-05	0.5	0.7	
16/May/2011			7.6E-06			6.1E-06	1.2	0.6	
17/May/2011			6.6E-06			1.9E-05	0.3	0.7	
18/May/2011			9.7E-06			2.8E-05	0.3	0.7	
19/May/2011			8.1E-06			7.4E-06	1.1	0.5	
20/May/2011			6.8E-06			1.6E-05	0.4	0.5	
21/May/2011			4.9E-06			1.8E-05	0.3	0.5	
22/May/2011			3.2E-06			1.4E-05	0.2	0.3	
23/May/2011			7.0E-06			1.9E-05	0.4	0.4	
24/May/2011			2.9E-06			1.6E-05	0.2	0.4	
25/May/2011			2.0E-05			2.3E-05	0.9	0.3	Near MP5
26/May/2011			3.9E-06			1.7E-05	0.2	0.3	West gate
27/May/2011			6.8E-07			1.5E-05	0.0	0.3	
28/May/2011			2.3E-06			9.0E-06	0.3	0.2	
29/May/2011			2.2E-06			7.5E-06	0.3	0.1	
30/May/2011			2.6E-06			2.7E-05	0.1	0.1	
31/May/2011			0.0E+00			7.6E-06	0.0	0.1	
1/Jun/2011			0.0E+00			7.5E-06	0.0	0.2	
2/Jun/2011			1.6E-06			9.8E-06	0.2	0.3	
3/Jun/2011			4.4E-06			8.1E-06	0.5	0.3	
4/Jun/2011			6.3E-06			7.1E-06	0.9	0.4	
5/Jun/2011			3.2E-06			2.2E-05	0.1	0.4	
6/Jun/2011			2.9E-06			2.6E-05	0.1	0.2	
7/Jun/2011			2.0E-06			2.4E-05	0.1	0.1	
8/Jun/2011			0.0E+00			3.0E-05	0.0	0.0	
9/Jun/2011			0.0E+00			2.3E-05	0.0	0.0	
10/Jun/2011			0.0E+00			1.8E-05	0.0	0.3	
11/Jun/2011			2.2E-06			2.4E-05	0.1	0.3	
12/Jun/2011			6.2E-06			4.0E-06	1.6	0.3	
13/Jun/2011			0.0E+00			1.7E-06	0.0	0.3	
14/Jun/2011			0.0E+00			3.8E-06	0.0	0.4	
15/Jun/2011			0.0E+00			8.3E-06	0.0	0.1	
16/Jun/2011			1.8E-06			5.7E-06	0.3	0.1	
17/Jun/2011			0.0E+00			3.0E-06	0.0	0.1	
18/Jun/2011			0.0E+00			6.2E-06	0.0	0.1	
19/Jun/2011			0.0E+00			1.5E-05	0.0	0.0	
20/Jun/2011			0.0E+00			1.0E-05	0.0	0.0	
21/Jun/2011			9.5E-07			5.7E-06	0.2	0.0	
22/Jun/2011			0.0E+00			9.5E-06	0.0	0.0	
23/Jun/2011			0.0E+00			4.3E-06	0.0	0.0	
24/Jun/2011			0.0E+00			3.2E-06	0.0	0.0	
25/Jun/2011			0.0E+00			1.2E-05	0.0	0.0	
26/Jun/2011			0.0E+00			3.4E-06	0.0	0.0	
27/Jun/2011			0.0E+00			1.9E-05	0.0	0.0	
28/Jun/2011			0.0E+00			3.2E-06	0.0	0.0	
29/Jun/2011			2.3E-06			9.3E-06	0.2	0.0	Main gate
30/Jun/2011			0.0E+00			0.0E+00	0.0	0.0	West gate

(C) Method based on human data with the detection of ^{131}I

Figure 4 shows individual CED ratios of ^{131}I to ^{137}Cs as a function of the intake day. The CEDs from ^{131}I and ^{137}Cs were obtained from thyroid measurements with NaI(Tl) survey meters and whole-body measurements with WBC(PL)s, respectively. It is noted that the body content of ^{137}Cs from WBC(PL)s includes that of ^{134}Cs as mentioned earlier. The plots in the figure were taken from around 500 subjects who were dispatched to the FDNPS site from the Kashiwazaki-Kariwa nuclear power station and were also measured with both WBC(PL) and a NaI(Tl) survey meter at the station after the surface contamination level was reduced. The solid line in the figure was drawn to superpose almost all of the plots, expecting to give conservative dose estimations.

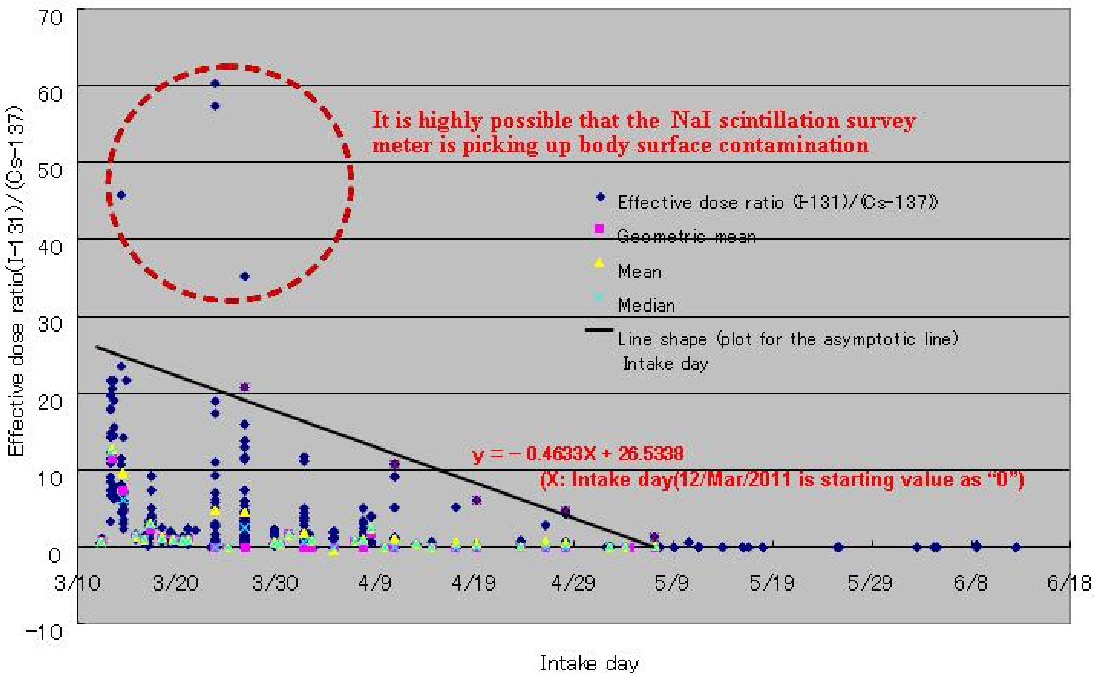

Figure 4 Individual CED ratios of ^{131}I to ^{137}Cs as a function of the intake day

(D) Method based on estimations from the subjects with the same working period

Method (C) was applied to those without the detection of ^{131}I in the measurements with WBC(PL)s. Method (D) was applied to the rest of the workers (those with no detection in their measurements with WBCs(PL)s or WBC(NaI)s.

4. Summary

The method described in this document was checked by the regulatory authority – the Ministry of Health, Labor and Welfare (MHLW) and its validity was also confirmed by Japanese experts. This method gave overestimated internal dose estimations by the most conservative intake scenario (acute intake on either March 12 or the first day of operation) and conservative assumptions in direct measurements. Although short-lived nuclides other than ^{131}I (e.g., ^{132}I, ^{133}I, ^{132}Te) were not considered in the present dose estimation, the contribution of these nuclides to the total internal dose would be negligible compared to realistic dose estimations. However, further dose reconstruction based on detailed information of individual behavior, a source term, and other available data in future is required.

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