The dosimetric endpoints assessed by the Dose Expert Panel were effective doses and equivalent doses to the thyroid, resulting from the exposure during the first year after the accident. An explanation of dosimetric quantities is shown in Box 6. Three age-at-exposure groups were included in the dose assessment: adults aged 20 years, children aged 10 years, and infants aged 1 year. Doses to 6-month-old infants were considered for the consumption of infant formula made up with water. Doses to the fetus and breastfed infant were considered by the Dose Expert Panel but were not evaluated separately.

4.1.2 WHO preliminary dose estimation for the first year following the accident

The WHO preliminary dose estimation relies on measurements available as of mid-September 2011 and extrapolated to exposure in the first year. Additional data published later could not be incorporated because of the Dose Expert Panel's timeframe. This is further discussed in Chapter 6.

As far as possible, the Dose Expert Panel based its assessment directly on measurements of levels of radioactive material in the environment, such as levels of different radionuclides deposited on the ground or in soil, or found in foodstuffs. Inside Japan, the primary sources were official measurement data published by the Government of Japan. Such measurement data were not generally available for the rest of the world and consequently the Dose Expert Panel used environmental modelling predictions based on an estimated source term in combination with atmospheric dispersion modelling and environmental measurements to estimate doses outside Japan.

The assessment contained a number of assumptions that are described in detail in the dose assessment report. Although the assessment was intended to be realistic, given the limited information available to the Dose Expert Panel during its period of work, some conservative assumptions were adopted to avoid any underestimation of doses. For example, it was assumed that people consumed only food produced in the area where monitoring was implemented (e.g. those living in Fukushima ate only food produced in Fukushima). Moreover, some assumptions regarding the implementation of protective measures were conservative. For instance, it was assumed that relocation in the "deliberate evacuation area" took place at 4 months although the inhabitants of this area were subjected to relocation at different times earlier than this. It was also assumed that all the food monitored was on the market although the data set included the results of food samples that were collected for monitoring purposes and were not allowed on the market. In fact, food restrictions were introduced in Japan with the aim of banning from the market those food commodities produced in highly contaminated areas or exceeding regulatory limits. As a consequence of these conservative assumptions, some dose overestimation may have occurred.

In the preliminary dose estimation report, the Dose Expert Panel presented the estimated doses in order-of-magnitude dose bands of "characteristic" individual doses for each region considered. The main sources of uncertainty in the dose estimates and the implications of using conservative assumptions, possibly leading to dose overestimation, are extensively discussed in the dose assessment report. Some information published later, including in vivo measurements conducted in Fukushima prefecture, reported doses lower than the dose bands presented in the preliminary dose estimation report (*3*) although these are not directly comparable.

The key results of the estimated effective doses in the first year are as follows:

- In the most affected areas of Fukushima prefecture the estimated effective doses are within a dose band of 10–50 mSv.
- In the rest of Fukushima prefecture the estimated effective doses are within a dose band of 1–10 mSv.
- In prefectures neighbouring Fukushima, the estimated effective doses are within a dose band of 0.1–10 mSv.
- In all other Japanese prefectures, the effective doses are estimated to be within a dose band of 0.1–1 mSv.
- In the rest of the world, estimated effective doses are less than 0.01 mSv and are usually far below this level.
- The exposure pathways that contribute most to effective dose vary with location and distance from the site. In the more affected regions the external dose from groundshine is important, but with increasing distance from the site the ingestion of food becomes the main contributor.

The key results of the estimated thyroid doses in the first year are as follows:

- In the most affected area of Fukushima prefecture, the estimated thyroid doses are within the dose band of 10–100 mSv, with the exception of one example location where estimated thyroid doses to adults are within a dose band of 1–10 mSv and another example location where the upper bound of the estimated thyroid doses to infants is 200 mSv.
- In the rest of Fukushima prefecture, the estimated thyroid doses are within a dose band of 1–10 mSv for adults and 10–100 mSv for children and infants.
- In other Japanese prefectures, the estimated thyroid doses are within a dose band of 1–10 mSv for all age groups considered.
- In the rest of the world, estimated thyroid doses are less than 0.01 mSv, and are usually far below this level.
- The exposure pathways that contribute most to thyroid dose vary with location and distance from the site. In the more affected regions, inhalation from the cloud and the external dose from groundshine are important, but with increasing distance from the site (i.e. when overall exposure is very low) the ingestion of food becomes the main contributor.

For the purposes of this HRA the HRA Expert Group was provided with the detailed results of the first-year exposure assessment, which included the actual calculations and the point estimates used to create the dose bands. Four distinct geographical areas were identified based on estimated doses, as described below.

- Group 1: the two locations within Fukushima prefecture with effective doses of 12–25 mSv;
- Group 2: locations in Fukushima prefecture where effective dosesare between 3 and 5 mSv;
- Group 3: the less-affected locations of Fukushima prefecture and the rest of Japan, where effective dose values are around 1 mSv;

- Group 4 – the neighbouring countries and the rest of the world, where effective doses are well below 1 mSv.

4.1.3 Calculation of first-year organ doses

An important contribution to the effective dose in the Fukushima Daiichi NPP accident is the internal exposure to isotopes of caesium. Since the bio-distribution of caesium in the body is quite homogeneous, all organs are almost equally irradiated, and therefore the effective dose is a good indicator of organ doses. In addition to the effective dose, the Dose Expert Panel assessed organ doses to the thyroid because the intake of ^{131}I is also likely to be an important contributor to overall exposure and in this case the distribution in the body is far from uniform, with the thyroid being the most exposed organ.

Although the HRA Expert Group agreed with the above, it was considered appropriate to use organ doses rather than effective doses to estimate health risks. The decision was made based on the fact that effective dose is primarily intended for use when nominal risk coefficients and tissue-weighting factors for age- and sex-averaged worldwide populations are applied (e.g. radiation protection), while the organ-absorbed dose is more appropriate for risk assessments on specific populations when age and sex-specific models are used to transfer risks (*12,94*).

It was decided to calculate organ doses for red bone marrow, thyroid, breast, and colon, as input data for the cancer risk models for leukaemia, thyroid cancer, breast cancer and all solid cancers, respectively. The colon dose had already been used as a surrogate for whole-body dose within the LSS cohort. The methodology used to calculate organ doses for the first year after the accident is described in Annex G.

The effective dose is the summation of all the organ equivalent doses, each multiplied by its appropriate tissue weighting factor. Values expressed as the ratio between the absorbed dose and the effective dose in each of the organs mentioned above were calculated. The estimations of organ doses for red bone marrow, breast and colon were performed by applying those ratios to the effective dose values for adults, children and infants. This approach was validated by comparison with the thyroid doses estimated by the Dose Expert Panel.

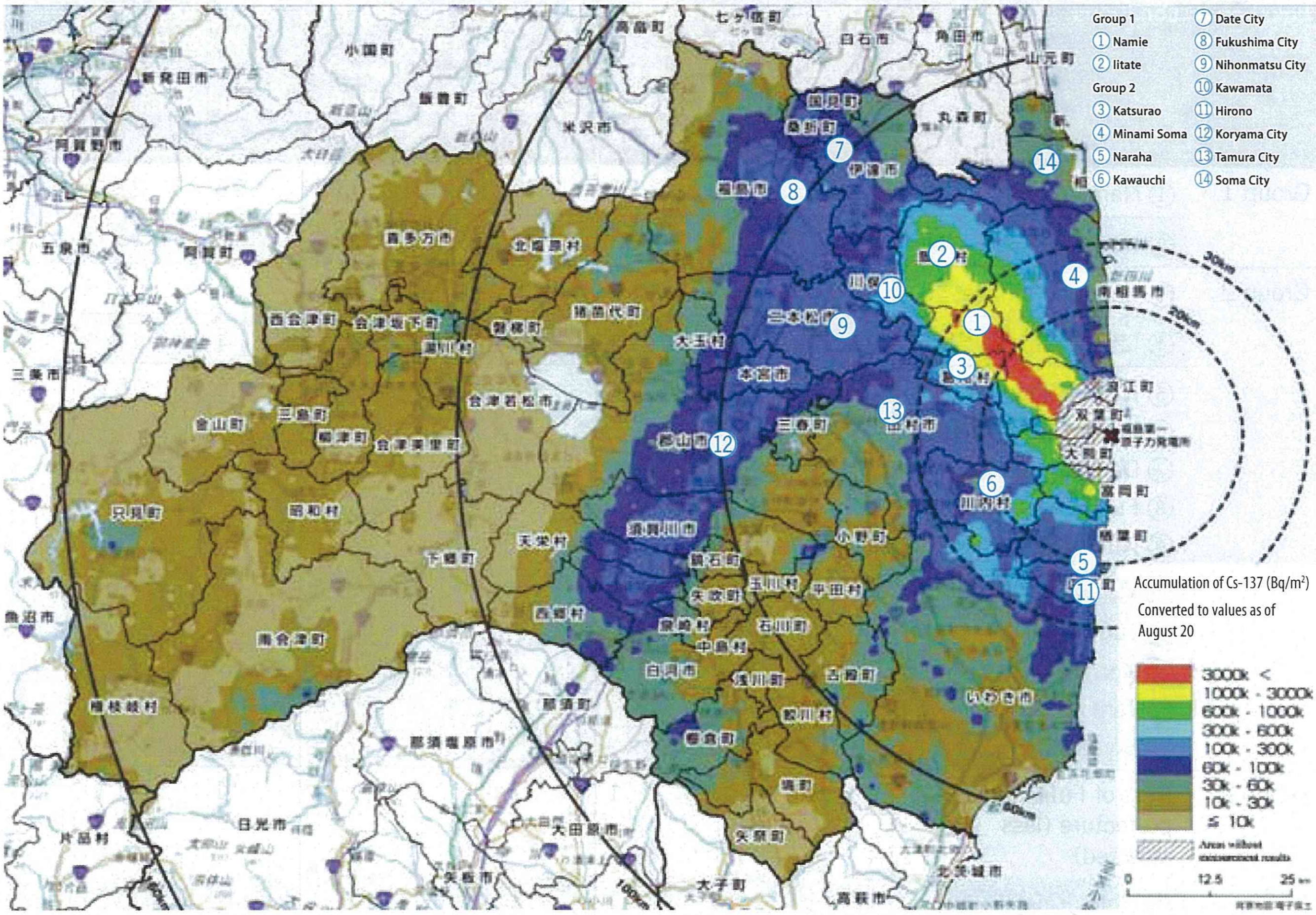
The first-year organ doses are reported in Tables 5 and 6 for the general population in the four distinct geographical areas representing the world. The example locations considered in the Fukushima prefecture are indicated in Figure 5. Table 5 shows the first-year organ doses for colon, breast and bone marrow estimated by the HRA Expert Group. Table 6 shows the first-year thyroid organ doses[3] assessed by the Dose Expert Panel and used as input data for the thyroid cancer risk model for the purposes of the HRA.

4.1.4 Calculation of lifetime doses

The WHO Preliminary dose estimation report presents doses from the first year after the Fukushima accident, based on data available up to mid-September 2011. As such, it includes extrapolations to estimate 1-year doses. The Dose Expert Panel considered that an estimation of doses beyond the first year would have resulted in a high degree of uncertainty.

3. For practical reasons, the first-year thyroid organ doses are presented in a separate table, because there are differences in the dose ranges and grouping of some locations compared to the other organ doses.

Figure 5. Locations in Fukushima prefecture considered in the assessment (Groups 1 and 2). Note that the rest of Fukushima (less affected) is part of Group 3.



Source: http://radioactivity.mext.go.jp/en/contents/4000/3168/24/1270_0912_2.pdf (Attachment 4 - Accumulation of Cs137 on the ground surface in Fukushima prefecture).

Lifetime doses in nuclear accidents

The radiation doses received in the second and subsequent years after a nuclear accident are expected to be considerably less than in the first year, even without application of remedial actions (*95*).

Experience from the Chernobyl accident showed that the radiation exposure decreased within the first year after the accident mainly due to radioactive decay of short-lived radionuclides (e.g. ^{131}I). Beyond the first year, the decrease was mainly due to radioactive decay of caesium and its migration into the soil (*93,96,97*). The shielding effect of this radionuclide migration in the soil was an important factor in reducing lifetime doses (*97*).

Besides the natural mechanisms mentioned above, the temporal distribution of the lifetime dose will also be influenced by a number of other factors, including additional protective measures (e.g. more stringent regulatory standards, such as those implemented for food) as well as long-term remedial actions (e.g. clean-up of buildings, remediation of soils and vegetation, treatment of agricultural fields, waste management), which would further reduce radiation exposure andconsequently lifetime doses.

Table 5. First year organ doses in the general population considered for the HRA (colon, breast and bone marrow).

Location Group	Locations	Organ dose for adults 20y (mSv)			Organ dose for children 10y (mSv)			Organ dose for infants 1y (mSv)		
		Colon	Breast	Bone marrow	Colon	Breast	Bone marrow	Colon	Breast	Bone marrow
Group 1	① Namie Town[a]	22	23	21	25	25	25	26	27	26
	② Iitate Village[a]	12	13	12	14	14	14	15	15	15
Group 2	③ Katsurao Village[a]	5	5	4	5	5	5	5	5	5
	④ Minami Soma City	5	5	5	5	5	5	5	5	5
	⑤ Naraha Town ⑥ Kawauchi Village ⑦ Date City ⑧ Fukushima City ⑨ Nihonmatsu City	4	4	4	4	4	4	5	5	4
	⑩ Kawamata Town ⑪ Hirono Town ⑫ Koriyama City ⑬ Tamura City ⑭ Soma City	3	3	3	3	3	3	3	3	3
Group 3	Rest of Fukushima prefecture (less affected)	1	1	1	1	1	1	1	1	1
	Neighbouring prefectures	1	1	1	1	1	1	1	1	1
	Rest of Japan	1	1	1	1	1	1	1	1	1
Group 4	Neighbouring countries	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	Rest of the world	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

a. Organ dose from the first 4 months after the accident only

Note: The first year organ doses shown here as rounded values were calculated by the HRA Expert Group on the basis of the point estimates of effective dose used to create the dose bands presented in the WHO Preliminary dose estimation report (*3*).

Ratio of lifetime dose to 1-year dose

For the internal dose, the dose calculated from inhalation for the first year is treated as non-recurring[4]. Although there might indeed be some additional dose owing to re-suspension, this is not considered an important pathway for the radionuclides released by the accident at the Fukushima Daiichi NPP. For the dose from ingestion of food, there will be an additional long-term dose owing to contamination of food crops and fodder by the soil-root and other pathways.

4. For this reason, for the calculation of the lifetime dose no contribution from the inhalation pathway was considered beyond the first year

Table 6. First year thyroid doses for the general population

Location Group	Locations	Thyroid dose for adults 20y (mSv)	Thyroid dose for children 10y (mSv)	Thyroid dose for infants 1y (mSv)
Group 1	① Namie Town[a]	63	95	122
	② Iitate Village[b]	34	52	73
Group 2	③ Katsurao Village[c]	17	28	48
	④ Minami Soma City	16	25	43
	⑤ Naraha Town ⑥ Kawauchi Village ⑦ Date City ⑧ Fukushima City ⑨ Nihonmatsu City ⑩ Kawamata Town	14	22	39
	⑪ Hirono Town ⑫ Koriyama City ⑬ Tamura City ⑭ Soma City	11	18	35
Group 3	Rest of Fukushima prefecture (less affected)[2]	8	15	31
	Neighbouring prefectures (Chiba, Gunma, Ibaraki, Miyagi, Tochigi)[3]	≤4	≤5	≤9
	Rest of Japan	~ 1	~ 1	~ 1
Group 4	Neighbouring countries	<0.01	<0.01	<0.01
	Rest of the world	<0.01	<0.01	<0.01

a. Organ dose from the first four months after the accident only

b. Although the preliminary estimated thyroid doses in this area (i.e. rest of Fukushima prefecture, less affected) are higher than the thyroid organ doses in the other locations in Group 3, the HRA Expert Group agreed to keep them within this group because the preliminary dose estimation was performed under very conservative assumptions and it is considered that in practice doses are much lower.

c. These are the rounded values for southern tip of Miyagi prefecture, and the other zones of the neighbouring prefectures are below those values

Note: These first year thyroid doses, calculated by the Dose Expert Panel, are the point estimates used to create the dose bands presented in the WHO Preliminary dose estimation report (*3*).

For the external dose, the Dose Expert Panelconsidered the long-term movement of caesium into the soil with the accompanying reduction in the external gamma-dose rate. This reduction factor, $r(t)$ is given in the equation below:

$$r(t) = 0.34 \times e^{-0.693 \times \frac{t}{1.5y}} + 0.66 \times e^{-0.693 \times \frac{t}{50y}}$$

where 34% of the exposure rate (groundshine) is projected to disappear with a half-time of 1.5 years and the remaining 66% is projected to disappear with a half-time of 50 years. These two half-times resulting from migration of caesium in the soil are in addition to the rate of disappearance of caesium due to its natural radioactive decay.

This equation was evaluated for the time periods of 1 year and 50 years and four radionuclides – ^{132}Te, ^{131}I, ^{134}Cs and ^{137}Cs (^{137m}Ba)[5]. The theoretically calculated ratio of long-term dose to 1-year dose was 7. An estimation was made using a similar approach during the initial UNSCEAR assessment of the Chernobyl accident (*98*), and a ratio of 8 was calculated. However, 20 years after the Chernobyl accident, the ratios predicted by this equation proved to be overestimated and the ratio of projected long-term dose to 1-year dose was identified as 3 (*99*).

This reduction of the theoretically calculated ratio from 7 to 8 to the ratio of 3 based on the Chernobyl experience is quite reasonable if the effects of countermeasures are considered. The reduction factor noted in the equation above comes from observations after Chernobyl of external dose rate measured over an undisturbed open field, i.e. not considering any remedial action. In urban environments the longer-term dose rates can be reduced by a factor varying from 1.5 to 15 (*93*) through efforts ranging from rather simple to strenuous.

The radiation doses received in the second and subsequent years after a nuclear accident are expected to be considerably less than in the first year, even without the application of remedial actions (*95*). A number of remedial actions were taken by the Government of Japan, municipal authorities and residents quite soon after the accident to lower radiation exposure (*100*), which will further lower lifetime radiation exposure resulting from this accident.

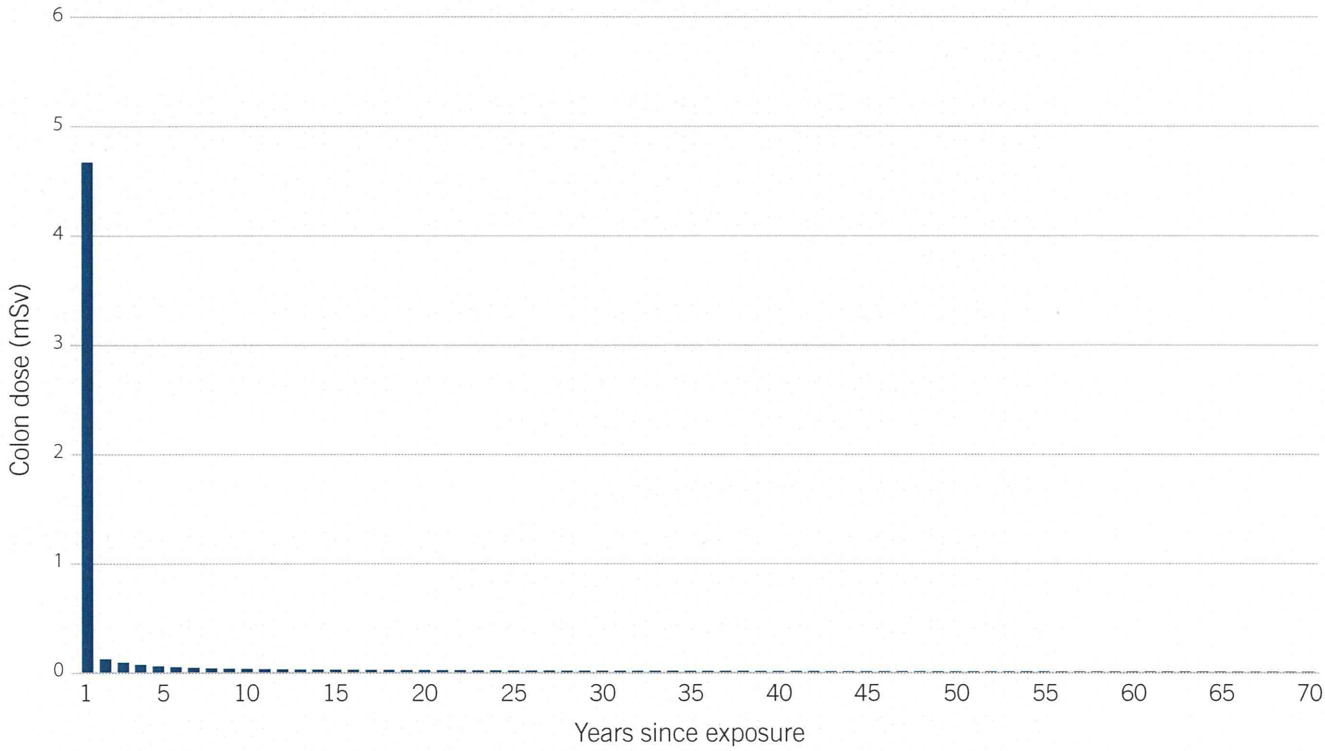
The Chernobyl experience showed that the ratio of long-term to 1-year dose was projected to be 3, with inclusion of data up to 20 years after the accident (99). On the basis of this experience, which appeared to be the most relevant, and taking into consideration the differences between the Chernobyl and Fukushima Daiichi NPP accidents, the HRA Expert Group considered it reasonable to assume that the ratio of long-term dose to 1-year dose would be equal to 2 and that the result should be treated as a lifetime dose commitment. Therefore, for purposes of calculating lifetime risk, it was agreed that the dose over the lifetime should be approximated to be twice[6] as much as the first-year dose. The results were provided on a year-per-year basis to the risk modellers for the health risk calculations. Figure 6 illustrates the distribution of the annual doses delivered to an organ over a lifetime using colon dose as an example.

4.2 Doses for the NPP emergency workers

Recognizing that occupational health is closely linked to public health, WHO is addressing all determinants of workers' health[7], including risks for disease and injury in the occupational environment. Taking into account that disease and injury in the workplace comprise both normal and accidental exposure situations, the health risk assessment of

5. ^{137m}Ba is metastable barium
6. With an exception for the locations where people were relocated (i.e. Namie town in Futaba county, Iitate village in Soma county and Katsurao village in Futaba county). In those locations it was assumed that relocation took place at 4 months after the accident. Therefore the dose over the lifetime was calculated as the sum of the doses received during the first 4 months after the accident plus the lifetime dose calculated for the locations within Fukushima prefecture zone 1 (western least contaminated).
7. WHO is implementing a Global Plan of Action on Workers' Health 2008-2014 endorsed by the World Health Assembly in 2007 http://www.who.int/occupational_health/en/

Figure 6. Calculated distribution of the annual doses delivered to an organ over lifetime (70 years). This example shows the lifetime distribution of the colon dose in a location where the first year organ dose is around 5 mSv



the emergency workers exposed during the emergency phase of the Fukushima Daiichi NPP accident was included in the scope of the present HRA.

The preliminary dose assessment conducted by the Dose Expert Panel (*3*) provided doses delivered to the general population and did not include occupational doses. Evaluation of occupational radiation exposure requires a different dosimetric approach.

Occupational radiation exposure is generally assessed retrospectively:

- for internal exposures, through individual bioassay monitoring either by in vivo direct measurements (e.g. whole-body counting, thyroid monitoring) and/or by in vitro assays (analysis of material excreted or removed from the human body);
- for external exposures, through personal dosimetry using monitoring devices ("personal dosimeters", e.g. thermoluminescent dosimeters [TLDs]).

In contrast, public exposure is commonly assessed prospectively through the application of dosimetric models, using environmental monitoring data as the input. While for the general population, both inhalation and ingestion are important routes of internal exposure, in the case of workers occupationally exposed to radiation, inhalation is the major route of internal exposure.

To evaluate health risks related to occupational exposure, the HRA Expert Group agreed to base its assessment on the occupational doses estimated by the operator TEPCO because this was the only exposure data available at the time of this assessment (Figure 3b). This HRA is focused on emergency workers employed by TEPCO or contractors.

Other categories of workers who may have been exposed to radiation during the response to the accident (e.g. rescue workers, firemen, policemen, self-defence forces, volunteers, government and municipal employees) were not included in the HRA because the information about their radiation doses was not available to the HRA Expert Group within the timeframe of its work.

Included in the exposure assessment, as reported by TEPCO in April 2012, are 23 172 emergency and mitigation workers, including 5 639 TEPCO employees (24%) and 17 533 contractors (76%). The data were provided to the HRA Expert Group in an anonymized way that ensured protection of the identity and privacy of the individuals concerned.

Owing to the extremely complex situation following the earthquake, tsunami and nuclear accident, the collection and reconstruction of data regarding workers' dosimetry are ongoing processes. Therefore, the estimates of workers' doses presented in this chapter should be considered as preliminary in nature.

4.2.1 Pathways for workers' exposure

Occupational exposure to radiation of Fukushima Daiichi NPP workers included internal and external exposure through four major pathways:

- internal exposure from inhalation of radioactive material in the workplace
- external exposure from radioactive material deposited in the workplace
- external exposure from radioactive material suspended in the workplace air
- external exposure from proximity to radiation sources within the damaged reactors.

Some workers were also exposed to radiation from radioactive material deposited on the skin or clothes (external contamination).

4.2.2 Radiation protection of female workers

Female workers are not considered in this HRA. Although most of the workers involved in the emergency response work at Fukushima Daiichi NPP were male, a few female workers were involved at an early stage after the earthquake. In May 2011 it was reported that two female workers had exceeded a cumulative effective dose of 5 mSv in 3 months, which is a regulatory limit established in Japan for female workers. TEPCO took measures so that working conditions for females would ensure that those limits were not exceeded again (e.g. working environment, personal protective equipment and alarms in the personal dosimeters pre-set at 4 mSv cumulative dose) (*101*).

4.2.3 Workers' exposure assessment reported by TEPCO

The assessment of exposure for emergency workers at the Fukushima Daiichi NPP was undertaken by TEPCO. The results were given by TEPCO to the Japanese authority to be considered by the HRA Expert Group in the preparation of this report. These results include information about effective dose ranges, mean effective doses and maximum effective doses for more than 23 000 workers from different age groups.

Table 7 shows the age distribution of the emergency workers considered in this HRA. Data from monitoring workers are available on TEPCO's website and are summarized in Annex H. In particular, information was provided on the contribution of internal and external exposure to the total effective dose (Table 8), as well as some information about the radionuclides involved (see Table 25 in Annex H). Ranges of thyroid doses based on individual measurements taken on 522 of the most highly exposed workers were given separately (see Table 24 in Annex H).

Table 7. Age distribution of workers as of 31 January 2012

Age distribution	TEPCO	Contractors	Total
80	0	1	1
70-79	1	24	25
60-69	27	1831	1858
50-59	693	4716	5409
40-49	1173	4720	5893
30-39	925	3254	4179
20-29	511	1546	2057
18-19	3	61	64
Unknown	6	611	617
Total	**3339**	**16764**	**20103**
Oldest age	73	84	84
Youngest age	19	18	18

Figure 7. Dose distribution of workers by age group (data provided by TEPCO)