Evaluation of Internal Exposure of the Workers and the Residents Caused by the Fukushima Nuclear Accident

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Abstract. The accident at the Fukushima Daiichi Nuclear Power Plant has resulted in many cases of internal exposure to radionuclides. JAEA staff has examined the workers and the residents by measurement with a various type of whole body counters. The committed effective dose was estimated using the intake scenarios according to the object of monitoring and expected level of exposure. In the examination of more than 500 workers who were in the plant at early stage of the accident or engaged in disaster-mitigation activities, ^{131}I, ^{132}Te-^{132}I, ^{134}Cs and ^{137}Cs were detected and the maximum committed effective dose estimated based on the most severe scenario was 590 mSv. The monitoring for extended residents begun about 4 months after the accident. In this monitoring project, only ^{134}Cs and ^{137}Cs were detected instead of radioiodine.

Keywords: Fukushima Daiichi Nuclear Power Plant, internal exposure, whole-body counter, worker, residents

1. Introduction

A 9.0-magnitude earthquake and subsequent massive tsunami on March 11, 2011, which devastated the east coast of Honshu island of Japan, deprived the Fukushima Daiichi Nuclear Power Plant of the ability to cool the cores of its reactors. The resultant loss of reactor integrity led to a series of releases of radioactive materials to the environment, the most serious of which occurred on March 15-16. During and after the initial confusion just after the disaster occurrence, hundred of workers of the Tokyo Electric Power Co., Ltd. (TEPCO), the plant operator, initiated mitigation actions in an attempt to maintain control of the situation. Throughout the course of these actions, they were exposed to high external dose rates and to significant air concentrations of released radionuclides.

Meanwhile, the Japanese government issued evacuation orders on March 12 for people living within 20 km of the plant and recommended those living within 30 km stay indoors to minimize any possible exposure. About 78,000 people were evacuated during the first days following the disaster, before the

major radiological release, from the evacuation zone.

As more detailed environmental monitoring results became available, however, there was growing concern among residents in Fukushima prefecture about the health effects due to external radiation and internal contamination due to any radionuclide intake. The Japan Atomic Energy Agency (JAEA) quickly responded to the accident at the Fukushima Daiichi nuclear power plant and provided technical assistance and advice on radiological monitoring and protective actions to national and local governments. The direct assistance provided by JAEA personnel included environmental monitoring outside the damaged plant site, external contamination measurements for screening of residents in Fukushima prefecture and assessment of human exposure.

This paper describes the internal contamination monitoring service provided, or currently being provided, by JAEA to the workers and residents in response to the requests both from TEPCO and the Fukushima government. Also presented is the interim summary of measurements and dose assessments, as well as some experiences gained in the process of the measurements.

2. Sequence of the Internal Contamination Measurement

2.1 Workers

The increased background ambient radiations at the Fukushima Daiichi plant site rendered all the on-site whole-body counters (WBCs) inoperative. At TEPCO's request, JAEA deployed two vehicle-mounted WBCs to the TEPCO Onahama Coal Center (OCC), about 60 km south of the damaged plant in late March, and started the body counting for workers. One WBC of them was later translocated to several points around Tokyo for the workers who had been moved off Fukushima to another worksite for personnel rotation. Over 4,000 workers in the plant at the early stage of the accident or engaged in disaster-mitigation activities were measured and their committed effective doses (CED) on the most severe scenario were estimated. Only workers with CED over 20 mSv were sent to the JAEA Tokai Research and Development Center for more precise internal dosimetry with a high-resolution whole- and partial-body counting system.

2.2 Residents

As for the people who left the evacuation zone within a few days of the disaster, there was initially a general expectation that the levels of inhalation exposure due to the released radioactive material would be minor because of the swift start of the evacuation prior to the major release.

However, the airborne survey conducted by the US Department of Energy in mid-March revealed that the released radioactivity had been spread beyond the 20 km evacuation zone and heavily deposited in such municipalities as Iitate village, northwest of the plant. In response to this situation, from March 26 through March 30, the local headquarters for nuclear emergency response conducted a screening measurement for possible thyroid uptakes of radioiodine in 1,080 children (0-15 year old) from some of the affected areas. The screening was based on the results of measurements of external gamma dose rates

at the surface of the front base of the neck with a gamma-detecting surveymeter, the methodology and criteria of which were recommended by the Nuclear Safety Committee (NSC) of Japan at the time. The screening revealed that while some higher-than-background readings observed, there were no readings above the screening level of 0.2 μSv/h, corresponding to a thyroid dose of 100 mSv for a one-year-old infant, indicating that serious uptakes of ^{131}I had not occurred. The central government and the NSC Japan did not issue any guide to decisions on further action to refine the initial rough estimates of internal exposures.

At three months after the disaster, although the plant had become relatively stabilized, public concerns remained high over the possible health effects of lingering contamination. In response to this public concern, in June, 2011, the Social Health and Welfare Department of the Fukushima government launched a WBC examination program for residents of Fukushima prefecture.

As a pilot study, whole-body and thyroid counting were conducted from June 27 to mid-July at the National Institute of Radiological Sciences (NIRS) for about 120 residents from the three municipalities of Iitate village, Namie town and the Yamakiya district of Kawamata town, which were located outside the 20 km zone. They were recommended to evacuate in late April and permitted to take more than a month to leave; therefore they were expected to have been exposed to relatively high doses. As a result, while radioiodine was no longer detectable, significant radioactivity of radiocesium above the minimum detection limit was found in ~50% of subjects, with the highest body content of 3,100 Bq for ^{134}Cs and 3,800 Bq for ^{137}Cs.

Following the pilot study, the program was extended to monitor about 3,200 people from the three municipalities, and then to cover the other neighboring seven municipalities that of the most residents had left there within a few days of the disaster. JAEA undertook the measurement in the extended program and arranged the facilities and procedures for a number of residents to be examined with WBCs. The subjects to be examined were organized according to their age and area of residence.

The measurements started in mid-July at JAEA Tokai R&D center and are still ongoing. Separate measurements were begun in September with another transportable WBC that was stationed in the west area of Fukushima prefecture, where some of the evacuee had temporarily settled, to provide easier access for this population.

3. Material and Methods

3.1 Materials

For the program of internal contamination monitoring, the JAEA contributed four fixed and three transportable vehicle-mounted WBCs, six of which utilize a sodium iodine scintillator and the other a germanium detector housed in a specially-designed ^{60}Co-free steel chamber. Specifications of the whole-body counters used are summarized in Table 1. Also shown are the specifications that of the WBC of NIRS for completeness purposes only.

Calibrations were made to accommodate subjects of all ages and physiques for the intended use. For

children shorter than around 130 cm, a stool of 30 cm was used to position the subject's trunk to match the NaI arrays of the FASTSCAN. Children under 4 years old were not measured because of the difficulty of maintaining them in the proper position.

Table 1 Specification of WBC

Location	Unit	Geometry	Type	Detector	Meas. time (min)	MDA* (Bq)	Remarks
Tokai	1	Chair	Fixed	Canberra GC5021, p-type Ge (relative efficiency 50%) 2 sets	10	^{131}I: 30 ^{134}Cs: 60 ^{137}Cs: 60	Installed in a steel chamber
Tokai	1	Chair	Fixed	Fuji Electric, NaI (8" φ × 4") 2 sets	3	^{134}Cs: 340 ^{137}Cs: 370	
Tokai	2	Standing	Fixed	Canberra FASTSCAN, NaI (16" × 5" × 3") 2 sets	2	^{134}Cs: 300 ^{137}Cs: 300	
Onahama, etc	2	Standing	Vehicle		2	—	
Western Fukushima	1	Standing	Vehicle		2	—	
Chiba (NIRS)	1	Bed	Fixed	OKEN, NaI (20 cmφ×10 cm) 4 sets	3	^{134}Cs: 320 ^{137}Cs: 570	

* The MDA values are as of July 2011 and those of vehicle-type WBCs are varied with the background radiation levels at the location.

3.2 Procedure

3.2.1 Workers

The measurement protocol for the TEPCO workers consisted of two steps: an initial screening measurement with vehicle-mounted WBCs (FASTSCAN) at OCC and, if necessary, a subsequent more accurate measurement with an HPGe detector system at Tokai. At OCC, over 6,000 workers were screened for surface and internal contamination by June, and 566 of these, identified as having been exposed to a committed effective dose > 20 mSv, proceeded to the next step of measurement at Tokai. Persistent surface contamination of the workers' bodies/clothes and increased levels of ambient radiation during the measurement might have interfered with the results at OCC; therefore, the results of this initial assessment would set an upper limit for the dose.

In contrast, each subject to be measured at Tokai was required to remove his/her clothes and don a disposable gown to prevent interference with the measurement before entering a steel chamber in which HPGe detectors were situated. While the measurement at OCC was made between late March and April, the following measurement at Tokai was made between late April and mid-August because the subjects engaged in the recovery operation were not always available.

3.2.2 Residents

The list of the residents to be internally examined was made by the Fukushima government in cooperation with the relevant municipality offices. A plan was initially made to examine 10 % of the population of the

evacuation area; priority was placed on pregnant women and children under 18. It was decided that if relatively high levels of radioactivity were detected in children, then their parent(s) would also be examined for cross checking.

Each subject who taken to Tokai was first given a brief explanation of the procedures, then checked for external contamination on the body surfaces, then examined for internal contamination with one of the three fixed NaI-type WBCs, and finally informed of the measurement results by health physics experts. Although the subjects were originally examined in their ordinary street clothes, beginning in January 2012 all the subjects were required to change into disposable T-shirts because a small amount of external contamination was occasionally detected on their clothes. The number of persons measured was about 100 per day and amounted to 9,900 in total by the end of January 2012.

3.3 Dose Assessment Model

Most of the subjects were measured only once; therefore, the internal exposure history was required to relate the body content at the time of the measurement to the original intake, from which the CED was calculated. In the Fukushima accident, multiple releases of radioactivity from the reactors on different days, resulting from the deliberate primary containment vessel (PCV) venting operations and accidental explosions around the suppression chamber, made the history complex and uncertain. In particular, on-site workers might have been affected by one or more of those releases.

However, since intake via inhalation was expected to dominate the pattern of radiological releases, it was assumed an acute single uptake had taken place on the day of the initial PCV-venting at Unit 1, i.e., March 12. This assumption, although not always strictly correct, was expected to result in conservative estimates of the original intakes.

The internal dose was evaluated in terms of the CED, which was calculated as a product of the dose coefficient and the estimated intake. The former is taken from ICRP Publ. 71,72 and 78 [1-3]; the latter is derived by dividing the measured body content by the retention function, or the fraction of the intake retained in the body at the time after intake, which is calculated by the MONDAL3 code [4]. It assumed the class of lung solubility with type-F and the particle size with a default AMAD (activity median aerodynamic diameter) of 5 μm for workers and 1 μm for public.

4. Results and Discussion

4.1 Workers

Over 6,000 workers were screened with the Fastscan at OCC, and of these 566 workers (560 males and 6 females) were re-measured with an HPGe system at Tokai. The results of the latter measurements are summarized here.

Gamma pulse height spectra for a worker with high levels of mixed radionuclides, measured both with an HPGe and Fastscan, are shown in Figure 1 for presentation purposes. The major fission and activation products identified in the spectrum are ^{131}I, ^{134}Cs and ^{137}Cs, with minor contributions of ^{136}Cs and ^{129m}Te.

Tellurium-132 (^{132}Te) and its daughter of ^{132}I, although both were encountered at OCC, were undetectable at the time of measurement at Tokai because of their short half-lives.

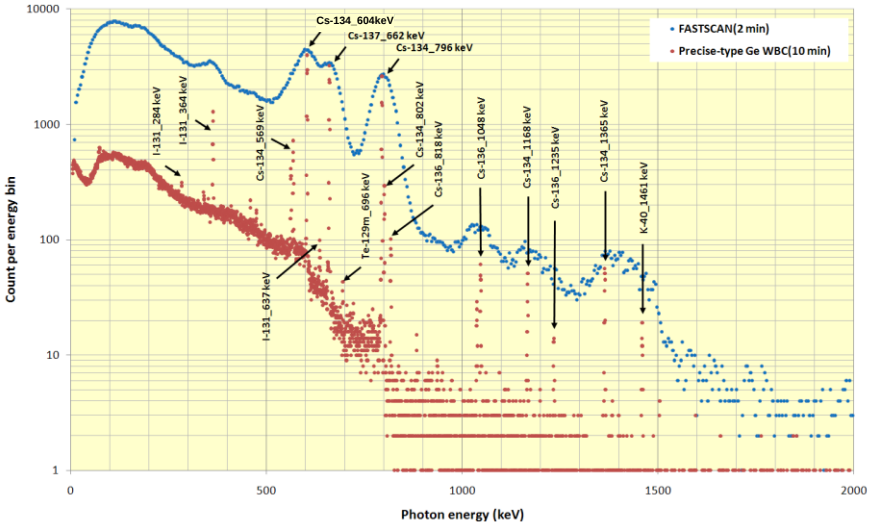

Figure 1. Gamma spectrum of a worker at the Fukushima Daiichi NPP

Figure 2 compares the body contents of ^{134}Cs and ^{137}Cs for 39 workers examined from April 20 through June 17, who were likely exposed to relatively high doses. The observed ratio of activity, 1.0, of ^{134}Cs to ^{137}Cs in the workers was found to be the same as that estimated based on reactor-fuel burn-up. For all the workers (including those measured at OCC), the maximum intakes of ^{134}Cs and ^{137}Cs, extrapolated back to March 12, were estimated to be 670 kBq and 660 kBq, respectively. These estimated intakes corresponded to maximum CEDs of 6 mSv for ^{134}Cs and 4 mSv for ^{137}Cs.

Figure 3 shows a comparison of intakes of ^{131}I and ^{137}Cs, both of which were extrapolated back to March 12, for the same subjects shown in Figure 2. In contrast to the result for radiocesium, a poor correlation was found. The intake ratio of ^{131}I to ^{137}Cs ranged from 1 to 100 with a median of 40, which is larger than the ratio of 10-20 estimated by the Nuclear and Industrial Safety Agency (NISA) as a release source term. This discrepancy probably has due to two causes. First, the respirators with charcoal filters were not exclusively always used in early vapor-particulate mixed environments, and second, inhalation exposure was extended over several days due to the prolonged period of release, allowing the intake to be overestimated. The maximum intake of ^{131}I was estimated to be 30 MBq, and the resultant committed thyroid dose and CED were 12 Sv and 600 mSv, respectively. Most of the internal exposure of workers was mainly accounted for by ^{131}I inhalation.

The contribution to the dose from ^{132}Te-^{132}I, measurable for only a short period of time, was relatively small, being at most 25 % of the doses from ^{131}I. However, the intake pattern of each individual during the course of the early plant stabilization is still uncertain, and the dose contributions from radioiodine with shorter half-lives have not been accounted for; therefore, a more sophisticated dosimetry model should be constructed to determine the initial intake and CED in a manner reflecting the details of the workers' individual activities.

Total – external plus internal – doses to the workers have been disclosed at the TEPCO website [5].

According to these data, the total doses of 6 workers were in excess of 250 mSv, with the highest dose being 670 mSv (the internal dose 590 mSv and external 80 mSv).[1]

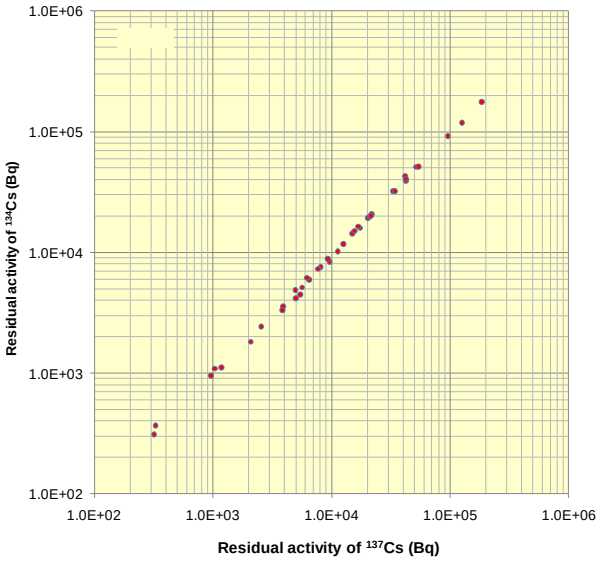

Figure 2. ^{134}Cs vs ^{137}Cs of 39 workers examined from April 20 through June 17, 2011.

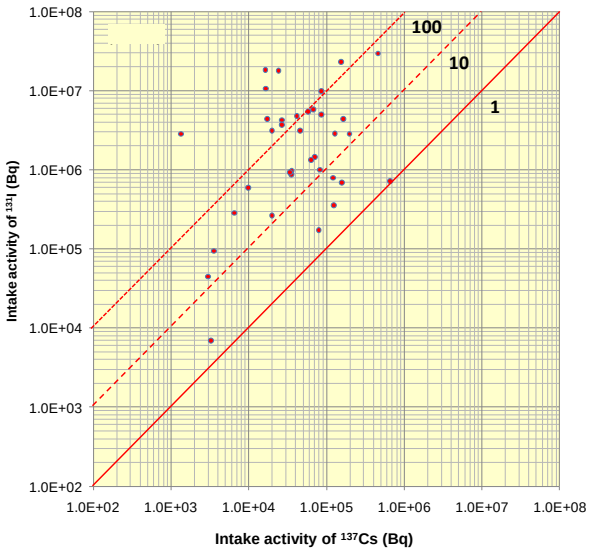

Figure 3. Estimated intake activity ^{131}I vs ^{137}Cs of 36 workers examined from April 20 through June17, 2011.

4.2 Residents

A total of 9,927 people from 10 towns have been measured by the end of January 2012; an age and sex breakdown of the population being summarized in Table 2.

Table 2. Number of subjects examined from Jul. 11, 2011 to Jan. 31, 2012 by JAEA

Age	Male	Female	Total
< 8	1,239	1,150	2,389
8 – 12	1,451	1,394	2,845
13 – 17	772	793	1,565
> 17	756	2,372	3,128
Total	4,218	5,709	9,927

Total levels of ^{134}Cs and ^{137}Cs ranged from the below-detection-limit to 14 kBq for adults, and up to 2.7 kBq for children under 8 years old. The ratios of ^{134}Cs to ^{137}Cs, when corrected for the time of the accident, coincided with those observed from the workers.

Table 3 presents the CED distribution calculated from the measured body contents of ^{134}Cs plus ^{137}Cs, assuming that a single acute inhalation took place on March 12. There were 22 people with CEDs exceeding 1 mSv. All of them were exclusively children and teenagers since one adult with a CED over

[1] JAEA evaluated the body contents for the workers and reported the values to TEPCO, from which TEPCO officially evaluated the intakes and relevant CEDs in accordance with our technical advices on internal dose assessment. Therefore, the figure presented in the paper might differ slightly from TEPCO's reported ones.

1mSv was later revealed to be a worker engaged in the damaged plant. A comparison of CED distributions between adults and children reveals that the estimated doses of children were distributed in the higher dose region beyond the adults' doses. This result was inconsistent with a general relation in doses expected from age-dependent differences in breathing rates and dose coefficients between children and adults. This suggests that the assumption of a single uptake on March 12 was not always valid for children with a shorter Cs retention halftime than adults, and that their actual doses were likely to be smaller than the estimated CEDs especially for younger children.

Table 3. The CED* distribution of subjects examined from Jul. 11, 2011 to Jan. 31, 2012 by JAEA

Age	< 1 mSv	1 mSv	2 mSv	3 mSv
< 8	2,373	6	8	2
8 – 12	2,840	5	0	0
13 – 17	1,565	0	0	0
> 17	3,127	1	0	0
Total	9,905	12	8	2

* The CEDs were recorded to 1 significant digit.

In addition, the latest measurement in February 2012 revealed that the highest body content of radiocesium – 12 kBq of ^{134}Cs and 17 kBq of ^{137}Cs – ever measured was detected in an adult, who had occasionally eaten contaminated foodstuffs from the evacuation area. This is a case in which the dose assessment should be based on a chronic ingestion model, and consequently the CED should be estimated as 1 mSv. For the residents, the CEDs of acute intake have been so far calculated in all cases as a compromise, but a series of chronic intakes should be also taken into consideration to calculate the CEDs appropriate to each case.

5. Summary

The accident at the Fukushima Daiichi nuclear power plant resulted in a substantial release of radionuclide into the environment with the potential of internal contamination in large population. JAEA provided the whole body counting service for emergency operation workers and residents, for the latter of which the measurement is still continuing. The examination in the workers revealed that over 300 workers showed very high levels of ^{131}I and radiocesium with CEDs above 20 mSv, the highest being a CED of 590 mSv.

In contrast, for the approximately 10,000 residents, some activity of radiocesium above MDA was detected in ~20 % of subjects, but the CEDs of 99.8 % of subjects were under 1 mSv. The reconstruction of the internal exposure from radioiodine is in progress.

The WBC program helped for the residents allay anxiety about the internal contamination as a consequence of the accident.

A portion of the dose estimates have been published on the websites of TEPCO and the Fukushima government [6,7].

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