ATTACHMENT D-1

ESTIMATION OF THE POSSIBLE CONTRIBUTION OF INTAKES OF SHORT-LIVED RADIONUCLIDES TO EFFECTIVE DOSE AND ABSORBED DOSES TO ORGANS FOR WORKERS AT THE FUKUSHIMA DAIICHI NUCLEAR POWER STATION

UNSCEAR 2013 Report, Annex A, Levels and effects of radiation exposure due to the nuclear accident after the 2011 great east-Japan earthquake and tsunami, Appendix D (Assessment of doses to workers)

Content

This attachment describes the methodology and results of the Committee's assessment of the possible contribution of intakes of short-lived radionuclides to internal exposure of workers at the Fukushima Daiichi Nuclear Power Station. This assessment had been conducted for the UNSCEAR 2013 Report, although this attachment describing the methods and results in detail was issued subsequently.

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Notes

The designations employed and the presentation of material in this publication do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory, city or area, or of its authorities, or concerning the delimitation of its frontiers or boundaries.

This publication has not been formally edited.

Contents

I. INTRODUCTION

1. Internal exposures of workers at the Fukushima Daiichi Nuclear Power Station (FDNPS) were mainly determined using the results of measurements of the activities of radionuclides in the body (in vivo monitoring). The radionuclides measured were typically limited to ^{131}I, ^{134}Cs and ^{137}Cs. For a few workers, particularly those with higher assessed internal exposures, the results of in vivo monitoring of the activities of ^{129m}Te and ^{136}Cs were also reported.

2. Delays in commencing in vivo monitoring with high energy resolution detectors meant that some radionuclides with short half-lives that were likely to have been present in the body early on had not been detected. In consequence, the contributions to dose from internal exposure from these short-lived radionuclides had not been included in the doses reported by TEPCO for FDNPS workers; see appendix D. The short-lived radionuclides of most interest in this context are ^{132}Te, ^{132}I, ^{133}I and ^{136}Cs. Because of the short half-lives of these radionuclides, their contributions to dose would have arisen mainly from intakes during the days immediately following the shutdown of the reactors.

3. In the absence of in vivo monitoring data for these short-lived radionuclides, the Committee made estimates of the additional contributions to dose arising from intakes of each of these radionuclides for three generic intake scenarios. This attachment describes the methodology used and the results of the assessment.

4. For each scenario, the Committee estimated the magnitude of the intake of each short-lived radionuclide scaled to unit intake of ^{131}I, using estimates of the relative amounts of radionuclides released to the atmosphere during specified time periods. This procedure implicitly assumed that the radionuclide content of the release at any particular time was representative of the radionuclide content of airborne radionuclides inhaled by workers at that time. Reference values of dose coefficients specifying dose per unit intake for each of the short-lived radionuclides, as well as for ^{131}I, were then used to determine the additional contribution to dose relative to the dose arising from ^{131}I intake. (For the FDNPS workers for whom independent assessments were performed, reported doses had been due almost entirely

to ^{131}I intakes; see appendix D, paragraphs D43 and D54.) The doses estimated in this way were the committed effective dose and the committed absorbed doses to the thyroid, red bone marrow and the colon.

5. For each short-lived radionuclide, the estimated intake per unit ^{131}I intake depended on the assumed time period over which intakes took place, because the activities of the short-lived radionuclides released decreased rapidly relative to ^{131}I following reactor shutdown. For an individual worker, the assumed intake period depended on their detailed work history while at the FDNPS site, as well as on information on their use of protective measures to limit or prevent intakes. Such information included the times and administered amounts of any stable iodine provided to individual workers for prophylactic use; and the periods when items of personal protective equipment such as respirators or face masks were being used effectively by each worker. These types of information, where available, were used in the Committee's independent assessments of individual dose for selected workers that are described in appendix D. Unfortunately, the level of information of this type provided to the Committee was variable and incomplete.

6. The aim of the assessment reported here was to provide estimates of the additional contributions to dose that could have arisen from intakes of short-lived radionuclides for the FDNPS workforce as a whole, rather than for individual workers. Therefore, the assessment was performed using intake periods that provide realistic upper and lower bounds for the estimated additional contributions to dose for the two groups of workers identified in appendix D, that is "workers with the highest internal exposure" and "workers with lower internal exposure". These generic scenarios are presented and discussed in the next section.

II. METHOD

A. Generic intake scenarios

7. The intake periods specified for the three scenarios were:

(a) *Scenario A:* intakes took place continuously during the first 4.5 h of the release (05:00 to 09:30 JST on 12 March 2011) and then stopped;

(b) *Scenario B:* intakes took place continuously from the start of the release at 05:00 JST on 12 March 2011 until 00:00 JST on 1 May 2011 and then stopped;

(c) *Scenario C:* intakes took place continuously from 05:00 JST on 12 March 2011 until 17:00 JST on 15 March 2011 and then stopped.

8. Scenarios A and C provided the upper and lower bounds of the estimated additional contributions to dose for the majority of the small group of workers with the highest internal exposure, as identified in appendix D. This group was made up of those workers with reported committed effective doses greater than 100 mSv. Work history information for 10 out of the 12 workers[a] within this group indicated there was reasonably good evidence that their intakes commenced on 12 March 2011. However, the available evidence did not allow a clear conclusion to be drawn about whether intakes effectively ceased at some time during 12 March, or continued for a few more days. For all of the workers in this group for whom

[a] As a result of a reassessment of worker doses made in Japan, a thirteenth worker with a dose close to 100 mSv was added to this group. This does not affect the assessment presented here.

intakes probably commenced on 12 March, information on their work history and protective measures taken indicated that intakes at a significant level had likely ceased by 15 March. (For the two remaining workers in this group, intakes could not have commenced until 18 March; they both had assessed doses at the lower end of the range, close to 100 mSv.)

9. The additional dose contribution from short-lived radionuclides is particularly sensitive to the intake period, which was the reason for giving special attention to this issue for this assessment. In the Committee’s earlier independent assessments of dose from ^{131}I intakes and the “Japanese” assessments performed by both Japan Atomic Energy Agency (JAEA) and National Institute of Radiological Sciences (NIRS), a single ^{131}I intake was assumed to have taken place on 12 March 2011 for 9 out of the 10 workers. This was reasonable because the assessed doses were not very sensitive to the precise period of intake because of the relatively long half-life of ^{131}I in this context. For the remaining worker, the ^{131}I intake was assumed to have commenced on 11 March and ceased on 14 March. For the 17 Japanese assessments of doses to the 10 workers, 13 were based on an assumed single ^{131}I intake on 12 March and 7 on an assumption that the ^{131}I intake commenced on 11 March and variously ceased on 12, 13 or 14 March. These assumptions about intake period made for the earlier assessments of individual dose are not inconsistent with those in the generic scenarios used in this assessment.

10. Scenarios A and B provided the upper and lower bounds of the estimated additional contributions to dose for the group of workers with lower internal exposure, as identified in appendix D. For these workers, individual work history information was not available to the Committee, and so the period of intake may have extended to later dates. However, for those workers in this group who could not have received a radionuclide intake before about 19 March, the additional contributions to dose from intakes of short-lived radionuclides would have been negligible. Such workers were therefore excluded from any consideration of dose from intakes of short-lived radionuclides.

B. Estimation of intakes of short-lived radionuclides relative to the ^{131}I intake

11. Table D1-1 shows the estimated time-dependent releases to the atmosphere of the radionuclides ^{132}Te, ^{131}I, ^{132}I, ^{133}I, ^{133}Xe[b], ^{134}Cs, ^{136}Cs and ^{137}Cs, during defined time periods in March and April 2011 (see section II-A of appendix B). The releases of ^{131}I, ^{134}Cs and ^{137}Cs are those estimated by Terada et al. [Terada, 2012] who limited their assessment to these radionuclides because they were deemed to be the most important. The estimates of the releases of the short-lived radionuclides were derived from measurements of their levels in the environment (relative to longer-lived radionuclides) and from their relative inventories in the three reactors.

12. For scenario A, the values for each radionuclide from the first row of the table were taken, covering the period from 05:00 to 09:30 JST on 12 March 2011. For scenario B, all of the values in the table were summed for each radionuclide, covering the period from 05:00 JST on 12 March 2011 to 00:00 JST on 1 May 2011. For scenario C, all values between 05:00 JST on 12 March 2011 and 17:00 JST on 15 March 2011 were summed for each radionuclide. Values for each radionuclide and scenario were normalized by dividing by the corresponding ^{131}I activity.

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[b] Xenon-133 was not considered further because it is not deposited in the respiratory tract, and so would not have given rise to an internal exposure.

Table D1-1. Estimated time-dependent releases of radionuclides to the atmosphere during the accident at FDNPS

Data were taken from Terada et al. [Terada, 2012], but supplemented by estimates made for short-lived radionuclides—see section II-A of appendix B. The activities released are the products of the release rates and the time periods given in table B5 of appendix B

Time period in 2011 (JST)		*Duration (h)*	*Activity released (Bq)*							
Start	*End*		^{132}Te	^{131}I	^{133}Xe	^{132}I	^{133}I	^{134}Cs	^{136}Cs	^{137}Cs
12 March 05:00	12 March 09:30	4.5	1.79E+14	1.67E+14	2.96E+16	1.79E+14	2.15E+14	1.71E+13	5.00E+12	1.67E+13
12 March 09:30	12 March 15:30	6	1.04E+14	1.02E+14	4.58E+17	1.04E+14	1.13E+14	1.05E+13	3.04E+12	1.02E+13
12 March 15:30	12 March 16:00	0.5	1.49E+15	1.50E+15	6.20E+15	1.49E+15	1.51E+15	1.54E+14	4.43E+13	1.50E+14
12 March 16:00	13 March 23:00	31	2.26E+15	2.60E+15	3.66E+18	2.26E+15	1.70E+15	2.68E+14	7.44E+13	2.60E+14
12 March 23:00	14 March 11:00	12	3.08E+14	4.32E+14	6.95E+16	3.08E+14	1.44E+14	4.44E+13	1.18E+13	4.32E+13
14 March 11:00	14 March 11:30	0.5	1.01E+15	1.50E+15	3.22E+15	1.01E+15	4.15E+14	1.54E+14	4.03E+13	1.50E+14
14 March 11:30	14 March 21:30	10	1.48E+14	2.30E+14	6.08E+16	1.48E+14	5.46E+13	2.36E+13	6.11E+12	2.30E+13
14 March 21:30	15 March 00:00	2.5	1.98E+15	3.25E+15	1.65E+16	1.98E+15	6.40E+14	3.33E+14	8.50E+13	3.25E+14
15 March 00:00	15 March 07:00	7	1.62E+15	2.45E+15	7.98E+17	1.62E+15	4.19E+14	2.86E+14	7.21E+13	2.79E+14
15 March 07:00	15 March 10:00	3	5.01E+15	9.00E+15	5.73E+17	5.01E+15	1.33E+15	9.24E+14	2.31E+14	9.00E+14
15 March 10:00	15 March 13:00	3	1.30E+14	2.40E+14	3.15E+17	1.30E+14	3.24E+13	2.46E+13	6.12E+12	2.40E+13
15 March 13:00	15 March 17:00	4	8.40E+15	1.60E+16	8.56E+17	8.40E+15	1.94E+15	1.64E+15	4.04E+14	1.60E+15
15 March 17:00	17 March 06:00	37	4.88E+14	7.77E+15	4.74E+17	4.88E+14	5.40E+14	1.14E+14	2.68E+13	1.11E+14
17 March 06:00	19 March 15:00	57	1.66E+15	2.34E+16		1.66E+15	4.32E+14	5.81E+14	1.24E+14	5.70E+14
19 March 15:00	21 March 03:00	36	2.37E+15	1.37E+16		2.37E+15	5.94E+13	1.27E+15	2.45E+14	1.24E+15
21 March 03:00	21 March 21:00	18	3.76E+14	2.52E+15		3.76E+14	4.77E+12	2.57E+14	4.68E+13	2.52E+14
21 March 21:00	22 March 23:00	26	1.51E+14	1.07E+16		1.51E+14	1.06E+13	1.25E+14	2.17E+13	1.22E+14
22 March 23:00	24 March 00:00	25	2.17E+14	1.78E+16		2.17E+14	8.30E+12	2.26E+14	3.70E+13	2.22E+14
24 March 00:00	25 March 00:00	24	5.42E+13	4.56E+15		5.42E+13	1.03E+12	7.03E+13	1.09E+13	6.91E+13
25 March 00:00	26 March 11:00	35	2.63E+13	1.96E+15		2.63E+13	1.89E+11	4.45E+13	6.48E+12	4.34E+13
26 March 11:00	28 March 10:00	47	3.44E+12	1.88E+14		3.44E+12	5.59E+09	8.32E+12	1.11E+12	8.18E+12
28 March 10:00	29 March 21:00	35	4.76E+13	2.63E+14		4.76E+13	2.24E+09	1.66E+14	2.04E+13	1.64E+14
29 March 21:00	30 March 11:00	14	2.87E+13	2.10E+14		2.87E+13	8.34E+08	1.25E+14	1.46E+13	1.23E+14
30 March 11:00	31 March 00:00	13	3.71E+14	2.34E+15		3.71E+14	6.23E+09	1.82E+15	2.05E+14	1.79E+15
31 March 00:00	31 March 22:00	22	1.76E+13	5.28E+14		1.76E+13	8.47E+08	1.01E+14	1.09E+13	9.97E+13
31 March 22:00	2 April 09:00	35	7.84E+12	6.30E+13		7.84E+12	4.48E+07	5.78E+13	5.92E+12	5.74E+13
2 April 09:00	4 April 09:00	48	2.64E+12	8.64E+13		2.64E+12	1.86E+07	2.81E+13	2.63E+12	2.79E+13

Time period in 2011 (JST)		*Duration (h)*	*Activity released (Bq)*							
Start	*End*		^{132}Te	^{131}I	^{133}Xe	^{132}I	^{133}I	^{134}Cs	^{136}Cs	^{137}Cs
4 April 09:00	7 April 17:00	80	6.21E+11	5.60E+13		6.21E+11	2.09E+06	1.15E+13	9.36E+11	1.14E+13
7 April 17:00	13 April 23:00	150	1.08E+12	1.05E+14		1.08E+12	2.13E+05	5.27E+13	3.36E+12	5.25E+13
13 April 23:00	1 May 00:00	409	1.86E+11	2.86E+14		1.86E+11	2.54E+03	7.12E+13	2.55E+12	7.16E+13
Total release (Bq)			2.85E+16	1.24E+17	7.32E+18	2.85E+16	9.56E+15	9.01E+15	1.77E+15	8.83E+15

C. Estimation of additional dose from intakes of short-lived radionuclides

13. The relative contributions to the total dose from each radionuclide listed in table D1-1 were estimated by multiplying the intakes of each radionuclide relative to the ^{131}I intake (determined as described above) by reference values of the dose coefficient for each radionuclide. These dose coefficients specify committed effective dose per unit intake or committed absorbed dose to a specified organ per unit intake, as appropriate.

14. The dose coefficients were selected (in the case of (b), (c) and (d) below) or evaluated (in the case of (a), below) using the following assumptions with regard to the physico-chemical form and characteristics of the radionuclides to which the workers were exposed:

(a) ^{131}I and ^{133}I comprised 50% elemental iodine vapour and 50% particulate material with an activity median aerodynamic diameter (AMAD) of 5 µm, the default value for occupational exposure recommended by the International Commission on Radiological Protection [ICRP, 1994a];

(b) ^{132}Te, ^{132}I and radiocaesium were in particulate form with an AMAD of 5 µm;

(c) Particulate forms of ^{131}I, ^{132}I and ^{133}I and radiocaesium were characterized by absorption type F and gastro-intestinal uptake factor, $f_1 = 1$ (0.99 by ICRP convention);

(d) ^{132}Te in particulate form was characterized by absorption type M and $f_1 = 0.1$.

15. For ^{132}Te, ICRP provides different default f_1 values for occupational and environmental exposures to unknown chemical forms of tellurium. These are 0.3 and 0.1, respectively [ICRP, 1994b; ICRP, 1995]. The dose assessment was relatively insensitive to this value, and the default value for environmental exposure was chosen here.

16. The resulting dose coefficients (dose per unit intake) for the intake of each radionuclide by inhalation are given in table D1-2 [Birchall et al., 2007; ICRP, 2002].

17. The relative contributions of each radionuclide to the total committed effective dose and to the total committed absorbed dose for each organ were then normalized so that the total relative dose was equal to unity; these values are given in section III, tables D1-3, D1-4 and D1-5.

18. For committed effective dose and committed dose to the thyroid, the dose from ^{131}I intake dominates and so the additional contributions to dose from the short-lived radionuclides relative to the dose from ^{131}I intake were then determined by normalizing to the latter dose. These results are discussed in section IV.

Table D1-2. Dose coefficients for intake of radionuclides by inhalation

The values are for radionuclides in the forms specified in section II. Values given for ^{131}I and ^{133}I are the averages of those for gaseous and particulate forms of iodine

	Organ	*Effective dose coefficient (Sv/Bq) or absorbed dose coefficient (Gy/Bq)*						
		^{132}Te	*^{131}I*	*^{132}I*	*^{133}I*	*^{134}Cs*	*^{136}Cs*	*^{137}Cs*
Effective dose	-	2.8E-09	1.55E-08	2.00E-10	3.05E-09	9.60E-09	1.90E-09	6.70E-09
Absorbed dose	Thyroid	6.4E-09	3.00E-07	1.90E-09	5.85E-08	9.00E-09	1.50E-09	6.30E-09
	Red bone marrow	2.8E-10	7.40E-11	1.80E-11	3.60E-11	9.00E-09	1.40E-09	6.30E-09
	Colon	6.4E-09	5.25E-11	1.80E-11	4.35E-11	1.00E-08	1.60E-09	7.40E-09

III. RESULTS

19. The relative contributions of each radionuclide to the committed effective dose and committed absorbed doses to the thyroid, red bone marrow and colon for the three generic intake scenarios, A, B and C, are shown in tables D1-3, D1-4 and D1-5, respectively. The intake scenarios are described in section II.

Table D1-3. Scenario A. Fractional contributions to the committed effective dose and committed absorbed doses to organs

	Organ	*Fractional contribution to total dose from each radionuclide*						
		^{132}Te	*^{131}I*	*^{132}I*	*^{133}I*	*^{134}Cs*	*^{136}Cs*	*^{137}Cs*
Effective dose	-	0.12	0.64	0.01	0.16	0.04	0.00	0.03
Absorbed dose	Thyroid	0.02	0.78	0.01	0.20	0.00	0.00	0.00
	Red bone marrow	0.15	0.04	0.01	0.02	0.45	0.02	0.31
	Colon	0.78	0.01	0.00	0.01	0.12	0.01	0.08

Table D1-4. Scenario B. Fractional contributions to the committed effective dose and committed absorbed doses to organs

	Organ	*Fractional contribution to total dose from each radionuclide*						
		^{132}Te	*^{131}I*	*^{132}I*	*^{133}I*	*^{134}Cs*	*^{136}Cs*	*^{137}Cs*
Effective dose	-	0.04	0.88	0.00	0.01	0.04	0.00	0.03
Absorbed dose	Thyroid	0.00	0.98	0.00	0.01	0.00	0.00	0.00
	Red bone marrow	0.05	0.06	0.00	0.00	0.52	0.02	0.35
	Colon	0.52	0.02	0.00	0.00	0.26	0.01	0.19

Table D1-5. Scenario C. Fractional contributions to the committed effective dose and committed absorbed doses to organs

	Organ	*Fractional contribution to total dose from each radionuclide*						
		^{132}Te	*^{131}I*	*^{132}I*	*^{133}I*	*^{134}Cs*	*^{136}Cs*	*^{137}Cs*
Effective dose	-	0.09	0.79	0.01	0.04	0.05	0.00	0.03
Absorbed dose	Thyroid	0.01	0.94	0.00	0.04	0.00	0.00	0.00
	Red bone marrow	0.09	0.04	0.01	0.00	0.50	0.02	0.34
	Colon	0.67	0.01	0.00	0.00	0.18	0.01	0.13

IV. DISCUSSION AND CONCLUSIONS

20. Tables D1-3, D1-4 and D1-5 show the estimated contributions to total committed doses from intakes of each radionuclide. Although the contribution to effective dose from ^{134}Cs and ^{137}Cs intakes was estimated to be 7–8% of the total for all three scenarios, assessments for individual workers based on measurements of radionuclides in the body indicated a contribution to assessed effective dose of only around 1–2% (see tables D10, D11 and D13 of appendix D). No obvious explanation could be provided for this discrepancy, but the finding does indicate that caution should be employed when using data on the activities of the radionuclides released to the atmosphere to infer the content of radionuclide intakes by workers.

21. Because ^{131}I intakes made such a dominant contribution to committed effective doses (98–99%), the estimated additional contributions to committed effective dose and committed absorbed dose to the thyroid from intakes of the short-lived radionuclides were expressed as a percentage of the estimated committed dose from ^{131}I intake. The contributions of committed absorbed doses to the red bone marrow and colon to committed effective dose were small compared with the contribution of the committed absorbed dose to the thyroid, and so the discussion presented here is limited to the estimated additional contributions from intakes of short-lived radionuclides to the committed effective dose and committed absorbed dose to the thyroid.

A. Additional contributions to effective dose for each scenario

22. For scenario A, the data in table D1-3 indicate that ^{132}I and ^{133}I could have made additional contributions of 1% and 25%, respectively, relative to the contribution from ^{131}I. Tellurium-132 could have made a further additional contribution of 19%, relative to the contribution from ^{131}I.

23. For scenario B, the data in table D1-4 indicate that ^{132}I and ^{133}I could have made additional contributions of 0.3% and 2%, respectively, relative to the contribution from ^{131}I. Tellurium-132 could have made a further additional contribution of 4%, relative to the contribution from ^{131}I.

24. For scenario C, the data in table D1-5 indicate that ^{132}I and ^{133}I could have made additional contributions of 0.8% and 4% respectively, relative to the contribution from ^{131}I. Tellurium-132 could have made a further additional contribution of 11%, relative to the contribution from ^{131}I.

B. Additional contributions to absorbed doses to the thyroid for each scenario

25. Iodine-131 is the main contributor to the total absorbed doses to the thyroid, with the main additional contribution arising from ^{133}I. For scenarios A, B and C, the additional contribution from the short-lived radionuclides is 28%, 2% and 6%, respectively, relative to the contribution from ^{131}I.

C. Additional contributions to dose from intakes of short-lived radionuclides

26. For the small number of FDNPS workers with the higher reported committed effective doses (>100 mSv), assuming that intakes took place only on 12 March (scenario A) provided an upper bound on the potential additional contribution to dose, while assuming that intakes could have taken place continuously between 12 and 15 March (scenario C) provided a lower bound. Thus, for this group of workers, the additional contribution to effective dose from intakes of short-lived radionuclides could have been in the range 16–45% relative to the contribution from ^{131}I intakes, depending on the time pattern of intake. The corresponding range for the additional contribution to absorbed dose to the thyroid is 6–28%.

27. For other FDNPS workers with lower reported committed effective doses, the period of intake may have extended to later dates and so the possible range on the additional contributions to dose extends to lower values (scenario B). For these groups of workers, the additional contribution to effective dose from intakes of short-lived radionuclides could be in the range 6–45% relative to the contribution from ^{131}I intakes, depending on the time pattern of intake. The corresponding range for the additional contribution to absorbed dose to the thyroid is 2–28%. These estimates of the additional contributions to dose assume that intakes could have commenced on 12 March. The additional contributions to dose from short-lived radionuclides would have been negligible for all workers who commenced work at the FDNPS after about 19 March.

28. For those members of the FDNPS workforce who commenced work during the period 12–19 March, the typical additional contribution to effective dose from intakes of short-lived radionuclides may be in the region of 20% relative to the contribution from ^{131}I, although this value is likely to be subject to large variations between individuals, mainly because of variations in the time period of intake.

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