Preliminary dose estimation

from the nuclear accident after the 2011 Great East Japan Earthquake and Tsunami

World Health Organization

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Lynn Anspaugh
Mikhail Balonov
Carl Blackburn
Florian Gering
Stephanie Haywood (Rapporteur)
Gerhard Proehl
Shin Saigusa
Jane Simmonds (Chair)
Ichiro Yamaguchi

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Contributors

Dr Lynn Anspaugh[3]
University of Utah, USA

Dr Mikhail Balonov[1,2,3]
Institute of Radiation Hygiene, Russia

Mr Peter Bedwell
Health Protection Agency, United Kingdom

Mr Antony Bexon
Health Protection Agency, United Kingdom

Dr Carl Blackburn[2]
Food and Agriculture Organization of the United Nations, Austria

Dr Volodymyr Berkovskyy[1]
International Atomic Energy Agency, Austria

Mr David Byron[1]
Food and Agriculture Organization of the United Nations, Austria

Dr Tom Charnock
Health Protection Agency, United Kingdom

Dr Michael Dinovi
Food and Drug Administration, USA

Dr Sergey Fesenko
Food and Agriculture Organization of the United Nations, Austria

Ms Brigitte Gerich[3]
Federal Office of Radiation Protection, Germany

Dr Florian Gering[1,2,3]
Federal Office of Radiation Protection, Germany

Dr Vladislav Golikov
Institute of Radiation Hygiene, Russia

Dr Stephanie Haywood[1,2,3]
Health Protection Agency, United Kingdom

Dr Jean-René Jourdain[1,2]
Institut de Radioprotection et de Sûreté Nucléaire, France

Dr Catherine Leclercq,
Istituto Nazionale di Ricerca per gli Alimenti e la Nutrizione, Italy

Dr Lionel Mabit[3]
Food and Agriculture Organization of the United Nations, Austria

Dr Gerhard Proehl[1,2]
International Atomic Energy Agency, Austria

Mr Jonathan Sherwood
Health Protection Agency, United Kingdom

Dr Shin Saigusa[1,2,3]
National Institute of Radiological Sciences, Japan

Dr Kazuo Sakai[1]
National Institute of Radiological Sciences, Japan

Ms Jane Simmonds[2,3]
Health Protection Agency, United Kingdom

Dr Diego Telleria[1,3]
International Atomic Energy Agency, Austria

Mr Joseph Wellings
Health Protection Agency, United Kingdom

Dr Ichiro Yamaguchi[2]
National Institute of Public Health, Japan

Dr Irina Zvonova
Institute of Radiation Hygiene, Russia

Observers

Mr Malcolm Crick[3]
United Nations Scientific Committee on the Effects of Atomic Radiation Secretariat

Mr Takashi Kiyoura[1]
Permanent Mission of Japan in Vienna, Austria

Mr Ichiro Ogasawara[1]
Permanent Mission of Japan in Vienna, Austria

Mr Yuji Otake[2,3]
Permanent Mission of Japan to the International Organizations in Geneva, Switzerland

Dr Ferid Shannoun[1,2]
United Nations Scientific Committee on the Effects of Atomic Radiation Secretariat

Dr Wolfgang Weiss[1]
United Nations Scientific Committee on the Effects of Atomic Radiation

World Health Organization

Dr Emilie van Deventer[2,3]
WHO headquarters

Dr Kazuko Fukushima[2,3]
WHO headquarters

Dr Dominique Maison[2]
WHO headquarters

Ms. Asiya Odugleh-Kolev
WHO headquarters

Dr Maria del Rosario Perez[1,2,3]
WHO headquarters

Dr Isabelle Thierry-Chef[3]
International Agency for Research on Cancer. France

Dr Angelika Tritscher[2,3]
WHO headquarters

Dr Philippe Verger[1,2,3]
WHO headquarters

[1] Participant in the International Expert Panel meeting in Vienna, June 2011

[2] Participant in the International Expert Panel meeting in Geneva, September 2011

[3] Participant in the International Expert Panel meeting in Geneva, October 2011

Contents

Executive summary

The earthquake and tsunami in Japan on 11 March 2011 led to releases of radioactive material into the environment from the Tokyo Electric Power Company's Fukushima Daiichi nuclear power station. This report describes an initial estimate of radiation doses resulting from this accident to characteristic members of the public in populations around the world.

In line with its defined role in radiation emergency response among international organizations, the World Health Organization (WHO) is responsible for public health risk assessment and response. Therefore soon after the accident, WHO initiated a health risk assessment to support the identification of needs and priorities for public health action and to inform Member States and the public.

The aim of the health risk assessment is to estimate at global level the potential health consequences of human exposure to radiation during the first year after the Fukushima Daiichi nuclear power plant accident. The assessment covers infants, children and adults living in the Fukushima prefecture, nearby prefectures, the rest of Japan, neighbouring countries, and the rest of the world.

Because the health risk assessment requires an estimation of radiation doses delivered to the population, WHO established an International Expert Panel to make an initial evaluation of radiation exposure of people both inside Japan and beyond, as a result of the accident. The panel members were required to sign a declaration of interests, and no conflicts of interest were identified for any of them. The dose assessment was conducted by more than 30 experts who served in their individual capacities, either participating in the Expert Panel meetings or providing technical contributions from their respective institutions. All participating experts were selected on the basis of their scientific competence and experience.

Additionally, the panel included representatives of the International Atomic Energy Agency, the Food and Agriculture Organization of the United Nations and WHO in view of the relevance of their areas of expertise. The United Nations Scientific Committee on the Effects of Atomic Radiation, which has initiated a two-year assessment of the exposure levels and effects that will be submitted to the United Nations General Assembly in 2013, participated as an observer in the WHO assessments to ensure compatible approaches and data sources for the two United Nations activities. The Government of Japan also designated representatives to attend the meetings of the panel as observers. Three panel meetings were convened in June, September and October 2011.

This report provides data on effective doses and equivalent doses to the thyroid in members of the public resulting from exposure over the first year after the accident for different regions of the world, with greater spatial detail for the estimated doses inside Japan and, in particular, in the Fukushima prefecture.

The assessment was designed to provide preliminary dose estimates and was based on information publicly available from relevant Japanese government institutions, collected up to mid-September 2011. To validate the results of the dose estimates, the panel used a variety of dosimetric approaches and made comparisons with existing data on human in-vivo monitoring measurements (e.g. whole body counting and thyroid measurement).

As far as possible, the input data were measurements of levels of radioactive material in the environment (e.g. levels of different radionuclides on the ground) and levels of activity concentration in foodstuffs. When direct monitoring data were not available, estimates based on simulations were used as input for the dose models.

The methodology used to calculate the doses relies on the most recent dosimetric and biokinetic models for different population subgroups (i.e. infants, children and adults). It considers all major routes of exposure – i.e. external exposure (from cloudshine and groundshine) and internal exposure (from ingestion of foodstuffs and inhalation).

The estimated doses are presented in order-of-magnitude dose bands of "characteristic" individual doses for each region considered. These are not the full ranges on the doses that may be received by all individuals within each region. The main sources of uncertainty in the dose estimates are discussed in the report.

This assessment is intended to be realistic. However, given the limited information available to the panel during the time frame of its work, the assessment contains a number of assumptions (e.g. radioactive cloud composition and dispersion, time spent indoors/outdoors, and consumption levels). In particular, some assumptions regarding the implementation of protective measures are conservative (e.g. the assumption that people in the most affected areas outside the 20-kilometre radius continued to live there for four months after the accident) and some possible dose overestimation may have occurred. All efforts were made to avoid any underestimation of doses.

In this context, using conservative assumptions, the assessment shows that the total effective dose received by characteristic individuals in two locations of relatively high exposure in Fukushima prefecture as a result of their exposure during the first year after the accident is within a dose band of 10 to 50 mSv. In these most affected locations, external exposure is the major contributor to the effective dose. In the rest of Fukushima prefecture the effective dose was estimated to be within a dose band of 1 to 10 mSv. Effective doses in most of Japan were estimated to be within a dose band of 0.1 to 1 mSv and in the rest of the world all the doses are below 0.01 mSv and usually far below this level.

The characteristic thyroid doses in the most exposed locations of Fukushima prefecture were estimated to be within a dose band of 10 to 100 mSv. In one particular location the assessment indicated that the characteristic thyroid dose to one-year-old infants would be within a dose band between 100 and 200 mSv, with the inhalation pathway being the main contributor to the dose. Thyroid doses in the rest of Japan were within a dose band of 1 to 10 mSv and in the rest of the world doses are estimated to be below 0.01 mSv and usually far below this level.

Outside the most affected areas of Fukushima prefecture, the exposure from food is the dominant pathway. Due to the assumptions applied the dose from ingestion may be over-

estimated, especially in locations outside Fukushima and its neighbouring prefectures, and the reasons are discussed in the report.

This report represents the first international effort to assess global radiation doses from the Fukushima Daiichi nuclear power plant accident considering all major exposure pathways. It provides timely and authoritative information on the anticipated scale of doses in members of the public for the first year after the accident, based on input data available to the International Expert Panel within the time frame. Nevertheless, this dose assessment should be considered as preliminary. The availability of further monitoring data and more detailed information about implementation of protective measures will allow for more refined assessments in the future.

Preface

The World Health Organization (WHO) conducts a programme on radiation and health which aims to promote safe and appropriate use of radiation to protect patients, workers and members of the public in planned, existing and emergency exposure situations. WHO's involvement in radiation and health began within a decade of its founding, and the International Commission on Radiological Protection has been in official relations with WHO since 1956. In 1972 the World Health Assembly requested the Director-General to cooperate with the International Atomic Energy Agency, the United Nations Scientific Committee on the Effects of Atomic Radiation, and other international organizations in evaluating the world situation regarding the medical use of ionizing radiation and the effects of radiation on populations.[1]

Global public health security is one of the key priorities of WHO's agenda. The World Health Assembly requested the Director-General in 2005 to enhance WHO's capacity to implement health-related emergency preparedness plans, and to prepare for disasters and crises through timely and reliable assessments.[2] The nature of WHO's work on emergencies – whether resulting from natural, intentional or accidental events – requires a high level of coordination with a variety of partners within the United Nations system, as well as with other external partners. One of the lessons from the 1986 Chernobyl nuclear accident was the need to strengthen international cooperation in radiation emergencies. The Joint Radiation Emergency Management Plan of the International Organizations, last published in 2010, establishes the mechanisms for implementing a coordinated response and defines the roles of each party. Within this joint plan, WHO is responsible for the coordination of public health risk assessment and response.

The decentralized structure of WHO – with its headquarters in Geneva, Switzerland, six regional offices and 149 country offices – provides optimal conditions for interacting with the Organization's 194 Member States. After the 11 March 2011 Great East Japan Earthquake and Tsunami, TEPCO's Fukushima Daiichi nuclear power station was severely damaged and a significant amount of radioactive material was released into the environment. The potential risks of human exposure to radiation resulting from this accident received priority attention around the world. As the United Nations directing and coordinating authority on international public health issues, WHO was directly engaged in assessing and communicating public health risks. Since the onset of the accident, WHO's response has been articulated through the Organization's Western Pacific Regional Office, based in Manila, Philippines, assisted by WHO headquarters and the WHO Centre for Health Development in Kobe, Japan.

1. See World Health Assembly resolution WHA25.57.
2. See World Health Assembly resolution WHA58.1.

Assessment of the health risks arising from this accident requires knowledge of the radiation doses delivered to populations within Japan and beyond. To that end, WHO established an International Expert Panel to undertake an initial assessment of radiation doses received by populations inside and outside Japan as a consequence of the Fukushima Daiichi accident. The panel consisted of independent scientific experts and representatives of WHO, the International Atomic Energy Agency and the Food and Agriculture Organization of the United Nations. The United Nations Scientific Committee on the Effects of Atomic Radiation and the Government of Japan participated as observers. This report summarizes the results of the dose assessment conducted by the panel. It represents the first international effort to estimate radiation doses from this accident at the global level, taking into account all the significant exposure pathways. This report is primarily intended for use by the WHO Health Risk Assessment Group to inform an initial assessment of health risks incurred as a consequence of the Fukushima Daiichi accident. It provides information to Member States and the public on the anticipated scale of doses for the first year after the accident.

1. Introduction

The earthquake and tsunami in Japan on 11 March 2011 led to releases of radioactive material into the environment from the Tokyo Electric Power Company's Fukushima Daiichi nuclear power station. This report describes an estimate of radiation doses to the public resulting from this accident. These doses, characteristic of the average doses, and presented in this report as "characteristic doses", are assessed for different age groups in locations around the world, using a set of assumptions described in the text.

The dose assessment described in this report was undertaken by an International Expert Panel convened by WHO in June 2011 with the aim of completing its work within a short timescale and is therefore preliminary in nature.

This dose evaluation forms one part of the overall health risk assessment of the global impact of the accident at the Fukushima Daiichi nuclear power plant, which is being carried out by WHO. This health risk assessment is the subject of a separate WHO report that is intended to inform public health actions.

The present assessment will form one input into a two-year scientific study to assess the radiological consequences of the Fukushima Daiichi nuclear power accident that is to be published by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) in 2013. More refined assessments will no doubt be conducted and reported in the future as additional data become available.

The panel agreed to concentrate on the most important contributors to dose rather than attempting to analyse all aspects comprehensively. As this assessment is intended to be realistic, the panel made conservative assumptions only when data were insufficient (e.g. with regard to the timeline of implemented protective actions). The dose estimates were based primarily on the best input data available up to mid-September 2011. The results are presented in a level of detail commensurate with the availability of data and the preliminary nature of the assessment. The report is the first study to present an estimate of the doses around the world, incorporating all exposure pathways that contribute significantly to radiation dose.

1.1 Background

On 11 March 2011 Japan suffered a magnitude 9 earthquake, the largest ever recorded in the country. The epicentre was just over 180 km from the site of the Fukushima Daiichi nuclear power plant that had six nuclear reactors, each with its own fuel storage pond. At the time of the accident, three of the site's nuclear reactor units (reactors 1–3) were operating at power. Reactor 4 was refuelling, and reactors 5 and 6 were shut down for maintenance. Reactors 1–3 were automatically shut down when the earthquake occurred. However, less than one hour after the earthquake a massive

tsunami generated by the earthquake inundated the nuclear site at Fukushima Daiichi with seawater.

The damage caused by the flooding of the site resulted in loss of cooling to the three reactor units. This led to eventual overheating, hydrogen explosions and a probable partial melting of the core of the three reactors. As a consequence, major releases of radioactive material to the environment occurred. These releases were initially to the air, but subsequently there were also radioactive releases to the sea through discharge of water used to cool the reactors and the spent fuel ponds (*1*). The nuclear accident was eventually classified at Level 7, the highest on the International Nuclear and Radiological Event Scale (INES) (*2*).

Measures were taken by national authorities to protect their populations from the consequences of the nuclear accident. In Japan, initially a three-kilometre evacuation zone was put in place around the site, which was soon increased to a 20-kilometre evacuation zone with a 30-kilometre sheltering zone. As the availability of environmental monitoring data increased, other protective actions were implemented to reduce doses in the longer term, including the relocation of people in some areas (designated by the Japanese authorities as “deliberate evacuation areas”) (Figure 1). Stable iodine for thyroid blocking was pre-distributed. Provisional regulatory limits for the radioactive content of food were established quickly after the accident, and monitoring was conducted by local governments based on testing guidelines prepared by the Government of Japan. Foods were to be tested before going to the market in early harvest season and the foods found to contain higher concentration of radioactive nuclides than the provisional regulatory limits were subject to appropriate measures. Furthermore, in the case that the contamination was spread over an area, distribution restrictions were implemented for the foods in that area. Similarly, monitoring of tap water was conducted, both by central and local government and by the water supply utilities, with especial emphasis in Fukushima and neighbouring prefectures.

Around the world, governments considered steps to protect their citizens. The primary concern was for those residing in or visiting the most affected regions of Japan in the days and weeks after the earthquake, but there was also consideration of whether any steps were needed within their own countries (such as restrictions on food imports from Japan).

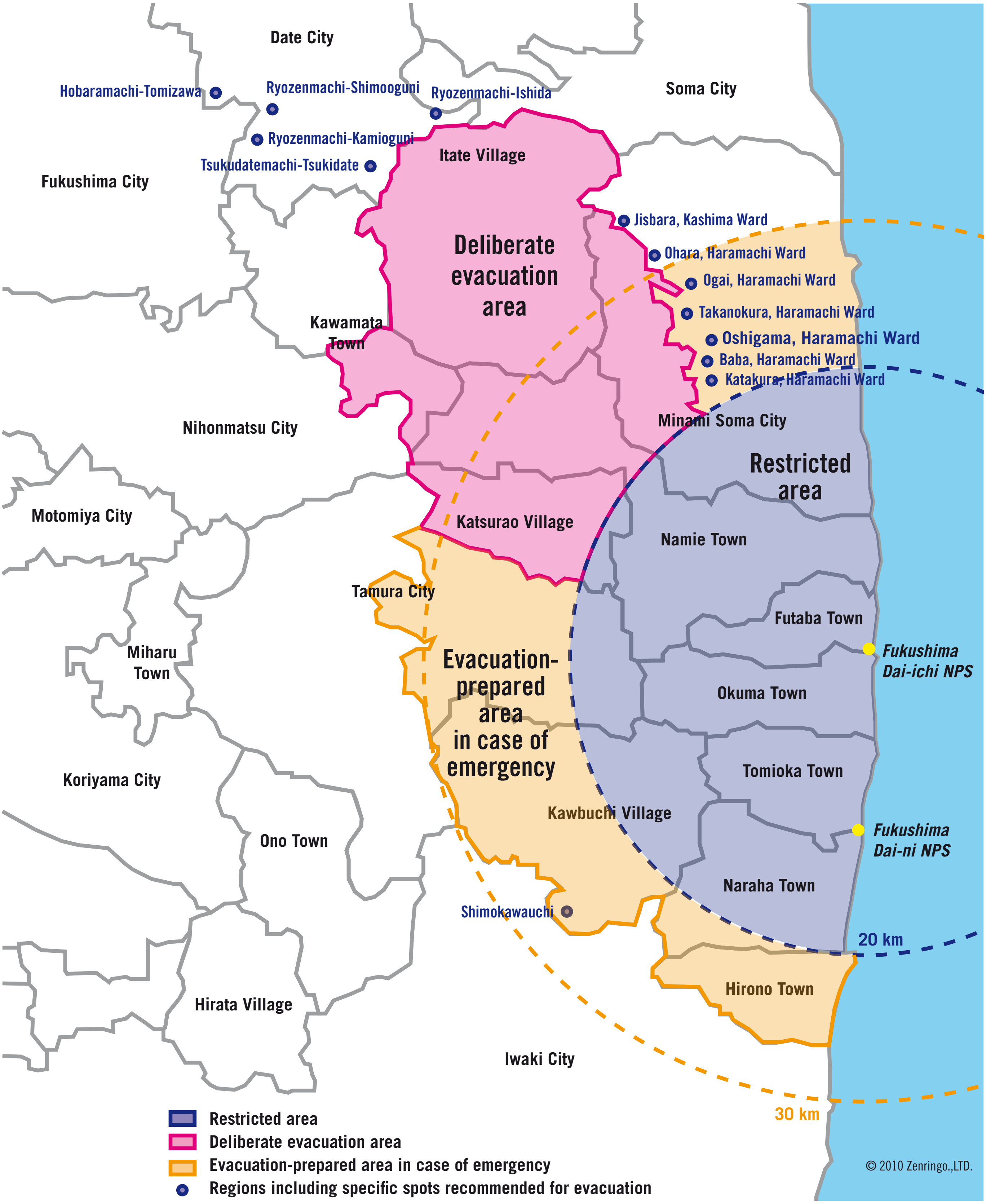
By mid-2011 detailed information was provided in authoritative reports relating to the nuclear accident issued by the Japanese government (*3*,*4*,*5*) and the IAEA (*6*).

1.2 Purpose and audience

The purpose of this study is to estimate radiation exposure for populations around the world in the first year following the Fukushima Daiichi nuclear power plant accident. The study focuses on radiation exposure of members of the public.

This report is primarily intended for use by the WHO Health Risk Assessment Group to inform an initial assessment of health risks incurred as a consequence of the Fukushima Daiichi accident. It also provides information to Member States and the public on the anticipated scale of radiation doses. Ultimately, the report is expected to serve as support for policy-makers and decision-makers.

Figure 1. Restricted area, deliberate evacuation area and regions including specific spots recommended for evacuation (as of November 25, 2011)



Source: Adapted from http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/evacuation_map_111125.pdf (reproduced with permission).

1.3 Scope

This report provides a preliminary estimate of radiation doses to the public resulting from the accident at the Fukushima Daiichi nuclear power plant. The doses are characteristic of the average doses, and are assessed for different age groups in locations around the world.

This report does **not** include:

- **doses within 20 km of the Fukushima site**, since most people in the area were rapidly evacuated. While some dose may have been received prior to evacuation, such assessment would have required more precise data than were available to the panel.
- **doses to workers,** because the evaluation of occupational radiation exposure requires a dosimetric approach different from the one used for members of the public. The assessment conducted by the WHO Health Risk Assessment (HRA) Expert Working Group will incorporate information on workers' exposure provided by the Government of Japan.
- **health risks and possible public health actions,** since the doses calculated here will serve as input to a subsequent analysis by the HRA Expert Working Group which will evaluate the health risks due to the radiation exposure resulting from the accident.

1.4 Overview of the methodology

An assessment of the doses received following a release of radioactive material to the environment requires data on a number of aspects, such as measured levels of radionuclides in the environment, in tap water and in foodstuffs, estimated amounts of radioactive material released, atmospheric dispersion and deposition patterns, the nature of subsequent transfer in the environment, and the location and habits of the population for whom doses are being assessed.

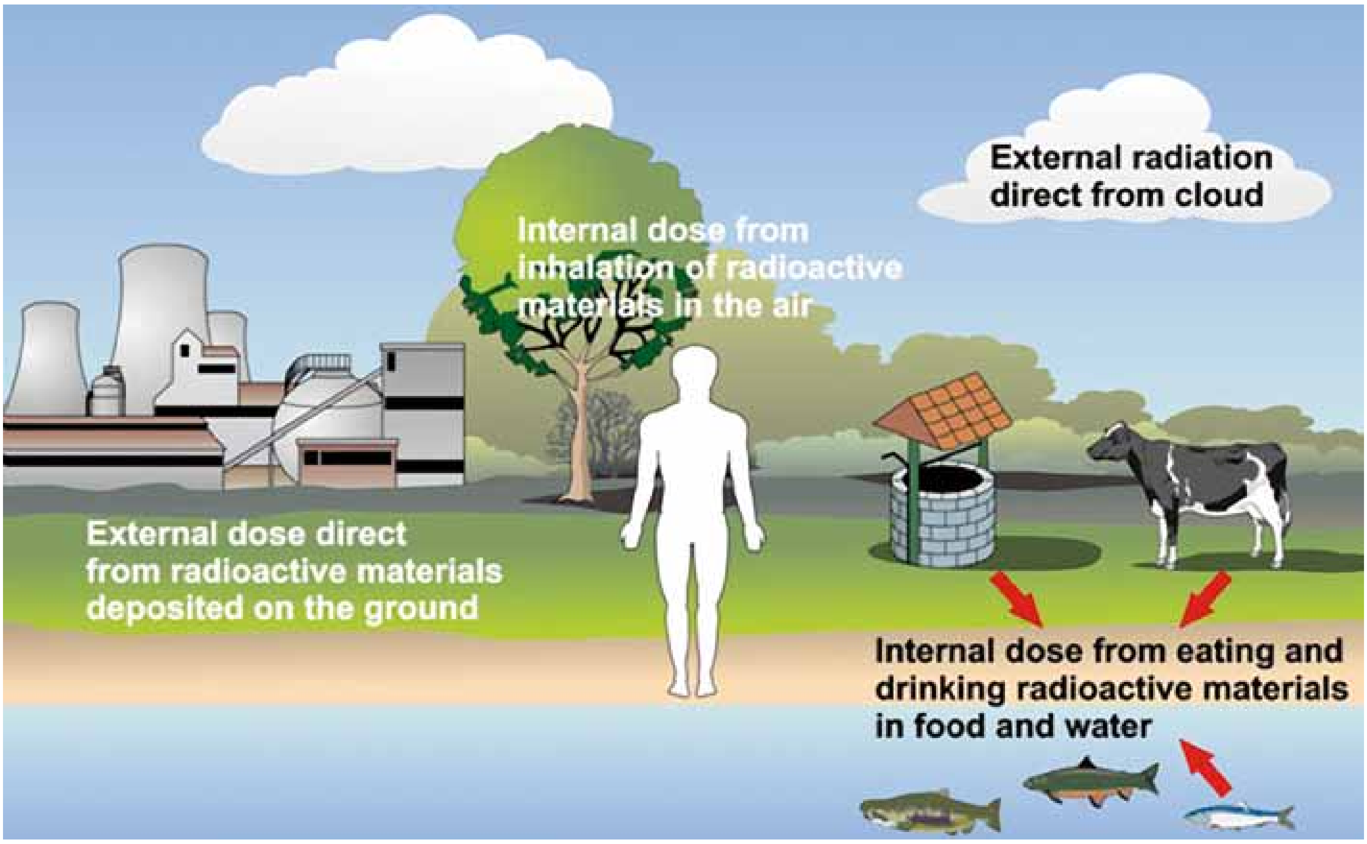
Following the Fukushima accident, humans were exposed to radioactive material by several pathways (Figure 2). The major exposure pathways were:

- external exposure from radionuclides deposited on the ground (groundshine);
- external exposure from radionuclides in the radioactive cloud (cloudshine);
- internal exposure from inhalation of radionuclides in the radioactive cloud (inhalation);
- internal exposure from ingestion of radionuclides in food and water (ingestion).

All of these exposure pathways were considered in the assessment. The expert panel also considered the relative importance of additional pathways, such as external radiation from material deposited on skin and clothing. The panel agreed that these additional pathways would be of much lower importance and therefore not included in this preliminary study.

As far as possible, the assessment described in this report has been based 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. This has been the approach to the estimates of dose in Japan, where official measurement data published

Figure 2. Exposure pathways to humans from environmental releases of radioactive material



Source: IAEA report on Environmental consequences of the Chernobyl accident and their remediation: twenty years of experience (2006) p. 100 (reproduced with permission).

by the Government of Japan have been the primary source. However, such data were not generally available for the rest of the world. Consequently, environmental modelling predictions based on an estimated source term in combination with atmospheric dispersion modelling and environmental measurements were used to estimate doses outside Japan.

1.5 Endpoints and scenarios

The Panel took into account a number of factors, assumptions and scenarios to estimate the radiation doses required. These are discussed below.

1.5.1 Dosimetric endpoints

The dosimetric endpoints of this study are effective doses and equivalent doses to the thyroid, resulting from exposure over the first year. Box 1 defines the dosimetric terms used.

The effective dose is calculated as the sum of the external dose received during the assessed period, which in this assessment is the first year following the start of the release, and the committed effective doses (to age 70 years[1]) from intakes of radionuclides by

1. The integration period is 50 years for adults and up to age 70 years for children.

ingestion and inhalation over the same period (Box 2). The effective dose in this report includes the contribution from dose to the thyroid.

In considering the radiological consequences of the Fukushima accident, the panel agreed that the use of effective dose would be an appropriate quantity for this dose assessment. The concept of effective dose enables external and internal exposures from different types of radiation to be combined (*7*). It is particularly appropriate to use effective dose for external gamma radiation that irradiates the whole body more or less uniformly. Radioactive isotopes of caesium are likely to be significant in terms of health consequences and environmental impact after a major nuclear accident. For internal exposures, an important contribution to the committed dose is likely to be due to the ingestion and inhalation of isotopes of caesium (*8*). Since the bio-distribution of caesium in the body is quite homogeneous, all organs are irradiated, and hence the effective dose is a good indicator of the impact of such intakes.

In addition to effective dose, the Panel agreed to assess thyroid doses because the intake of iodine-131 (^{131}I) is also likely to be an important contributor to overall exposure. In this case the distribution in the body is far from uniform, with the thyroid being the most exposed organ. After the Chernobyl accident in 1986, elevated incidence of thyroid cancer was found in people who were children at the time of the accident (see, for instance, WHO's 2006 report on health effects of the Chernobyl accident (*9*).

The thyroid doses were assessed in terms of equivalent dose, which is the dose delivered to an organ allowing for the biological effectiveness of different types of radiation. The

Box 1. Dosimetric quantities

Dosimetric quantities are needed to assess human radiation exposures in a quantitative way. The International Commission on Radiological Protection (ICRP) provides a system of protection against the risks from exposure to ionizing radiation, including recommended dosimetric quantities.

The fundamental measure of radiation dose to an organ or tissue is the **absorbed dose**, which is the amount of energy absorbed by that organ or tissue divided by its weight. The international unit of absorbed dose is the gray (Gy), which is equal to one joule per kilogram.

The response of tissues and organs varies for different types of radiation. Also, tissues and organs have **different radiosensitivity to radiation. The equivalent** dose in a tissue or organ is the absorbed dose averaged over that tissue or organ, further applying a *radiation weighting* factor that varies by radiation type and is related to the density of ionization created. The international unit of equivalent dose is the sievert (Sv).

An additional and frequently used concept is the **effective dose**, which is the sum of the products of absorbed dose to each organ multiplied by the *radiation weighting factor* mentioned above and a *tissue weighting factor* that takes into account the radiosensitivity of tissues and organs. The international unit of effective dose is also the sievert (Sv).

The **radioactivity** of a substance (also called "activity") is the rate at which the radioactive decay processes take place. It is measured in becquerels (Bq), defined as one disintegration per second. The ICRP has developed a set of dose coefficients for use in assessing the exposures resulting from inhalation or ingestion of radionuclides. These dose coefficients, expressed as Sv/Bq, have been specified for a range of body organs.

Source: Adapted from Ref. *10*

thyroid dose is the sum of external dose to the thyroid in the first year and the committed equivalent doses to the thyroid (to age 70 years[2]) from intakes by ingestion and inhalation over the first year following the start of the release.

It should be noted that, although the units are the same, thyroid doses and effective doses are two different quantities that cannot be compared. Thyroid doses are organ-specific equivalent doses, while the effective doses represent the sum of the products of the absorbed doses to each organ multiplied by the respective tissue weighting factors (see Box 1). Effective doses were estimated using ICRP dose coefficients which incorporate tissue weighting factors as specified in ICRP publication 60 (*7*). Based on this, the tissue weighting factor used for thyroid is 0.05.

1.5.2 Age groups considered

For the purposes of this assessment, three age groups were considered: adults, children aged 10 years, and infants aged one year. These age groups are judged to be sufficient to ensure consideration of younger, more sensitive members of the population (*11*). Doses to the fetus and breastfed infant were also considered (see section 3.2) but were not evaluated separately. Doses to six-month-old infants have been considered for the consumption of formula milk made up with tap water.

2. The integration period is 50 years for adults and from time of intake up to age 70 years for children.

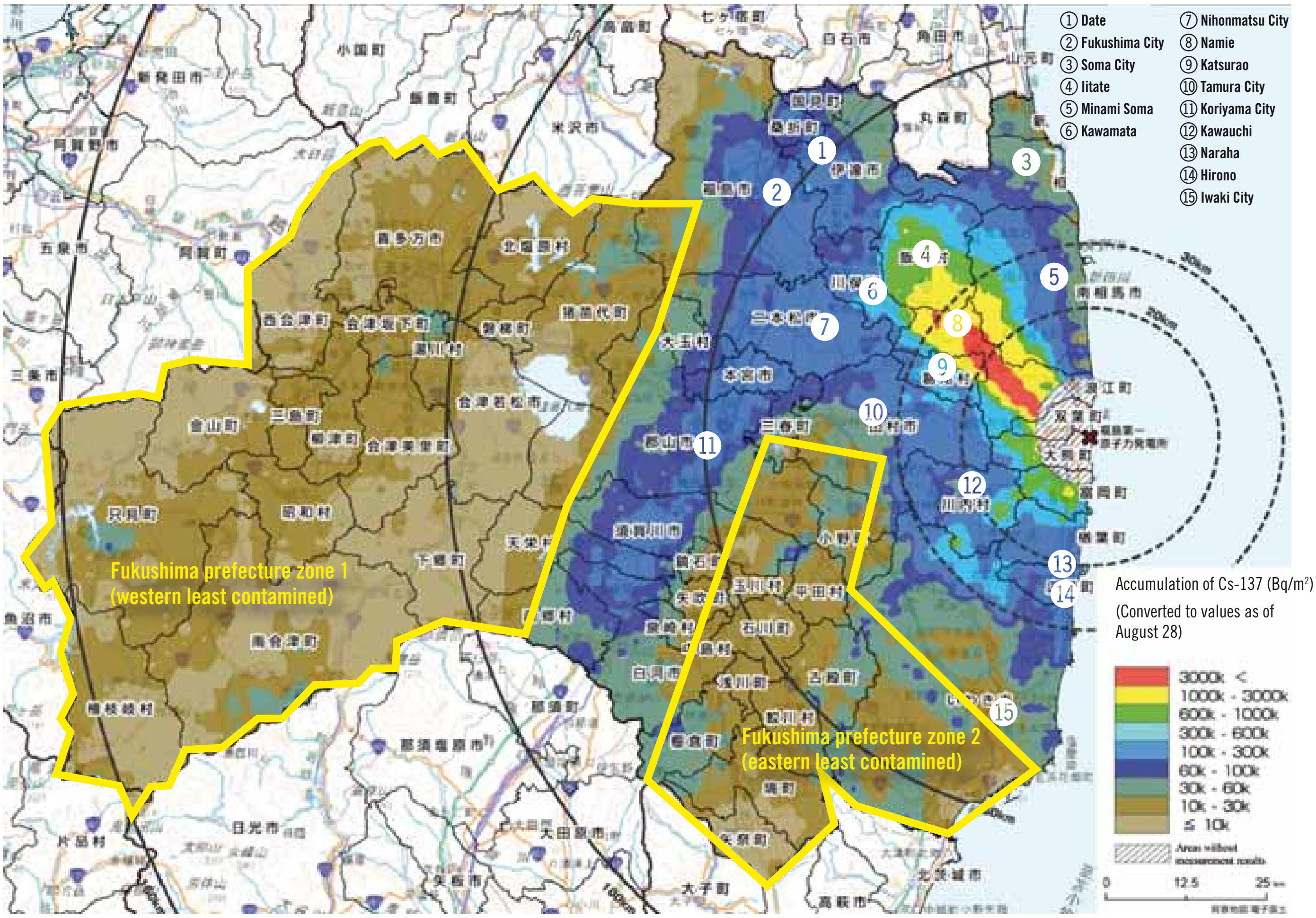
Box 2. Temporal distribution of the exposure after intake of radionuclides

The **physical half-life** is the period of time for one-half of the atoms of a radionuclide to disintegrate. Physical half-lives can range from a few microseconds to billions of years. The **biological half-life** is the period of time required to eliminate one-half of the radioactivity from the body. The actual rate of halving the radioactivity in a living organism is determined by a combination of both the physical and biological half-lives of the radionuclide, called the **effective half-life**. While for certain radionuclides the biological processes are dominant, for others physical decay is the dominant influence. For instance, the physical half-life of ^{134}Cs and ^{137}Cs is 2 years and 30 years respectively, but their biological half-life is much shorter (several months). In adults, 10% is excreted in the first few days after the intake and the rest leaves the body with a biological half-life of about a hundred days. The biological half-life of cesium increases as a function of body mass and age, which means that it leaves the body quicker in children and adolescents compared to adults (e.g. data from urinary assays and whole-body counting suggested that the biological half-life of ^{137}Cs in children is around 50 days).

In assessing radiological exposures arising from inhalation and ingestion, there is a distinction between the time period over which the intake occurs and the time over which the exposure (the radiation dose) to the body ensues. For example, intake from inhalation on a single day may give rise to the body being internally exposed to radiation over a period of days and months, and possibly over a much longer period, depending on the effective half-life.

The **committed dose** (effective or equivalent) is the dose that an individual will receive once a radionuclide intake has taken place. When it is not specified, the integration period considered for the assessment is 50 years for adults and the period of time needed to reach the age of 70 years for children.

Figure 3. Locations in Fukushima prefecture considered in the assessment



Source: http://radioactivity.mext.go.jp/en/contents/4000/3168/24/1270_0912_2.pdf (reproduced with permission). Readngs of the Airborne monitoring survey by MEXT in the Western part of Fukushima prefecture.

1.5.3 Geographical coverage

Estimates have been made of doses in different regions of the world, with greater spatial detail in the estimated doses presented for Japan, and in particular for the Fukushima prefecture.

Doses in the following five areas have been considered:

- the Fukushima prefecture, where doses are likely to be among the highest of those received by members of the public (see Figure 3);
- the prefectures in Japan nearest to the Fukushima region (see Figure 4);
- all other prefectures in Japan (see Figure 4);
- countries neighbouring Japan;
- other areas of the world.

Figure 4. Neighbouring prefectures considered in the assessment

1.5.4 Time frame

The estimated doses rely on measurements available until mid-September 2011. The doses estimated are those resulting from intakes and external exposures during the first year after the accident. Extrapolation beyond this time frame on the basis of the input data used for this preliminary assessment would be uncertain and therefore was not performed. While intakes are considered over the first year, some of the exposures resulting from the intake will continue beyond that period (see Box 2).

For the radionuclides released in the Fukushima accident, the great majority of the committed doses from inhalation and ingestion are expected in the first year. This is particularly the case for the isotopes of iodine due to their short physical half-life. For caesium isotopes, although the physical half-life is longer, the biological half-life is not long, particularly in children (see Box 2) (*8*).

1.5.5 Protective actions

During the Fukushima Daiichi nuclear power plant emergency, public health protective actions were implemented at different times. In the early phase, urgent protective actions aimed at preventing the short-term radiation exposure included evacuation, sheltering, pre-distribution of stable iodine, and food and water restrictions. As the availability of environmental monitoring data increased, other protective actions were implemented,

including relocation of people to reduce doses in the long term. Protective actions are discussed below together with the modelling approach adopted to account for each.

Movement of people

Evacuation – Most people within 20 kilometres of the nuclear power plant were rapidly evacuated. Therefore, the panel chose not to estimate doses in this area. Some dose may have been received prior to evacuation but the assessment of this required more precise data than were available to the panel at the time of the assessment, including detailed information about the implementation of protective actions (see Box 3).

Sheltering – Sheltering was implemented in the short term for residents within a zone between 20 and 30 kilometres radius from the plant (see Box 3). It is possible that in some locations sheltering was prolonged (i.e. beyond the first few days) and in such cases it could not be observed as stringently as a very short-term measure. People would, for example, have to leave the house for at least short periods to obtain food supplies if the measure was in place for periods in excess of a few days. The panel had no access to detailed information on the stringency with which this countermeasure was implemented, nor the timing of the introduction of the countermeasure and its duration. Therefore, the effect of sheltering in reducing dose during the early phase of the emergency has not been considered for the present dose assessment.

However, the first year doses account for the shielding provided by buildings, resulting in reduced external radiation dose during the period of time people are assumed to be

Box 3. Movement of people

Movement of people in the early phase of the response

In the early phase of a nuclear emergency (within the first few hours/days), urgent protective actions regarding movement of people may be implemented to prevent radiation exposure, taking into account projected doses that people may received in the short-term (e.g. effective dose within 2-7 days, thyroid dose within one week). Decisions are based on nuclear power plant conditions, amount of radioactivity actually or potentially released into the atmosphere, prevailing meteorological conditions (e.g. wind speed and direction, precipitation), and other factors. **Evacuation** is the urgent removal of populations within a radius around the event site, which is most effective when used as a precautionary action before an airborne release takes place. **Sheltering** is an urgent protective action implemented primarily to provide shielding against external exposure and by using a structure for protection from an airborne plume and/or deposited radionuclides (e.g. people being advised to remain permanently indoors with the doors and windows sealed). In contrast to sheltering, which is an urgent action in the early phase of the emergency, people spend a proportion of time indoors as part of their normal lifestyle. The shielding provided by the building while people are indoors would reduce external exposure compared to outdoor doses, but the protection against inhalation exposure would be much less due to air exchange between the indoor and outdoor environments.

Movement of people in a later phase of the response

As environmental and human monitoring data increases, other protective actions may be implemented, taking into account the doses that a population may receive over the long-term (e.g. effective dose during one year). **Temporary relocation** is a non-urgent movement of people from a contaminated area to a temporary housing to avoid chronic radiation exposure. It may be a continuation of the urgent protective action of evacuation (as a longer-term action). If return after relocation is not foreseeable within one or two years, relocation is considered as permanent and is often called **re-settlement**.

indoors as part of a normal lifestyle. No protection from inhalation doses for such normal indoor residency has been assumed since, in the longer term, radioactivity concentrations in indoor air are expected to become similar to those outdoors and the protection provided against inhalation doses would be small.

Relocation – Outside the 20 kilometre radius, inhabitants of the most affected area, coined the "deliberate evacuation area" (Figure 1), were subject to relocation at different times after the accident. For the assessment of doses in this area, only doses in the first four months of the first year have been estimated, with the assumption that relocation took place at four months, and therefore that no doses were received beyond the first four months. Information provided by the Government of Japan indicates that in parts of this zone the relocation occurred before four months.

Stable iodine uptake

Stable iodine was pre-distributed but it is thought that only a small number of persons in specific locations in Japan actually consumed stable iodine as actual consumption (as opposed to distribution) of stable iodine was not officially recommended in most places. Therefore, the Panel assumed that stable iodine tablets were not taken by members of the public, either in Japan or elsewhere.

Food and water restrictions

The assessment of ingestion doses was based on the results of all monitoring tests, including food on the market, food before shipment and food produced in the distribution-restricted areas. The assessment does not explicitly model the effect of the imposition of food restrictions.

It is known that restrictions on tap water were applied in several villages. The assessment of doses from ingestion of water in this study is cautious and is based on official data on levels of radioactivity measured in tap water not assuming any water restrictions.

1.6 Procedures

An International Expert Panel was established to make an initial assessment of the possible range of radiation doses produced as a consequence of the accident in populations inside and outside Japan. The panel consisted of independent experts, selected on the basis of their scientific competence and experience, and representatives from WHO, the International Atomic Energy Agency (IAEA) and the Food and Agriculture Organization of the United Nations (FAO). The participation of technical staff from these three United Nations agencies was essential, given the relevance of the assessment to the agencies' respective roles, mandates and expertise.

The experts were selected on the basis of their scientific competence and experience in the assessment of human exposures arising from radioactive material in the environment. The panel included experts on internal and external dosimetry, food and water safety, public health, and radioecological modelling. The experts were required to disclose any interests. No conflicts of interest were identified for any of the participants.

UNSCEAR has initiated a two-year assessment of the exposure levels and effects of the Fukushima accident, and its main scientific report will be submitted to the United Nations General Assembly in 2013. UNSCEAR participated in the panel as observer to ensure that approaches and data sources for the two United Nations assessments were compatible. Close cooperation was maintained while the two assessments were in progress.

Collaboration with the Government of Japan and relevant Japanese institutions was deemed to be crucial for the successful completion of the work as they provided much of the official data for the dose assessment.

The panel met on three occasions during 2011 (on 30 June in Vienna, 5–6 September in Geneva, and 13–14 October in Geneva) and chiefly worked electronically. The detailed dose calculations, not included in this report, have been shared with the participating organizations in order to inform their respective activities.

The technical work was distributed between the experts. There were three components to the dose assessment, namely:

- Doses in Japan from external irradiation and from inhalation were assessed on the basis of measurements by both the Institute of Radiation Hygiene in Russia and the Federal Office of Radiation Protection in Germany. The two institutes used similar but not identical assumptions. These are presented in chapter 2, sections 2.3.1, 2.4.1 and 2.5.1, and are further explained in Annex 6.
- On the basis on food monitoring data, WHO assessed estimates of dose to the Japanese people from ingestion of food produced in certain regions of Japan. This assessment also included consideration of the doses outside Japan from consumption of food produced in Japan and exported. This assessment is presented in chapter 2, section 2.6, and is further explained in Annex 8.
- Doses in the rest of the world were assessed by the United Kingdom's Health Protection Agency on the basis of assumed source terms combined with dispersion modelling and environmental measurement data from around the world.[3] Where appropriate, this assessment assumed a methodology and input data consistent with those used in the measurement-based assessments. This assessment is presented in chapter 2, sections 2.3.2, 2.4.2 and 2.5.2, and is further explained in Annex 7 and Annex 9.

3. For the ingestion pathway outside Japan, consumption of locally-produced food was considered.

2. Methodology

This chapter summarizes the approaches and input data used in the estimation of doses to population groups living in particular locations. The different exposure pathway models and related assumptions are presented (see Figure 5).

2.1 Approaches

As described in section 1.4. the dose contribution from the following four pathways was taken into account in different geographical locations within and outside Japan:

- external exposure from radionuclides deposited on the ground (groundshine);
- external exposure from radionuclides in the radioactive cloud (cloudshine);
- internal exposure from inhalation of radionuclides in the radioactive cloud (inhalation);
- internal exposure from ingestion of radionuclides in food and tap water (ingestion).

Several approaches were used to calculate the doses to corroborate the results. For the external radiation and inhalation pathways inside Japan, two approaches were developed using different assumptions (Approach A and Approach B), providing a range of results and a validation mechanism for the chosen methods. Outside Japan, an approach based on an atmospheric dispersion model was used (Approach C). For the ingestion pathway within Japan, a model (Approach D) based on food measurements (mainly around the Fukushima prefecture) was developed, while outside Japan an environmental model estimating radionuclide concentrations in locally-produced food from an assumed source term (Approach E) provided the relevant data

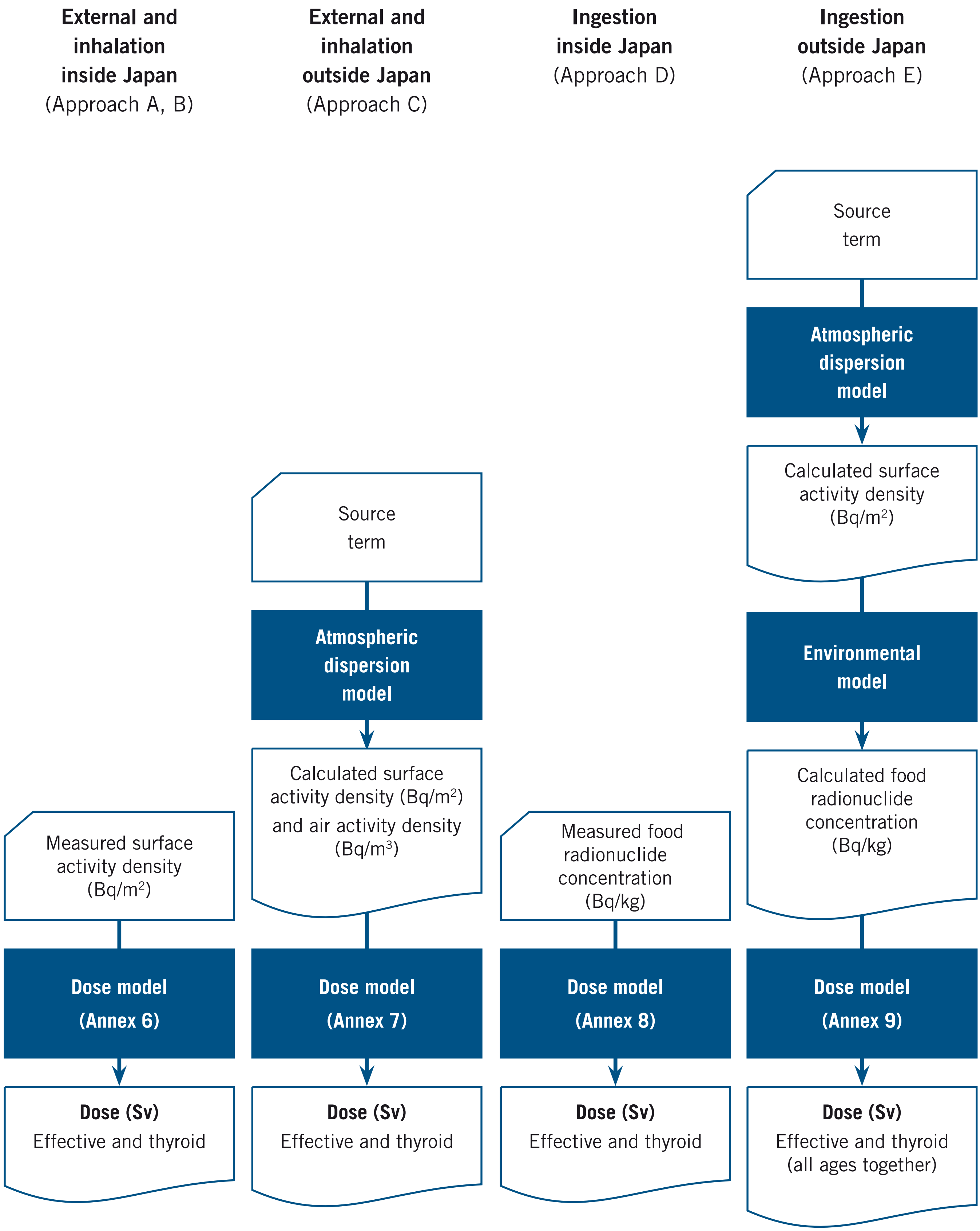
2.2 Input data

All the available radiological measurement data used in this assessment are publicly available on the web sites of Japan's Ministry of Education, Culture, Sports, Science and Technology (*12*) and Ministry of Health, Labour and Welfare (*13*). The Government of Japan has provided this information to the Incident and Emergency Centre of the IAEA in Vienna on a regular and frequent basis since the Fukushima accident. The information has been collated by IAEA into a database. Relevant information available within the timescale of the assessment has been shared with the panel for the purpose of this study.

2.2.1 Radionuclide composition and deposition

Assessment of the impact of the accident requires consideration of the spectrum of all significant radionuclides released. In this assessment, this has been done through assumed radionuclide compositions and assumed source terms.

Figure 5. Approaches used in the assessment



Measurements of radionuclides in the environment, which form the basis of the dose assessment for Japan, are available for only a subset of radionuclides released in the accident. Fortunately, the radionuclides that contribute most significantly to dose are represented in those measurements. In this study, different radionuclides were accounted for in the various exposure pathways. The assessment of doses from inhalation and external radiation in Japan assumed a radionuclide composition for the releases which covered nine key radionuclides (see Annex 6). For the rest of the world, up to 16 radionuclides were specified in the estimated released source terms used in the study (see table A4.1 and more detailed information in Annex 4). The assessment of doses from ingestion of food in Japan was based on the measured levels of iodine-131 (^{131}I), caesium-134 (^{134}Cs) and caesium-137 (^{137}Cs) in food samples reported by the Government of Japan.

At present, source term estimation for the Fukushima accident is associated with considerable uncertainty. The source terms used in this assessment are applied only to estimation of doses outside Japan. Two source terms were used as input to an atmospheric dispersion model, which are similar in terms of the overall magnitude of the main radionuclides released but differ in the time dependence of the releases (see Annex 4).

2.2.2 Environmental monitoring data

Environmental monitoring data for Japan include measurements of radionuclides in air, soil, foodstuffs, drinking-water and fresh water. More data are available for the areas with higher levels of radioactive material than for the less affected areas.

The environmental measurement data used as primary input to the assessment are surface activity densities. Measured levels of deposited radionuclides are available for all 47 Japanese prefectures, and levels in Fukushima prefecture show significant variation with location. These measurements include a very small component from the global fallout from nuclear weapons-testing.

Gamma dose rates are available from a wide range of monitoring locations in Fukushima prefecture and show considerable variation with location. Gamma dose rates are also available for the other 46 Japanese prefectures and, by September 2011, they indicated levels which were within the background range for Japan (the natural background range reported to the panel was 30–100 nSv/h, which is consistent with the data reported by the Fukushima prefecture authorities) (*14*).

The data on radioactivity concentrations in air are very limited. This is partly due to the failure of equipment in many locations close to the nuclear power plant as a result of the earthquake and tsunami. Where data do exist there is insufficient coverage for the early days of the release to enable the data to be used in this assessment. For this reason, radioactivity concentrations in air in Japan have been derived from modelling on the basis of the measured levels of radioactivity deposition on the ground.

2.2.3 Food monitoring and consumption data

To assess exposure from radionuclides in food the International Expert Panel decided to use measurements rather than modelling wherever possible. The monitoring of food

produced in Japan was published on the Japan's Ministry of Health Labour and Welfare web site (*13*). The monitoring data included the results of foods that were not distributed on the market such as marine products from Fukushima prefecture and other foods from distribution-restricted areas.

The results of food radionuclide concentration monitoring around the world have been received by the International Food Safety Authorities Network (INFOSAN)[1] and compiled in a comprehensive database. Data from monitoring of food exported from Japan is generally available on the web sites of the corresponding authorities.

Regarding food consumption in Japan, the Japanese National Institute for Health and Nutrition (NIHN) provided data based on the 2009 National Health and Nutrition Survey Outside Japan, food consumption data were taken from the WHO GEMS/Food consumption cluster diet G (*15*).

2.3 External radiation doses from radionuclides deposited on the ground (groundshine)

External radiation doses from radionuclides deposited on the ground (groundshine) represent a significant long-term exposure pathway. For the purposes of this assessment, the external gamma dose integrated over the first year following the accident was calculated for locations both in Japan and in the rest of the world.

2.3.1 Inside Japan

In the study, two slightly different approaches (A and B) were applied to estimate the external effective and thyroid doses from radionuclides on the ground. The full details of the model are given in Annex 6 and the input parameters are provided in Annex 3.

The doses in Japan have been estimated on the basis of the measured ground deposition levels (surface activity densities). In Approach A the dose calculations were performed using dose rate coefficients, representing the values of gamma dose rate in the air (at one metre above the ground) normalized to a unit deposit of each radionuclide in combination with dose conversion factors to convert these to effective and thyroid doses. Approach B directly used both effective and thyroid dose coefficients per unit deposit of each radionuclide. Unlike Approach B, Approach A accounted for the shielding effect from radionuclide penetration in soil, leading to a small (approximately 5%) reduction in the estimated external doses in the first year. Finally, small differences were assumed in the composition of the deposited radionuclides, based on alternative sources for the soil contamination measurements used (see Annex 6 for references on this issue). Both approaches took into account the radioactive decay over the period for which the dose was calculated.

External doses can be significantly lower indoors than outdoors due to the shielding effects of the building. This was taken into account by using a location factor of 0.4 for building type and an assumed occupancy factor of 66% (i.e. two thirds of the time per day spent indoors). Details of the method are presented in Annex 3 (Table A3.9).

1. The International Food Safety Authorities Network (INFOSAN) is a joint initiative of FAO and WHO.

2.3.2 Outside Japan

For the rest of the world, very few data were available on the levels of ground deposition as a result of the accident. Therefore, instead of a measurement-based approach, a modelling approach (Approach C) was adopted to estimate the global ground depositions required to assess external doses. The calculations were undertaken with estimated source terms (Annex 4) and using atmospheric dispersion modelling to predict depositions and hence external doses using the dose coefficients (see Tables A3.6 and A3.7 in Annex 3) as in the measurement-based approach.

The doses outside Japan were based on an atmospheric dispersion model utilizing global weather data for the period of dispersion and recirculation. The United Kingdom Met Office's NAME III (Numerical Atmospheric dispersion Modelling Environment, version 5.2) dispersion model (*16*) was used. NAME III is a complex model used to estimate dispersion and deposition of gases and particulates. It incorporates both radioactive decay processes and estimates of the external dose from the radioactive cloud. Input data for this model include time-varying three-dimensional meteorological data and estimations from radar-measured rainfall data and the Met Office's numerical weather prediction unified model (*17*). The output represents time-averaged and time-integrated activity concentrations in air, and in wet, dry and total ground depositions of radionuclides.

The panel was aware that international experience using complex dispersion models such as NAME III to predict the global dispersion arising from Fukushima indicates that, at far distances, model predictions are in general substantially lower than measurements. To ensure that doses in the rest of the world are not consistently underestimated, the predictions of the NAME III model for two different source terms (see Annex 4) were used in conjunction with measured concentrations of radionuclides from around the world,[2] to obtain global distributions of activity concentrations in air and ground depositions for input into the dose calculations. As a result of this combined approach, the estimations of the NAME III model showed good agreement with the radiological measurements and were considered to form a sound basis for the subsequent dose estimation.

2.4 External radiation doses from the radioactive cloud (cloudshine)

2.4.1 Inside Japan

In the context of this accident, external exposure from cloudshine is of secondary importance to external exposures arising from groundshine. However, it is the only pathway of relevance for noble gases, which do not deposit on the ground and for which any inhalation doses are negligible. Most releases of noble gases from the Fukushima site would have occurred early in the release and are not expected to provide a significant contribu-

2. These data include locations in Austria, Denmark, France, Germany, Sweden, Philippines, North America, and Alaska, but at November 2011 they were still largely unpublished. Published examples are in: (Preparatory Commission for the Comprehensive Nuclear-Test-Ban Organization, or CTBTO) air monitoring station data published on the web site of the Philippines Nuclear Research Institute. The United States' Environmental Protection Agency's RadNet data can be seen at: http://www.epa.gov/japan2011/.

tion to radiation exposure inside Japan and thus, this exposure to noble gases has not been included in this estimation of doses inside Japan.

Because measured external dose rates were not available in sufficient locations in the first few days after the release started, it was not possible to use measurements for the assessment of external exposure from cloudshine. Instead, external doses from cloud-shine were reconstructed by modelling.

To calculate the external dose from radionuclides in the cloud, it was necessary to convert ground deposition levels to time-integrated activity concentrations in air. The full details of the method for estimating time-integrated activity concentrations in air from the ground deposition levels is given in Annex 6 section 2.

Two slightly different approaches were applied to estimate the external effective and thyroid doses from radionuclides in the air. In Approach A, the calculations were performed using dose rate coefficients representing the values of gamma dose rate in air (at one metre above the ground), normalized to a unit radionuclide concentration in the radioactive cloud in combination with factors to convert these to effective and thyroid doses. Approach B directly used effective and thyroid dose coefficients per unit air concentration. These calculations were undertaken for each radionuclide. As for deposited activity, small differences were assumed in the composition of the deposited radionuclides.

In Approach A, two different sets of radionuclide deposition velocities were applied, depending on the surface activity density of ^{137}Cs, while in Approach B a single deposition velocity was assumed for all radionuclides and in all areas (assuming predominantly wet deposition).

The shielding effects of buildings in reducing external doses from radionuclides in the air was accounted for in the same way as for external radiation from radionuclides deposited on the ground (see Annex 3, Table A3.8 and Table A3.9).

The full details of the method for estimating external effective and thyroid doses from radionuclides in air are given in Annex 6.

2.4.2 Outside Japan

Outside Japan, a modelling approach to reconstruct external doses from radionuclides in the atmosphere was adopted. This modelling was based on the predictions of the NAME III model (see section 2.3.2). This was necessary because there are very few suitable measurement data available outside Japan. The calculations were undertaken with estimated source terms (discussed in Annex 4), using atmospheric dispersion modelling to estimate concentrations in air and the semi-infinite cloud approach to assess external doses (*18*). The details of the method for estimating external effective and thyroid doses from radionuclides in air outside Japan are given in Annex 7.

2.5 Internal radiation doses from inhalation

This section summarizes the assessment methodology for the inhalation exposure pathways. The model is described in Annex 6, and input parameters are presented in Annex 3 (Tables A3.1, A3.2 and A3.5).

2.5.1 Inside Japan

Intakes by inhalation occur during the passage of the radioactive cloud resulting from a release. There is also the possibility of additional inhalation later of material resuspended from the ground. For the radionuclides released in the Fukushima accident, the panel agreed that resuspension is not expected to provide a significant contribution to radiation exposure and this pathway was therefore not considered in this initial assessment.

Ideally, estimates of inhalation dose should be based on measurements of concentrations of radionuclides in air during the period of time for which the radioactive cloud is present over each location. Instantaneous measurements are not helpful unless they form part of a detailed time-series, as integrated concentrations in air are required. However, because there were insufficient measurements taken in Japan of concentrations in air internal doses had to be reconstructed by modelling. To calculate the internal dose from inhalation, it was necessary to convert ground deposition levels to time-integrated activity concentrations in air, as described in Annex 6, section 3. The full details of the method for estimating internal doses from inhalation using the two approaches A and B are given in Annex 6.

The calculations in approaches A and B differ in the estimation of activity concentrations in air from ground deposits. As described above, for Japan the measured ground depositions have been used to estimate activity concentrations in air, taking into account generic information available on precipitation and other key factors to obtain the best scaling factor.

Most air samplers measure only particulate material, whereas radioactive iodine will have been in the atmosphere in both vapour and particulate forms. Additional assumptions are therefore required on the ratio of the different chemical forms of iodine to enable the measurements to be used in an assessment. In Approach A, a ratio of 50:50 is assumed for vapour and particulate forms of iodine, while approach B assumes 100% vapour iodine. In each case, doses have been estimated using standard ICRP dose coefficients and inhalation rates for the three age groups of interest (see Annex 3).

Neither Approach A nor Approach B assumed any protection due to being indoors for a portion of the time. Generally, sheltering indoors provides a reduction in the intakes of radioactive material through inhalation. However, to be cautious, no account has been taken here of any reduction in the indoor air compared to outdoor.

2.5.2 Outside Japan

Outside Japan, a modelling approach was adopted to reconstruct internal doses from radionuclides in the atmosphere as there are relatively few locations where a comprehensive time-series of air concentrations is available and for which the levels are mostly

above limits of detection. This modelling was based on the predictions of the NAME III model presented in section 2.3.2. Atmospheric dispersion calculations based on estimates of the amount of radionuclides released at different times, together with measured concentrations of radionuclides around the world, have been used to estimate time-integrated activity concentrations in air at relevant locations outside Japan. These estimated time-integrated activity concentrations in air are scaled by ICRP dose coefficients and inhalation rates (as detailed in Annex 3) to estimate inhalation doses. More details of the method for estimating internal effective and thyroid doses from inhalation of radionuclides in air are given in Annex 7.

2.6 Internal radiation doses from ingestion of food

This section summarizes the models for the ingestion exposure pathway. The models for calculating doses inside and outside Japan are described in Annex 8 and Annex 9 respectively. The input parameters for assessment of ingestion dose outside Japan are presented in Annex 3 (Table A.3.3 and Table A3.4).

The assessment of doses resulting from the ingestion of food containing radionuclides requires estimates of activity concentrations in food as a function of time, together with levels of consumption of the various foods for different age groups. As for the external dose and inhalation pathways, several scenarios have been used in this assessment to estimate the dose from food consumed during the first year.

2.6.1 Ingestion doses inside Japan

The results of the Japanese national food consumption survey, which provides the mean and the high consumption of some 20 food categories, were made available by the Japanese National Institute for Health and Nutrition (see Annex 8 for details). Due to the lack of information regarding the mean consumption of one-year-old children, the mean consumption of children aged 1–6 years was used. Over 31 000 food samples were collected in various areas of Japan between March and September 2011 and were monitored for the following three radionuclides: ^{131}I, ^{134}Cs and ^{137}Cs. The results were made available through the INFOSAN network. The majority of data were from food produced in Fukushima and neighbouring prefectures.

Important assumptions were made in this estimate of food ingestion dose, as described below:

1. It was assumed that consumers only consumed food produced in the area where monitoring was implemented (i.e. in Fukushima and neighbouring prefectures). The consumption of food produced in other areas of Japan not affected by the accident would have decreased the exposure to radionuclides. Similarly, the total food self-sufficiency ratio of Japan is about 70% on a production-value basis (40% on a calorie basis) with the other 30% being imported. However, the proportion of food monitored compared with the total food on the Japanese market is not known and therefore it was decided not to use an uncertain correction factor but to assume that all food consumed was produced in the area where monitoring was implemented. Moreover the possibility cannot be excluded that a fraction of the Japanese population ate only food produced in these areas even if such a popula-

tion cannot be quantified. Regarding doses in Japan from food consumption, the International Expert Panel was also aware that food sourcing and normal food distribution practices would additionally have been significantly altered by the impact of the tsunami, the earthquake and public protection measures, as well as by possible reduced levels of consumption due to concerns over radiation. At present this effect cannot be clarified, but it results in some uncertainty in the assessment of food doses.

2. No delay between harvesting and production of foodstuffs and their consumption was considered. Although the measurements of radioactive material in foods used in this assessment were not taken at the actual time of consumption, losses due to radioactive decay between the point of "harvesting" or “marketing” and the time of consumption are not reflected in the dose estimates, nor are losses due to home preparation.

3. It was assumed that the measured radioactivity concentrations are representative of the whole food market for Fukushima and neighbouring prefectures. It has to be noted that:

    a) The average radioactivity concentrations in each food category used for the estimation is not proportional to the consumption level of each food included in the food category. Monitoring tests have been conducted giving priority to the foods which are likely to be contaminated by radioactive material. For example, many tests were conducted on non-headed leaf vegetables which showed high level radioactive contamination. The proportion of tests for non-headed leaf vegetables is about 50% and that for spinach is about 25% of tests for vegetables in the first month. On the other hand, the total consumption of non-headed leaf vegetables is only about 7% among total consumption of all vegetables. This is potentially a source of overestimation.

    b) Similarly foods which are not expected to be contaminated (e.g. candies, soft drinks) were not monitored. Therefore, the total average food consumption considered in this assessment represents 800–900 grams (see Annex 7, Table A7.1), whereas the total average daily consumption is about 2000 grams. This is potentially a source of underestimation.

    c) It was assumed that all the food monitored was on the market although the dataset included the results of food samples collected just for monitoring purpose (e.g. fish caught in the no-fishing areas). The food monitoring data submitted to the INFOSAN network and used in this study reflect the concentrations of activity in food mainly from Fukushima and neighbouring prefectures. Food restrictions were introduced in Japan with the aim of banning from the market those food commodities produced in highly contaminated areas. However, because it is not possible to test each and every food before going to the market, the dataset includes a limited number of samples which are in excess of the food restriction levels and which were not eliminated by the enforcement measures (*19*, *20*).

4. For both iodine and caesium radionuclides, analytical results reported to be below the level of detection were assumed to be 10 Bq/kg for each radionuclide, except

for iodine levels after four months which were considered to be 0. For most of the measurements recorded as being below the limit of detection, the individual limits of detection were not provided. This assumption is conservative if one considers the possibilities of analytical techniques available for radionuclides for which the limit of detection (LOD) can be considerably lower than 10 Bq/kg. However, due to the need for the throughput of a large number of samples in a short time frame, less sensitive techniques have also been used. Overall, this assumption is considered to be a realistic estimate.

5. The contribution from iodine to the total exposure was considered to be zero from four months after the start of the release. For ^{131}I, all samples collected after 15 July 2011 were reported to be below the limit of detection or below 10 Bq/kg. Due to the short half-life of iodine, it is appropriate to consider the levels of iodine after four months as zero (i.e. the values used are 0 rather than 10 Bq/kg).

6. The calculated effective dose and thyroid ingestion doses over the first year were estimated by summing the doses for each of the first six months and then extrapolating the exposure of the sixth month to the remaining six months of the first year.

Staple foods (rice, fish and seafood)

As rice is a staple food in Japan, potential doses arising from the consumption of rice were specifically considered by the panel. Japanese members of the panel advised that rice is harvested in Japan annually in September, with consumption of the year's harvest occurring throughout the subsequent 12 months (and beyond). Measured levels of activity in marketed rice harvested in 2011 were available in August and September 2011 and none of the reported levels was above the limit of detection. Ingestion doses from the consumption of rice would therefore be anticipated to be very low. However, this assumption should be verified once further monitoring data on rice are available.

Doses from ingestion of seafood in Japan have been taken into account on the basis of measured data. The approach described for ingestion of terrestrial foods based on measurements was also used for seafood.

Tea leaves and spices

Radionuclides were measured in tea leaves, but not in prepared tea ready to drink, and this beverage was therefore not included in the dose estimation. At international level it is generally assumed that two grams of tea leaves are used for 100 ml of tea and that 100% of chemicals present in the leaves are migrating into the liquid. These assumptions were not verified for the present case and were therefore not introduced in the dose assessment to avoid adding uncertainty.

Similarly, analytical results for spices, herbs and other condiments consumed in small amounts were not used in the assessment.

Several scenarios for the estimation of ingestion dose in Japan have been taken into account to cover the variability of dietary exposure within the population. These are summarized in Table 1 and are further described below.

Table 1. Summary of the food ingestion scenarios considered

Scenario	Consumption	Radioactivity concentration in food
Fukushima prefecture		
Scenario 1	Mean	Median
Scenario 2*	Mean	Mean
Scenario 3	Mean	90th percentile
Neighbouring prefectures and rest of Japan		
Scenario 4	Mean	Median
Scenario 5**	97.5th percentile	Median
Scenario 6	97.5th percentile	Mean

* This scenario was used for the estimation of ingestion doses in Fukushima prefecture, as shown in Tables 3 and 4.

** This scenario was used for the estimation of ingestion doses in prefectures neighbouring Fukushima and the rest of Japan, as shown in Tables 3 and 4.

The reported origin of the food was related to an entire prefecture. The radioactivity concentrations in food measured in Fukushima prefecture only were used for scenarios 1, 2 and 3. The radioactivity concentrations in food measured in Fukushima and other prefectures were used for scenarios 4, 5 and 6. For prefectures far away from Fukushima the population was assumed to consume only food coming from contaminated areas. Even if such a situation cannot be excluded, it seems to be very unlikely.

For the population living in the most affected area, Fukushima prefecture, three scenarios were developed. These were based on the mean consumption of the Japanese population combined with the mean, median or 90th percentile of radioactivity concentration. None of these three scenarios for Fukushima assumed a high consumption because it was assumed that consumers were not consuming vegetables and fish at a high level due to information from the Japanese authorities that these foods were likely to be contaminated. In the unlikely case of regular high consumption of these foods, the dose could be underestimated.

Scenario 1 is based on the median concentrations of radioactivity in food in Fukushima prefecture for each of the relevant food categories. The use of the median concentrations is expected to represent consumers choosing randomly from the foods on the market. However, this scenario may underestimate the exposure of specific groups of consumers who regularly consume food containing radioactivity concentrations which are in the top half of the radioactivity concentration distribution.

Scenario 2 is based on the mean concentrations of radioactivity in food in Fukushima prefecture for each of the relevant food categories. Using the mean concentration ad-

dresses the potential underestimation from using the median concentration (scenario 1), considering that the occurrence of radioactivity is not normally distributed. The use of the mean concentrations is still a conservative estimate since it assumes that foods containing higher-than-median levels of radioactivity are consumed regularly.

Scenario 3 is based on the 90th percentile of the distribution of the concentrations of radioactivity in food in Fukushima prefecture for each of the relevant food categories. The assumption that a consumer could consume the highest 10% of contaminated food from all food categories during a month is conservative even in the case of potential hot spots.

For the populations living in neighbouring prefectures and in the rest of Japan, three scenarios were developed which combine the median or the mean concentration of radioactivity in food with the mean of a high level of consumption. The high level of consumption is defined according to international guidance (*21*) as the consumption at the 97.5th percentile of the two main food contributors to radionuclide exposure and the mean consumption of other food categories. All the contributions are combined with the levels of radioactivity concentration in all samples collected in various prefectures for the corresponding food categories and are then summed. The two main contributors to ingestion doses in Japan have been identified as vegetables and fish based on the assumptions listed above. This scenario assumes that high consumers consume at a high level every day during a year and is therefore likely to be conservative.

Scenario 4 is based on the mean level of consumption and the median concentrations of radioactivity in food for each of the relevant food categories. The use of median concentrations is expected to represent consumers choosing randomly from foods on the Japanese market and assumes that available results are representative of the whole Japanese food market.

Scenario 5 is based on a high level of consumption and median concentrations of radioactivity in food for each of the relevant food categories.

Scenario 6 is based on a high level of consumption and mean concentrations of radioactivity for all relevant food categories. The use of the mean concentrations of radioactivity is a conservative estimate for consumers eating only foods on the market and assumes that available results are representative of the whole food market. It is expected to cover the uncertainty about analytical results reported to be below the levels of detection/quantification.

2.6.2 Monitoring of Japanese food outside Japan

Several countries around the world analysed food imported from Japan, and submitted information to INFOSAN.

For countries neighbouring Japan: Information was submitted to INFOSAN regarding Japanese food exported to Australia, to China, to Hong Kong Special Administrative Region (SAR), and to Indonesia. For Hong Kong SAR, 43 487 samples were tested and only three of them were higher than 100 Bq /kg for ^{131}I on 23 March 2011. For Australia, 82

samples of food imported from Japan were analysed for ^{131}I, ^{134}Cs and/or ^{137}Cs; all results were found to be below 2 Bq /kg. For Indonesia, 619 samples of food imported from Japan were analysed for ^{131}I, ^{134}Cs and/or ^{137}Cs and all results were found to be below 0.2, 0.13 and 0.8 Bq /kg respectively.

For the rest of the world: Information was submitted to INFOSAN by Austria, Canada, Germany, Greece and Lithuania. For Canada, 165 samples of food imported from Japan, 34 samples of domestic milk products and 14 pooled samples of domestic wild fishes were analysed for ^{131}I, ^{134}Cs and/or ^{137}Cs; all results were below the minimum detectable concentration of about 2 Bq /kg. For the European countries, 550 samples were analysed and, with the exception of three green tea samples, all the measurements were either non-detectable or (in a few cases only) at levels close to the detection limit.

In view of these data, no further assessment was done regarding ingestion doses arising from the consumption of foods originating in Japan and exported to other countries.

2.6.3 Ingestion doses outside Japan

In the rest of the world, the ingestion doses from food produced outside Japan were calculated on the basis of assumed food consumption levels and calculation of food radionuclide concentrations by a modelling approach.

The modelling approach used to reconstruct ingestion doses was based on the predictions of the NAME III atmospheric dispersion model presented in section 2.3.2. As shown in Figure 5, the results of atmospheric dispersion modelling were used to estimate average doses from consumption of terrestrial foods produced in the country/region of interest in the first year following the releases. Models exist which estimate the concentrations of radionuclides that would arise in food following a deposition on the land where the food is produced. Such models also indicate the time dependence in the build-up and fall-off of concentrations in food over time. The concentrations of radionuclides in food following an accidental release would vary rapidly as a function of time and this needs to be taken into account in estimating the doses from intakes integrated over the first year following the releases. The model used in this assessment was the FARMLAND model (*22*). FARMLAND was developed to represent conditions and practices in the United Kingdom and was applied in this assessment to the world. Ingestion doses for the rest of the world from locally produced food were based on food-chain model predictions, assuming agricultural practices typical of early summer. While this is a cautious assumption for those parts of the world where the practices at the time of the accident were more typical of cool spring conditions, it will be less conservative for warmer regions, and the assessment covers countries that span the equator and those in the northern hemisphere. However, given the overall uncertainties in the assessment, the use of such a model in other areas around the world was considered adequate to give an estimate of ingestion dose due to consumption of food from domestic production. Only doses from terrestrial foods were estimated by this method. Doses from seafood consumption in the rest of the world were considered by the International Expert Panel to be low and were not considered further.

Food consumption levels as used in the estimate of food doses outside Japan were selected from WHO's GEMS/food data (*15*). For the assessment, Cluster diet G was se-

lected, and the details are shown in Annex 9. The food consumption is based on average consumption weighted for the total population and so represents the average across all age groups; for this reason, the same consumption was applied to all age groups.

2.7 Internal doses from ingestion of tap water

Tap water has many uses. Only the ingestion of tap water was taken into account in this assessment as the panel considered other uses (bathing, heating, etc) to have low radiological significance.

Estimates of radiation doses from the ingestion of tap water have been made based on measured activity concentrations. Doses have been estimated for the three age groups considered in the report and, additionally, for six-month-old infants drinking formula milk made with tap water. Daily per capita ingestion rates of 2 litres, 1 litre, 0.75 litre and 1.2 litres were assumed, respectively, for the age groups of adults[3], 10-year-old children[3], 1-year-old infants[3] and infants fed exclusively on formula milk prepared using tap water.

Activity concentrations for ^{131}I and ^{137}Cs levels in tap water, as reported by each prefecture and published by the Japanese Ministry of Education, Culture, Sports, Science and Technology, were used for the assessment. It was cautiously assumed that consumption of tap water occurred during the whole period when activity concentration values were found. Levels were detectable only for a limited period of a few days[3] and have been assumed to be negligible at other times.

2.8 Doses due to the releases of radionuclides to the sea

Significant quantities of radionuclides were released to the sea following the accident. For such releases, the potentially important exposure pathways would be internal irradiation from the intake of radionuclides in seafood and external irradiation from radionuclides on sand and sediment on the shore.

The external exposure pathways were not included in the assessment because the panel considered that dilution of levels in seawater would result in the doses being of significance only close to the release point, and access to this area was not permitted since it was within the exclusion zone. Other pathways such as exposure through swimming in the sea, inadvertent ingestion of sand/sediment and inhalation of resuspended material were also considered by the panel to be insignificant exposure routes and are not considered further.

2.9 Summary of key assumptions

Table 2 summarizes the key assumptions made in the assessment, and indicates areas where conservative approaches have been adopted.

3. Restrictions on tap water were applied in several villages for a few days at the end of March, with the exception of Iitate where the restriction was in place until 10 May.

Table 2. Assumptions made in calculations

General assumptions	
Source term for use in dispersion-based calculations	Two different source terms based on different approaches were used in the calculations of atmospheric dispersion (Annex 4). At the time of the assessment, source estimation for the Fukushima accident was associated with considerable uncertainty. There is a view that the releases may be somewhat underestimated (*23*). However, the source terms used here are considered by the panel to be the most appropriate for use at the current time. The source terms are applied in this assessment only to estimate doses in the world beyond Japan, and these estimated doses are below 0.01 mSv, the level of dose cut-off used here to present the results. An underestimate, or an overestimate, in the source terms used would therefore have little or no effect on the majority of the doses presented. The source terms do not include information on chemical form or deposition velocity. In the absence of this information, subsequent parts of the assessment have made further assumptions that are described in Annex 4.
Assumed nuclide composition used in conjunction with measurements	The dose assessment based on ground measurements of ^{137}Cs required an assumption about the radionuclide composition (Annex 6, Table A6.1). Values in Approach A and Approach B are similar for the key radionuclides but are not identical. The radionuclide compositions which have been measured are varying, and it is possible that in some areas the ^{131}I to ^{137}Cs ratio in soil may have been higher than the average value assumed here; this is an uncertainty in the assessment.
External and inhalation calculation assumptions	
Reduction factor for external dose from radionuclides in air and from ground deposits	A reduction factor to represent the saving in external dose from radioactivity in the air and from ground deposits, due to being indoors for a proportion of the time, has been applied in the assessment on the basis of a location factor and building occupancy factor. On the basis of information provided by the Japanese experts and observers, the reduction effect of wooden buildings (0.4) when staying outdoors for eight hours and indoors for 16 hours was considered, giving a final reduction factor of 0.6 (Annex 3). This assumption is thought to be cautious for Japan and for much of the rest of the world.
Reduction factor for inhalation dose	No protection from inhalation dose due to being indoors for a proportion of the time has been assumed in the assessment. The factor is very uncertain, and would not in any case alter the doses significantly. However, as the reduction has been ignored, the early doses from inhalation are likely to be overestimated.

Ingestion calculation assumptions	
Radionuclide concentration factors in food outside Japan	Activity concentrations in food per unit deposit for use in conjunction with the source term and dispersion-based part of the assessment have been taken from the food chain model FARMLAND. This has been the basis for the estimates of doses from ingestion for the world excluding Japan. A subset of the radionuclides has been considered for the radionuclides making the most significant contribution to the dose. The FARMLAND results applied in the assessment assume that the release occurred in early summer. This is a cautious assumption for many regions of the northern hemisphere for an accident occurring in mid-March, but it was chosen because agricultural practices around the world vary and for some southerly regions more food production and harvesting may have been occurring than in more northerly regions.
Radionuclide concentrations in food in Japan	Ingestion doses in Japan have been based on measured levels of key radionuclides in food (^{131}I, ^{134}Cs and ^{137}Cs), as contained in the dataset of measurements made available to INFOSAN by the Ministry of Health, Labour and Welfare of Japan. These measurements reflect the activity in food mainly from Fukushima and neighbouring prefectures. Although the dataset includes a proportion of measurements of food before shipment and of food from distribution-restricted areas which were not distributed, it was assumed that all the foods analysed were on the market. Moreover, some people may have consumed little or no fresh food due to concerns over radiation, and their radiation doses would be lower than those estimated. It is also possible that unrestricted food originating from the Fukushima prefecture was deliberately avoided by the Japanese population in the months following the accident. Lastly, there is usually a delay between harvesting and production of foodstuffs and their consumption, but for the purposes of this assessment the delay period was ignored; this may lead to conservatism in the estimation of doses (i.e. possible overestimation), as radionuclides will partially decay during the delay.

3. Results

The results of the dose assessment presented in this chapter are estimated to arise as a direct result of the Fukushima Daiichi nuclear power plant accident.

3.1 Presentation of results

Results for effective doses (Table 3) and thyroid doses (Table 4) are presented for the standard three age groups considered. The tables show the estimated individual doses for each region considered and include some example locations in the most affected part of Fukushima prefecture (see Figure 3). It should be noted that the example locations considered in Fukushima prefecture are not located exactly at the positions shown in Figure 3. Dose assessment was based on input data averaged over the whole area of each town, as shown in Annex 5 for some example locations. Measurements from parts of towns located inside the evacuation zone – which stretches up to 20 km – were not considered.

The dose estimates are principally shown in order-of-magnitude dose bands, with decreased band width at the higher levels of estimated dose. The presentation of doses to greater levels of numerical accuracy was considered by the panel to be inappropriate for this report given the inherent uncertainty of the assessment and its preliminary nature. However, the calculated values for the different scenarios were provided to the expert group working on the health risk assessment.

The dose bands simply indicate the scale of the estimate to a characteristic individual, representative of the average dose to a person living in the region or location of interest. The characteristic doses presented as dose bands are not intended to span the spread of exposures that may be received by the population of the area, as such a calculation would have required distributions of input data parameters (e.g. ranges of dietary consumption of population groups, types of building occupied) not available to the panel within the time frame of this preliminary assessment.

In general, the dose assessment has considered the committed doses resulting from being resident in the area for one year after the accident. This is with the exception of a few locations in the most affected part of Fukushima prefecture (in the deliberate evacuation zone, outside the 20-kilometre immediate evacuation zone) where the dose was calculated for the first four months after the accident, thus taking into account relocation measures.

3.2 Age dependence of dose estimates

For both effective and thyroid doses, the age dependence was accounted for through the use of appropriate age-dependent inhalation and ingestion dose coefficients, inhalation rates and external doses per unit deposit (Annex 3). For younger children, the dose coef-

ficients tend to be higher due to their smaller size and hence the effective and thyroid dose can also be higher for infants and children. However this does not invariably lead to the predicted doses to infants and children being higher due to other factors, such as lower intake rates.

Doses to the fetus and breastfed infant have also been considered in this assessment. It was recognized that, in general, doses to the embryo, fetus and breastfed infant need to be calculated explicitly only when the unborn child or breastfed infant could receive higher doses than children or adults. Doses in Japan, as a result of inhalation and ingestion, are dominated by isotopes of caesium and iodine. For both inhalation and ingestion of isotopes of caesium, the fetus and breastfed infant will receive lower doses than the mother. For inhalation and ingestion of isotopes of iodine, the fetus will receive doses similar to or less than the dose to the mother. For isotopes of iodine, including ^{131}I, the breastfed infant may receive doses of up to a factor of 2 higher than the mother. Dose coefficients for the embryo, fetus and breastfed infant have been issued by ICRP (*24*, *25*, *26*, *27*) and guidance on their application has been published (*28*). The panel concluded that, overall, the differences in dose between the fetus, the breastfed infant and the mother are small and that the differences are insignificant in terms of the overall accuracy of this preliminary assessment.

3.3 Geographical distribution of doses

In this section, the results for estimated effective doses and thyroid doses are summarized for different areas of the world. The relative contribution of the different pathways is provided in Tables 3 and 4.

3.3.1 Estimated effective doses

- Of the example locations considered in Fukushima prefecture, several are in the area 20–30 km from the site where characteristic effective doses in the first year, to all age groups, are estimated to be in the dose band of 10–50 mSv. The dominant pathway in these locations is estimated to be external dose from ground deposits but there are also contributions from the other exposure pathways. In these locations, only the first four months of exposure from external dose have been included as it has been assumed that relocation would have occurred at that time.
- At other locations considered as examples in Fukushima prefecture, the characteristic effective doses in the first year, to all age groups, are estimated to be in the range 1–10 mSv. In these locations the major exposure pathways are external dose from ground deposition and ingestion doses.
- In prefectures neighbouring Fukushima, characteristic effective doses in the first year, to all age groups, are estimated to be in the dose band of 0.1–10 mSv. This wider range of dose band for these neighbouring prefectures reflects the wide variation in deposition levels across these areas. The dominant pathway here is estimated to be external dose from ground deposits.
- In other Japanese prefectures, characteristic effective doses in the first year, to all age groups, are estimated to be in the dose band of 0.1–1 mSv, with the dominant pathway being food ingestion.

- In countries neighbouring Japan, characteristic effective doses in the first year, to all age groups, are estimated to be less than 0.01 mSv, with the dominant pathway being ingestion of locally-produced food.
- For the rest of the world, characteristic effective doses in the first year, to all age groups, are also estimated to be less than 0.01 mSv, and are usually far below this level. Again, the dominant pathway is ingestion of locally produced food.

3.3.2 Estimated thyroid doses

- For most of Fukushima prefecture, the estimated characteristic thyroid doses in the first year, to all age groups, are in the dose band of 10–100 mSv. The exception is Namie town in Futaba county, which lies partially within the 20km restricted area and the deliberate evacuation area (Figure 1). Dose estimates were calculated for the part of the town located in the area 20–30 km from the site, showing thyroid doses to infants within the dose band of 100–200 mSv. In several of the most affected locations, the doses were estimated only for the first four months, as relocation was assumed to have occurred at that time. It should be noted that a significant contributor to thyroid dose in some of these locations is inhalation[1] of the early radioactive cloud. Earlier relocation, at for example two months, would not have reduced thyroid doses significantly. Such reduction would only have been obtained if early evacuation had occurred prior to the arrival of the radioactive cloud.
- In the locations in Fukushima prefecture that are further away from the site, the dominant contributor to thyroid dose is food ingestion .
- In other Japanese prefectures the characteristic thyroid doses in the first year, to all age groups, are estimated to be in the dose band of 1–10 mSv. The dominant pathway here is estimated to be food ingestion .
- For the rest of the world, characteristic thyroid doses in the first year, to all age groups, are estimated to be less than 0.01 mSv and are usually far below this level. The dominant pathway is ingestion of locally produced food.

The numerical values of the estimated doses to the thyroid are higher than the estimated effective doses. Although the units are the same, these are two different quantities that cannot be compared (see section 1.5.1 and Box 1) .

3.3.3 Doses to the southern hemisphere

The dose assessment for the world apart from Japan, which has been based on atmospheric dispersion modelling, has not included consideration of regions in the southern hemisphere (with the exception of countries which span the equator) because doses in the southern hemisphere are expected to be considerably smaller than those in the northern hemisphere and extensive time would have be required to model full global dispersion in both hemispheres over the period considered in this assessment.

Global circulation models for krypton-85 suggest that after one year the integrated activity in the southern hemisphere (from a release in the northern hemisphere) is approximately 15% of the average activity over the northern hemisphere. For Fukushima

1. Since protection from inhalation exposure due to being indoors for a proportion of the time has not been generally assumed in this assessment, the early doses from inhalation are likely to be somewhat overestimated.

radionuclides this value is cautious because it was derived for a noble gas which does not deposit and also assumes that the gas is dispersed uniformly and instantaneously throughout the northern hemisphere.

It was noted that, for the first four weeks after the start of the release, the radioactive materials remained confined to the northern hemisphere, with the equator initially acting as a dividing line between the northern and southern air masses. From mid-April radioactive material was detected at stations located in Australia, Fiji, Malaysia and Papua New Guinea, indicating some spread to the southern hemisphere of the Asia Pacific region (*29*).

The panel therefore considered that doses in the southern hemisphere in the first year after a release in the northern hemisphere are likely to be considerably lower – of the order of one fifth and probably less – than those in the northern hemisphere.

3.4 Results for food ingestion doses in Japan

The estimation of doses from food is an important factor in the assessment of overall doses, especially outside Fukushima prefecture. For Fukushima prefecture the estimated effective dose from food per month was highest in month 1 and decreased until month 6. The highest estimated exposures using the assumptions applied in this study are to infants aged one year.

To provide a single estimate of the food contribution, the doses in Table 3 and Table 4 include the estimate described as scenario 2 and 5 in Table 1 (section 2.6.1). The estimated effective dose to all age groups in Fukushima prefecture from one year's intake of radionuclides in food is less than 2 mSv, while the estimated thyroid dose from food to all age groups in Fukushima prefecture from one year's intake is less than 40 mSv. Based on the selected scenarios described above, the dietary exposure assessment for other prefectures is about two times lower than those estimated for Fukushima prefecture. Doses from ingestion of food estimated using the other scenarios outlined in section 2.6.1 would remain of the same order of magnitude both for Fukushima prefecture and all other prefectures. It should be noted that the dietary exposure assessment is for a Japanese consumer consuming exclusively food produced in areas where the food monitoring was implemented. Therefore, assuming that the monitoring data do not underestimate the food radioactivity concentration, the more conservative scenario (i.e. scenario 3 and scenario 6) should be seen as an absolute upper bound of the dietary exposure.

3.5 Results for tap water

The panel's assessment indicated that the doses from tap water were low in comparison with doses from other pathways. Also, the assessment undertaken was a simple scoping calculation based on maximum detected levels in tap water. Therefore, the estimated doses from drinking tap water have not been incorporated into the dose estimates presented here. Even if cautiously assessed, the highest effective doses were estimated to be less than 0.1 mSv and the highest thyroid doses were estimated to be at most about 2 mSv (in both cases the maximum dose was estimated to be for 6-month-old infants fed on formula milk prepared using tap water).

Table 3. Characteristic estimated effective doses[1] in the first year following the Fukushima accident, presented in dose bands

Location	Committed effective dose Adult Dose band, key pathways to nearest 10%[2,3]		
Fukushima prefecture, more affected locations (examples only, for location of measurements used see Figure 3)			
Futaba county, Namie town (committed dose from the first four months only[1])	10–50	External (groundshine) Inhalation	90% 10%
Soma county, Itate village (committed dose from the first four months only[1])	10–50	External (groundshine) Inhalation	90% 10%
Futaba county, Katsurao village (committed dose from the first four months only[1])	1–10	External (groundshine) Inhalation	80% 20%
Minami Soma city	1–10	External (groundshine) Inhalation	90% 10%
Futaba county, Naraha town	1–10	External (groundshine) Inhalation	80% 20%
Iwaki city	1–10	External (groundshine) Inhalation	90% 10%
Rest of Fukushima prefecture (less affected)	1–10	Ingestion External (groundshine)	50% 50%
Neighbouring Japanese prefectures[4]	0.1–10	External (groundshine) Ingestion	80% 20%
Rest of Japan[5]	0.1–1	Ingestion External (deposit)	70% 30%
Neighbouring countries[6]	<0.01	Ingestion External (groundshine)	80% 20%
Rest of the world	<0.01	Ingestion External (groundshine)	80% 20%

1. All doses are those arising from the release, summed over all the exposure pathways. The dose band reflects the uncertainty in the calculation of the dose. The band does not reflect the range of doses received by the population in a particular location or in a region. The characteristic committed effective doses include the external doses received during the first year as well as the internal doses that people are committed to receive up to the age of 70 years, from the radionuclide intake that has taken place during the first year. In the particular cases of Namie town in Futaba county, Itate village in Soma county and Katsurao village in Futaba county, the dose is that committed from the first four months only as it has been assumed that relocation took place at four months. In some parts of the affected areas, relocation is thought to have occurred prior to the end of the first four months, and it is therefore likely that the actual doses are lower since the contribution from external dose to these total doses will not have been fully received.
2. The pathways considered are external exposure from ground deposited activity (groundshine), external dose from cloud (cloudshine), inhalation dose and ingestion dose. Where multiple counties and prefectures are contained in a single regional category, the pathway contributions may differ with county/prefecture. The contributions shown in the table reflect those found in the parts of the region with higher doses.

in first year following accident, mSv					
Child (10 years) Dose band, key pathways to nearest 10%[2,3]			Infant (1 year) Dose band, key pathways to nearest 10%[2,3]		
10–50	External (groundshine) Inhalation	90% 10%	10–50	External (groundshine) Inhalation	90% 10%
10–50	External (groundshine) Inhalation Ingestion	80% 10% 10%	10–50	External (groundshine) Inhalation Ingestion	80% 10% 10%
1–10	External (groundshine) Inhalation Ingestion	80% 10% 10%	1–10	External (groundshine) Inhalation Ingestion	70% 20% 10%
1–10	External (groundshine) Ingestion Inhalation	80% 10% 10%	1–10	External (groundshine) Ingestion Inhalation	80% 10% 10%
1–10	External (groundshine) Ingestion Inhalation	80% 10% 10%	1–10	External (groundshine) Ingestion Inhalation	80% 10% 10%
1–10	External (groundshine) Ingestion	60% 40%	1–10	External (groundshine) Ingestion	60% 40%
1–10	Ingestion External (groundshine)	50% 50%	1–10	Ingestion External (groundshine)	80% 20%
0.1–10	External (groundshine) Ingestion Inhalation	80% 10% 10%	0.1–10	External (groundshine) Ingestion	80% 20%
0.1–1	Ingestion External (groundshine)	70% 30%	0.1–1	Ingestion External (groundshine)	80% 20%
<0.01	Ingestion External (groundshine)	80% 20%	<0.01	Ingestion External (groundshine)	80% 20%
<0.01	Ingestion External (groundshine)	80% 20%	<0.01	Ingestion External (groundshine)	80% 20%

3. The food dose for Fukushima prefecture is based on scenario 2 (see Table 1 on mean intakes and mean food radioactivity concentrations). The food dose for neighbouring prefectures and the rest of Japan is based on scenario 5 (see Table 1 on high intakes and median food radioactivity concentrations). The estimation was conducted by using all the results of monitoring tests, including tests for food which were not distributed. For the rest of the world, food doses were based on the predictions of the FARMLAND model, and the food consumption from WHO's GEMS database Cluster diet G.
4. The neighbouring Japanese prefectures considered were Chiba, Gunma, Ibaraki, Miyagi and Tochigi. A larger dose band is seen for these neighbouring prefectures, reflecting a wide variation on deposition levels across these areas.
5. For the rest of Japan, exposure from food is the dominant pathway. In this location where food was not monitored, it was assumed that people consumed only food coming from Fukushima and neighbouring prefectures, which is a very conservative assumption. Therefore, for the rest of Japan the doses are clearly overestimated.
6. The neighbouring countries and regions to Japan considered in this table were Far Eastern Russia, Indonesia, Philippines, Republic of Korea, and South-East Asia.

Table 4. Characteristic estimated thyroid doses[1] in the first year following the Fukushima accident, in dose bands

Location	Committed equivalent dose		
	Adult Dose band, key pathways to nearest 10%[2,3]		
Fukushima prefecture, more affected locations (examples only, for location of measurements used see Figure 3)			
Futaba county, Namie town (committed dose from the first four months only[1])	10–100	Inhalation	50%
		External (groundshine)	40%
		Ingestion	10%
Soma county, Itate village (committed dose from the first four months only[1])	10–100	Inhalation	40%
		External (groundshine)	40%
		Ingestion	20%
Futaba county, Katsurao village (committed dose from the first four months only[1]),	10–100	Ingestion	40%
		Inhalation	40%
		External (groundshine)	30%
Minami Soma city	10–100	External (groundshine)	40%
		Ingestion	40%
		Inhalation	20%
Futaba county, Naraha town	10–100	Ingestion	40%
		External (groundshine)	40%
		Inhalation	20%
Iwaki city	1–10	Ingestion	80%
		External (groundshine)	20%
Rest of Fukushima prefecture (less affected)	1–10	Ingestion	80%
		External (groundshine)	10%
		Inhalation	10%
Neighbouring Japanese prefectures[4]	1–10	External (groundshine)	40%
		Ingestion	30%
		Inhalation	30%
Rest of Japan[5]	1–10	Ingestion	90%
		External (groundshine)	10%
Neighbouring countries[6]	<0.01	Ingestion	90%
		External (groundshine)	10%
Rest of the world	<0.01	Ingestion	70%
		Inhalation	20%
		External (groundshine)	10%

1. All doses are those arising from the release, summed over all the exposure pathways. The dose band reflects the uncertainty in the calculation of the dose. The band does not reflect the range of doses received by the population in a particular location or in a region. The characteristic committed thyroid doses include the external doses received during the first year as well as the internal doses that people are committed to receive up to the age of 70 years, from the radionuclide intake that has taken place during the first year. In the particular cases of Namie town in Futaba county, Itate village in Soma county and Katsurao village in Futaba county, the dose is that committed from the first four months only as it has been assumed that relocation took place at four months. In some parts of the affected areas, relocation is thought to have occurred prior to the end of the first four months, and it is therefore likely that the actual doses are lower since the contribution from external dose to these total doses will not have been fully received.
2. The pathways considered are external exposure from ground deposited activity (groundshine), external dose from cloud (cloudshine), inhalation dose and ingestion dose. Where multiple counties and prefectures are contained in a single regional category, the pathway contributions may differ with county/prefecture. The contributions shown in the table reflect those found in the parts of the region with higher doses.

to thyroid in first year following accident, mSv					
Child (10 years) Dose band, key pathways to nearest 10%[2,3]			Infant (1 year) Dose band, key pathways to nearest 10%[2,3]		
10–100	Inhalation External (groundshine) Ingestion	60% 30% 10%	100–200	Inhalation External (groundshine) Ingestion	50% 30% 20%
10–100	Inhalation External (groundshine) Ingestion	50% 30% 20%	10–100	Inhalation Ingestion External (groundshine)	40% 40% 20%
10–100	Ingestion Inhalation External (groundshine)	50% 30% 20%	10–100	Ingestion Inhalation External (groundshine)	60% 30% 10%
10–100	Ingestion External (groundshine) Inhalation	50% 30% 20%	10–100	Ingestion External (groundshine) Inhalation	60% 20% 20%
10–100	Ingestion External (groundshine) Inhalation	50% 30% 20%	10–100	Ingestion External (groundshine) Inhalation	70% 20% 10%
10–100	Ingestion External (groundshine) Inhalation	80% 10% 10%	10–100	Ingestion External (groundshine)	90% 10%
10–100	Ingestion External (groundshine)	90% 10%	10–100	Ingestion External (groundshine)	90% 10%
1–10	Ingestion External (groundshine) Inhalation	40% 30% 30%	1–10	Ingestion External (groundshine) Inhalation	60% 20% 20%
1–10	Ingestion	100%	1–10	Ingestion	100%
<0.01	Ingestion External (groundshine)	90% 10%	<0.01	Ingestion	100%
<0.01	Ingestion Inhalation External (groundshine)	70% 20% 10%	<0.01	Ingestion Inhalation External (groundshine)	80% 10% 10%

3. The food dose for Fukushima prefecture is based on scenario 2 (see Table 1 on mean intakes and mean food radioactivity concentrations). The food dose for neighbouring prefectures and the rest of Japan is based on scenario 5 (see Table 1 on high intakes and median food radioactivity concentrations). The estimation was conducted by using all the results of monitoring tests, including tests for food which were not distributed. For the rest of the world, food doses were based on the predictions of the FARMLAND model, and the food consumption from WHO's GEMS database Cluster diet G.
4. The neighbouring Japanese prefectures considered were Chiba, Gunma, Ibaraki, Miyagi and Tochigi. A larger dose band is seen for these neighbouring prefectures, reflecting a wide variation on deposition levels across these areas.
5. For the rest of Japan, exposure from food is the dominant pathway. In this location where food was not monitored, it was assumed that people consumed only food coming from Fukushima and neighbouring prefectures, which is a very conservative assumption. Therefore, for the rest of Japan the doses are clearly overestimated.
6. The neighbouring countries and regions to Japan considered in this table were Far Eastern Russia, Indonesia, Philippines, Republic of Korea, and South-East Asia.

4. Discussion

4.1 Temporal distribution of the dose

The pattern of radionuclide deposition shortly after a nuclear accident depends on the composition of the release and the prevailing meteorological conditions, particularly wind direction and occurrence of precipitations (e.g. rain, snow) during the passage of the cloud. Short-lived radionuclides, such as I^{131} (eight days half-life), are the main contributors to human exposure in the short term while in the longer term, only a few radionuclides dominate, such as ^{134}Cs (two-year half-life) and ^{137}Cs (30-year half-life) (*30*).

The experience of the Chernobyl accident shows that the effective dose rate decreased within the first year after the accident mainly due to radioactive decay of short-lived radionuclides (e.g. iodine), but during the following decade the decrease was due mainly to radioactive decay of caesium and its migration into the soil (*8*,*31*). The shielding effect of this radionuclide migration in the soil was an important factor in reducing lifetime doses. About 30% of the lifetime effective dose was delivered during the first year and about 70% during the first 15 years (*31*).

In the Chernobyl accident, ^{137}Cs was the dominant radionuclide in the longer term, with a ratio between ^{134}Cs and ^{137}Cs of around 0.5. In contrast, in the Fukushima Daiichi nuclear power plant accident this ratio is close to 1 (*32*) and this will influence the temporal distribution of the lifetime dose. Indeed, the ratio between the shorter-lived ^{134}Cs and ^{137}Cs observed in Fukushima indicates that the fraction of the lifetime dose to be delivered beyond the first year would be lower than in Chernobyl.

This report presents effective doses and thyroid doses committed in the first year after the Fukushima accident, based on data available to the International Expert Panel up to mid-September 2011. Therefore, it includes extrapolations to estimate one-year doses.

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 (*33*). In the present assessment, an estimation of doses beyond the first year was not performed as it would have resulted in a great degree of uncertainty. Besides the natural mechanisms mentioned above, the projection of doses has to take into consideration a number of other factors such as the implementation of long-term remedial actions which would further reduce radiation exposure.

4.2 Influence of protective actions on the dose

Doses have not been estimated for the zone within 20 kilometres from the Fukushima Daiichi site because most people in the area were evacuated rapidly and an accurate es-

timation of dose to these individuals would require more precise data than were available to the panel at the time of this assessment.

Outside the 20-kilometre radius, several example locations in the deliberate evacuation area were considered, for which only doses in the first four months of the first year were estimated[1]. On the basis of information provided by the Government of Japan (*34*), relocation occurred earlier in some areas and the effective doses and thyroid doses to relocated people in such areas would be expected to be lower than those presented here. Examples of the temporal distribution of effective dose and thyroid dose during the first four months are presented in Figure 6. For instance, in areas where relocation occurred at two months instead of four months as assumed, the external doses from groundshine would be reduced by about one third but the dose from early pathways (inhalation[2] and external dose from cloudshine) would remain unchanged. The contribution to the dose from those early pathways would only be reduced in case of evacuation prior to the arrival of the radioactive cloud.

In the zone between 20 and 30 kilometres from the Fukushima Daiichi site the effect of sheltering in reducing dose during the early phase of the emergency was not accounted for, as discussed in 1.5.5. Sheltering can reduce external doses significantly, and inhalation doses to some extent. It is estimated that, for a typical Japanese house, this effect would be about a factor of 2–3 during the time of sheltering (*35*) which can typically be applied only for a few days. The influence of this protective action on the estimated dose over the first year would be very small.

The assessment has assumed that no stable iodine was taken, either in Japan or elsewhere. Therefore the estimated equivalent thyroid doses are higher than those expected in people who have undergone thyroid blocking to reduce the uptake of radioactive iodine.

The food monitoring data used in this study reflect the concentrations of activity in food mainly from Fukushima and neighbouring prefectures. It was assumed that all the foods analysed were available on the market though results of monitoring tests for foods which were not distributed were included. A small percentage of food as monitored had radioactivity levels exceeding the food restriction levels that were implemented. However, since total control of all foods and complete enforcement cannot be assumed, these higher levels were not excluded from the analysis.

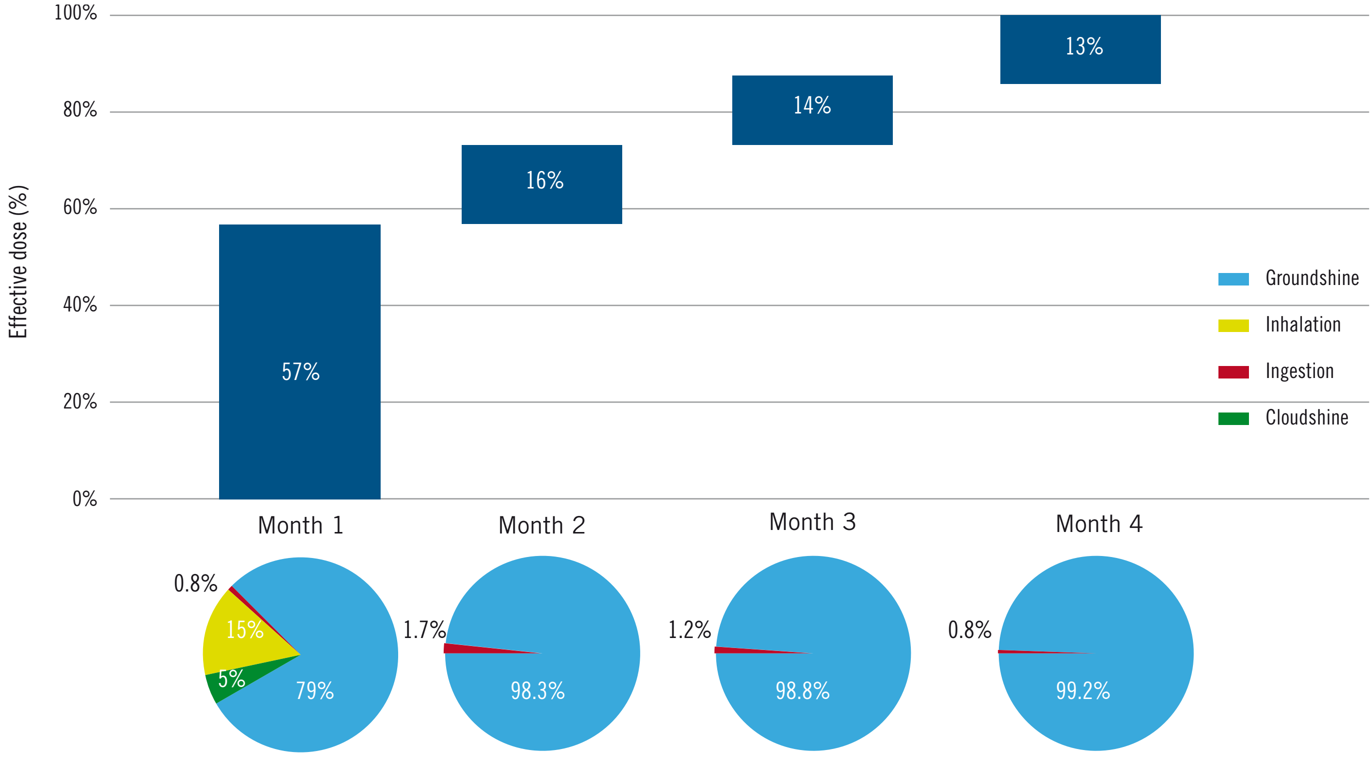
Further protective measures (e.g. more stringent regulatory standards) as well as remedial actions (e.g. clean-up of buildings, remediation of soils and vegetation, treatment of agricultural fields, waste management) may be taken in the future to significantly decrease dose rates and therefore reduce longer-term doses.

1. The example locations considered in the assessment (all in the deliberate evacuation area) where the doses were calculated only from zero to four months after the accident rather than for the full first year were Namie town in Futaba county, Itate village in Soma county, and Katsurao village in Futaba county.

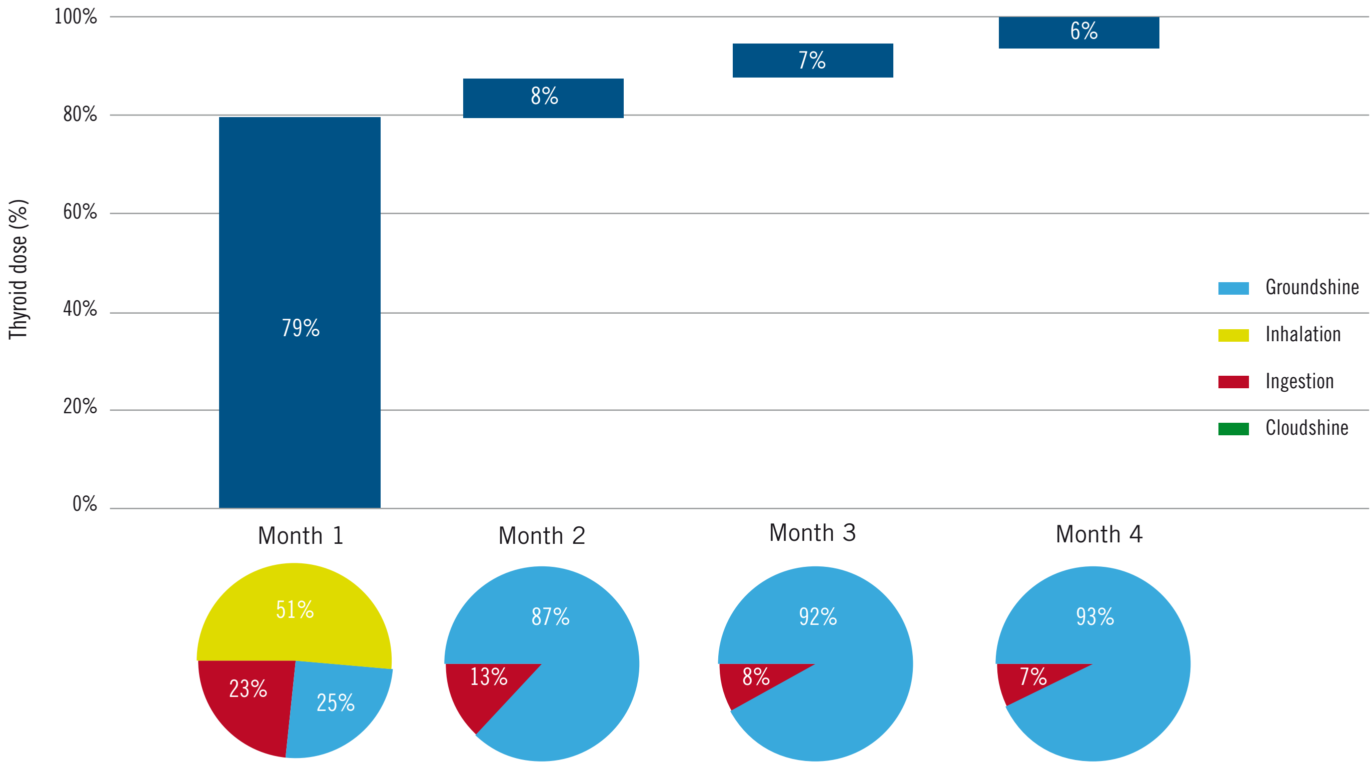
2. Since protection from inhalation exposure due to being indoors for a proportion of the time has not been assumed in this assessment, the early doses from inhalation are likely to be somewhat overestimated.

Figure 6. Temporal distribution of the dose to a child aged 10 years living in the most affected locations of the Fukushima prefecture over the first 4 months following the accident: (a) effective dose and (b) thyroid dose

6a. Cumulative effective dose, including relative pathway contribution



6b. Cumulative thyroid dose, including relative pathway contribution



4.3 Contribution of the different exposure pathways

The exposure pathways that contribute most to the effective dose vary with location and distance from the site. In the most affected regions of Fukushima prefecture, external exposure from groundshine is by far the dominant pathway contributing to effective dose, but with increasing distance from the site the ingestion pathway becomes the main contributor to the effective dose.

The exposure pathways that contribute most to the thyroid doses also vary with location and distance from the site. Internal exposure from inhalation and external exposure from groundshine are the most important contributors to the thyroid dose in the most affected areas of Fukushima prefecture. With increasing distance from the site (e.g. less affected areas of Fukushima), the ingestion pathway becomes dominant for thyroid doses. This relative dominance can be related to the fact that estimated thyroid doses from ingestion are the same in all the prefectures, whereas the other two pathways (i.e. inhalation and external exposure from groundshine) are very dependent on the specific location and significantly decrease with distance. The relative contribution of ingestion to the thyroid doses is therefore higher in locations with relatively low contamination and vice versa.

4.4 Comparison to doses from other radiation sources

The doses calculated give an indication of the impact of the accident in different parts the world. To put these results in perspective, the estimated doses are compared with exposures arising from other sources (see Figures 7 and 8 and Annex 2).

Figure 7. Relative contribution of different sources to the annual average effective dose, worldwide.

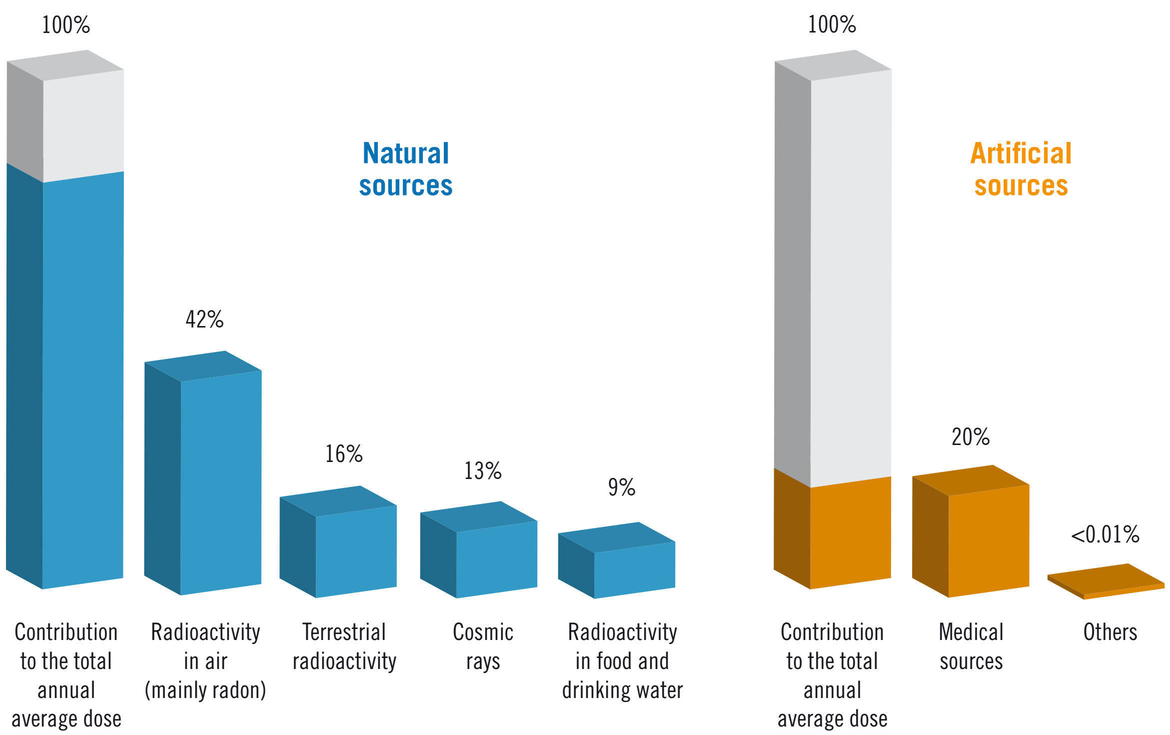


Figure 8. Comparative radiation effective dose levels in different contexts

According to the radiation protection system recommended by the ICRP, individuals can be exposed to radiation as members of the public (*public exposures*), for medical purposes (*medical exposures*), or as a result of their work (*occupational exposures*). Moreover, people can be exposed to radiation sources in different situations:

- **Planned exposure situations** that arise from the planned operation of a radiation source or from any planned activity that results in an exposure to a radiation source (e.g. a radiological medical procedure);
- **Existing exposure situations** which already exist when a decision on the need for control has to be taken (e.g. radon in dwellings, chronic exposures in the recovery phase after an accident).
- **Emergency exposure situations** that arise as a result of an accident, a malicious act, or any other unexpected event (e.g. a nuclear emergency)

The doses to members of the public calculated in this report for the first year after the Fukushima Daiichi nuclear power plant accident can be compared with the levels of human exposure to radiation in other emergency exposure situations such as the Chernobyl nuclear power plant accident (*8,36*).

The doses calculated in this report can be also compared with the levels of human exposure under planned and existing exposure situations. When making such comparisons it should be taken into account that exposures resulting from the Fukushima Daiichi nuclear power plant accident were received under unique/exceptional circumstances (a nuclear accident combined with other disasters) while planned and existing radiation exposures are radiation exposures occur in the daily life under normal conditions.

On a daily basis people are exposed to radiation from natural and man-made sources in the environment (see Box 4). There can be large variability in the dose received by individual members of the population depending on where they live, their dietary preferences and other lifestyle conditions. A worldwide average annual dose from natural background radiation is about 2.4 mSv, with a typical range of 1–10 mSv in various regions of the world (*37*).

The International Basic Safety Standards (BSS) for Protection Against Ionizing Radiation and for the Safety of Radiation Sources (*38*) provide the requirements for protection and

Box 4. Background radiation exposure

People are exposed to radiation on a daily basis. UNSCEAR has estimated that the global average effective dose per person from all natural and manmade sources of radiation in the environment is approximately **3.0 mSv/year**. Annual average doses and typical ranges of individual doses are presented in Table A2.1 in Annex 2 (*37*).].

About 80% of the annual radiation dose that a person receives is due to natural radiation coming from the cosmos, the earth and naturally-occurring radioactive materials in food and drink. People receive a radiation dose of several millisieverts every year through this natural exposure (on average, **2.4 mSv**) (*37*). Due to geological differences, several parts of the world have high natural background radiation areas where people can receive annual effective doses significantly higher than the global average.

Human exposure to ionizing radiation also comes from industrial and medical applications. Today, the most significant manmade sources of human exposure to ionizing radiation are radiological medical investigations and treatment (*40*).

safety that serve as a basis for the development of a regulatory framework, including dose limits and reference levels such as the following ones:

- An effective dose of **50 mSv** in a single year is the dose limit for occupational exposure of workers, provided that the annual effective dose averaged over five consecutive years does not exceed **20 mSv** (i.e. not more than 100 mSv in five years) (*38*).
- The internationally agreed reference level of 300 Bq/m^3 of radon concentration in air of residential dwellings represents approximately an annual effective dose of **10 mSv** (*38*,*39*).
- An annual effective dose of **1 mSv** is the dose limit for public exposure (*38*).

The International Commission on Radiological Protection (ICRP) provides reference levels to be applied after an accident. During the emergency phase, a reference level between 20 and 100 mSv per year is proposed to implement protective actions driven by urgency, taking into account the prevailing conditions. Once the emergency is over, a reference level for existing exposure situations between 1 and 20 mSv per year is proposed (*30*).

Doses below 10 µSv (0.01 mSv) are regarded by the international radiological protection community as small. An annual dose of 10 µSv corresponds to the radiological criteria for exemption[3] of materials from the need of regulatory control and for clearance[4] of materials from any further regulatory control as described in the International Basic Safety Standards (BSS) for Protection Against Ionizing Radiation and for the Safety of Radiation Sources (*38*).

4.5 Comparison of different methodologies

In this report the dose estimates for Japan, based entirely on monitoring data (Approach A, B), have been compared to the dispersion modelling approach (Approach C). The estimates of doses based on the predictions of the NAME III model for Japan are broadly consistent with the doses based on measured levels.

Similarly, the dose estimates outside Japan, based entirely on the dispersion modelling approach, were validated against an approach based on monitoring data for dose assessment of external exposure for population of the Russian Far East. Dose reduction factors averaged for the first year after deposition were calculated on the basis of Russian location factors depending on the time since deposition and Russian seasonal occupancy factors based on the Chernobyl experience, as follows:

- rural environment 0.27–0.43;
- settlements, small towns 0.17–0.37;
- urban environment (cities, towns) 0.15–0.32.

3. In the context of BSS, exemption is the determination by a regulatory body that a source or practice need not be subject to some or all aspects of regulatory control on the basis that the exposure and the potential exposure due to the source or practice are too small to warrant the application of those aspects, or that this is the optimum option for protection irrespective of the actual level of the doses or risks.
4. In the context of BSS, "clearance" means the removal of regulatory control by the regulatory body from radioactive material or radioactive objects within notified or authorized practices.

The estimations using the two different approaches showed some discrepancies that may be linked to the modelling of deposition processes or to the assumed magnitude and temporal variability of the source terms.

4.6 Comparison with in vivo human measurements

After the Fukushima accident, levels of radioactivity in humans have been measured both in Japan and elsewhere. Both thyroid monitoring and whole body monitoring were undertaken in Japan. In addition to Japanese human monitoring, measurements were taken in France and Germany on people returning to these countries after a stay in Japan, and measurements were undertaken on Russian citizens in Tokyo. These in vivo human measurements are important as they enable some comparison between doses estimated on the basis of measured levels of radioactivity in individuals and the assessed doses presented in this report in Tables 3 and 4.

However, there are significant differences in the nature of the doses estimated by the two methods which should be borne in mind when the estimated doses are compared:

- The in vivo human measurements are a snapshot of the levels in the human body at a particular time, and therefore obviously do not include intakes that may take place later over the first year. The doses derived from these measurements reflect this timing. The thyroid/whole body monitoring results include the contribution to thyroid/whole body content from intakes into the body only up to the time of the measurement In contrast, the estimated doses in this assessment include intakes for the whole first year.
- The results of the thyroid/whole body monitoring may not consider the contribution of short-lived radionuclides, depending on the time when the monitoring was performed. In contrast, all the estimated doses in this assessment include the contribution from ^{131}I, a short-lived radionuclide that may significantly contribute to thyroid doses.
- The measurements reflect only radioactivity incorporated into the body by internal exposure. In contrast, the estimated doses in this assessment include the dose to the thyroid/whole body arising from both internal exposure (inhalation and/or ingestion) and external exposure (from groundshine and cloudshine). It should be noted that external exposure is a significant contributor to the thyroid/whole body dose in the most affected areas (see Section 4.3).
- The monitored individuals are not necessarily representative of the population characterized by the assumptions adopted in this report. The exact locations of the individuals on whom the measurements were taken, their habits and behaviour, as well as detailed information on the protective actions taken by those individuals (e.g. whether they were in affected locations at the time the radioactive cloud was present) can significantly influence the levels of exposure, resulting in an heterogeneous distribution of individual exposures. Thus the extent to which the assumptions made in this study are relevant to the monitored individuals is unclear.

It is therefore anticipated that the estimated doses based on in vivo human monitoring will in general be smaller than the doses assessed in this study, which are estimated for the full first year and include both internal and external exposures

4.6.1 Monitoring in Japan

Thyroid monitoring of children in Japan

The panel had access to the results of the thyroid monitoring of 1080 children living[5] in Iitate village, Kawamata town and Iwaki city in Fukushima prefecture. The monitoring was undertaken between 24 and 30 March 2011. No detectable radioactive iodine was found in 60% of those measured. The Japanese authorities estimated thyroid doses based on these measurements, indicating that 93% of the children monitored had received thyroid doses less than 10 mSv and estimating that the maximum value from these measurements indicated a dose to the thyroid of around 50 mSv in the first year.

Thyroid monitoring in Japan by Russian researchers

Preliminary results of a dose estimate based on thyroid measurements of ^{131}I for Russian citizens in Tokyo have indicated that the maximum estimate of equivalent dose to the thyroid reached a few millisieverts for the period of interest, assuming that all intake was by inhalation during the first day of fallout in Tokyo on 15 March 2011 (41). The dose estimate based on these monitoring results excludes the external irradiation contribution to dose and the long-term ingestion doses. The characteristic thyroid doses estimated in this study for non-neighbouring prefectures in Japan, for all age groups, range from 1 to 10 mSv. These doses are not directly comparable with the doses assessed by the Russian researchers on the basis of thyroid monitoring, as the doses based on monitoring results exclude the external irradiation contribution to dose and the longer-term ingestion doses whereas the estimated dose ranges from the study presented in this report include the external irradiation contribution to dose and ingestion doses from the first year's intake. The total first year thyroid dose in this study, for non-neighbouring prefectures, is dominated by the contribution from the ingestion pathway; a proportion of the ingestion dose will be included in the Russian dose estimates based on thyroid monitoring, but not all.

Whole body measurements in Japan

Whole body measurements undertaken in Japan were also made available to the panel. The individuals monitored are understood by the panel to be inhabitants of the "restricted area" and the "deliberate evacuation area" – mostly residents of Iitate, Kawamata and Namie.[6] In total, the results of monitoring on 3373 residents were available to the panel by mid-September. On the basis of these data, it was concluded by the Japanese authorities that the internal effective radiation exposure doses for ^{134}Cs and ^{137}Cs were less than 2 mSv in total in all individuals monitored, and the great majority (99.8%) were less than 1 mSv, assuming that the intake of radioactivity into the body occurred by inhalation on 12 March 2011. As for the thyroid doses, these estimated effective doses assessed by the Japanese authorities on the basis of whole body monitoring are not directly compa-

5. The precise evacuation status of the children was not known to the panel at the time of the assessment (e.g. whether they had been resident in the locations at the time the radioactive cloud was present, whether they had been evacuated prior to the monitoring being undertaken, or whether they were still in the locations at the time of monitoring).

6. As for the thyroid monitoring results, the precise evacuation status of the individuals for whom whole body monitoring was undertaken was not known to the panel (e.g. whether they had been resident in the locations at the time the radioactive cloud was present, whether they had been evacuated prior to the monitoring being undertaken, or whether they were still in the locations at the time of monitoring).

rable with the effective doses assessed in the study presented in this report. The doses based on monitoring results exclude the external irradiation contribution to dose and the longer-term ingestion doses, whereas the estimated dose ranges from the study presented in this report include the external irradiation contribution to dose and ingestion doses from the first year's intake, and are dominated (with a contribution of 80–90%) by the external dose from deposited activity, which is not included in the whole body measurements. Doses from internal contamination are estimated to contribute only 10–20% of the total first-year effective dose, and are estimated to be of the order of a few mSv.

4.6.2 Monitoring outside Japan

Data from France are for areas less than 100 kilometres from the site of release and include detailed travel information for each individual (*42*). For Germany, the results are for people returning to Germany from Japan and do not include travel information (*43*).

In vivo measurements performed in Germany after the Fukushima accident

Between 14 March and 13 September 2011, 360 in vivo measurements – whole body, thyroid measurements or both – were performed in Germany for people (mostly adults) returning from Japan. For some of the returning people, the location of residence in Japan after the accident is known. This includes people returning from the prefectures of Chiba, Fukushima, Miyagi and Tokyo.

In 63 people (20% of all those examined), radionuclides above the detection limit were detected, most of them in March 2011. In April, measurable amounts of radionuclides were detected in six people, in May measurable amounts were detected in three people, and between June and September measurable amounts were detected in another 15 people. The detected radionuclides include ^{131}I, ^{132}Te, ^{132}I, ^{134}Cs and ^{137}Cs.

The maximum amount of radionuclides reported for the whole body were 980 Bq for ^{131}I, 280 Bq for ^{132}Te and ^{132}I, 550 Bq for ^{137}Cs and 640 Bq for ^{134}Cs. The maximum amount of ^{131}I found in the thyroid was 500 Bq.

Dose assessments were made for some of the measurements above the detection limit. These indicated a maximum value of effective dose of about 0.5 mSv, and a maximum value for thyroid dose of about 1 mSv. The assessed doses based on these monitoring results exclude the external irradiation contribution to dose and the ingestion doses from intakes after the time of measurement.

In vivo measurements performed in France after the Fukushima accident

The French data are for areas relatively close to the site of release, and include detailed travel information for each individual (*42*). From 14 March to 30 August 2011, 250 whole body measurements and 250 thyroid measurements were taken on 250 people, mostly adults, returning from areas 80 kilometres around the Fukushima site. In addition, 90 urine measurements were performed.

Among the 250 people who were measured, 146 were examined in March, 32 in April, 20 in May, 12 in June, 25 in July, and 21 in August. The radionuclides for which detection was attempted were: ^{54}Mn, ^{58}Co, ^{60}Co, ^{110m}Ag, ^{124}Sb, ^{131}I, ^{132}I, ^{132}Te, ^{134}Cs, ^{137}Cs and ^{90}Sr. The detected radionuclides were ^{131}I in 99 persons, ^{132}Te in 19 persons, ^{137}Cs in

12 persons, ^{132}I in nine persons, ^{134}Cs in two persons, ^{125}I in one person and ^{129}I in one person. All the urine measurements were below the limit of detection.

Dose calculations were performed for those people in whom measureable activity was found. The average effective dose was estimated to be 0.006 mSv (range 0.0003–0.09 mSv) and the average thyroid equivalent dose was estimated to be 0.098 mSv (range 0.005–1.4 mSv). The doses based on these monitoring results exclude the external irradiation contribution to dose and the longer-term ingestion doses.

The characteristic thyroid doses estimated in this study for the less affected parts of Fukushima prefecture and for neighbouring and non-neighbouring prefectures range from 1–10 mSv for adults. These doses are not directly comparable with the doses assessed by the French and German researchers on the basis of thyroid monitoring. The doses based on monitoring results exclude the external irradiation contribution to dose and the longer-term ingestion doses, whereas the estimated dose ranges from the study presented in this report include the external irradiation contribution to dose and ingestion doses from the first year's intake. For adults in the less affected parts of Fukushima prefecture and in neighbouring and non-neighbouring prefectures, the contribution to the total first-year thyroid dose from external irradiation is approximately 10–40% and the contribution of ingestion doses from the first year's intake to the total first-year thyroid dose is 30–90%, depending on location. A proportion of the ingestion dose will be included in the French and German dose estimates based on thyroid monitoring, but not all.

The characteristic effective doses estimated in this study for the less affected parts of Fukushima prefecture and for neighbouring and non-neighbouring prefectures range from 0.1 to 10 mSv for adults. These doses are not directly comparable with the doses assessed by the French and German researchers on the basis of whole body monitoring. The doses based on monitoring results exclude the external irradiation contribution to dose and the longer-term ingestion doses, whereas the estimated dose ranges from the study presented in this report include the external irradiation contribution to dose and ingestion doses from the first year's intake. For adults in the less affected parts of Fukushima prefecture and in neighbouring and non-neighbouring prefectures, the contribution to the total first-year effective dose from external irradiation is approximately 30–80% and the contribution of ingestion doses from the first year's intake to the total first-year effective dose is 20–70%, depending on location. A proportion of the ingestion dose will be included in the French and German dose estimates based on whole body monitoring, but not all.

The doses from internal contamination are estimated to be of the order of 1 mSv or less.

The estimates of both effective and thyroid doses assume generic anatomical and physiological human data based on the reference person as defined by the ICRP and through the use of the ICRP values of the inhalation and ingestion dose coefficients. Ingestion and inhalation dose estimates presented in this report remain based on the standard ICRP dosimetry, but it is recognized that these coefficients may result in some overestimation of doses arising from inhaled and ingested intakes for the Japanese population (see section 4.7.4).

In summary, taking into consideration the assumptions applied, the doses implied by both the thyroid measurements and the whole body measurements may be regarded as broadly in accordance with the doses estimated in the assessment. The apparent discrepancies reflect the distinction between the estimated doses in this study being an attempt to assess the full dose commitment arising from the first year after the accident, and the doses assessed on the basis of in vivo human monitoring which only reflect the internal exposure pathways at the time of the monitoring. It can be concluded that the comparison gives confidence that the estimated results in this study are neither underestimating nor very significantly overestimating the doses in Japan, and that the methodology and data used are robust.

Box 5 describes an ongoing study in Fukushima prefecture that includes calculation of external doses and compares its preliminary findings to those of the International Expert Panel. The dose band reported in this study is of the same order of magnitude as the dose band of 1–10 mSv estimated in this report for the most affected area of Fukushima prefecture, with the exception of two example locations where the effective doses were estimated to be in a dose band of 10–50 mSv. Given the conservative assumptions adopted by the International Expert Panel when detailed information was not available, both assessments may be regarded as broadly in accordance.

Box 5. Survey of 2 million Fukushima prefecture residents

Fukushima prefecture and Fukushima Medical University have begun a health management survey of some 2 million Fukushima residents, in cooperation with the National Institute of Radiological Sciences (NIRS). This survey includes questions on the actions of the residents for the period 11 March to 11 July 2011 (four months), including information about individuals' behaviours, movements, habits, and intakes of locally produced food and milk. NIRS developed an external dose calculation system based on the information collected through the survey and developed dose rate maps using data calculated by the System for Prediction of Environmental Emergency Dose Information (SPEEDI) and environmental monitoring data reported by the Ministry of Education, Culture, Sports, Science and Technology. Before estimating individual doses for each resident, NIRS carried out an initial estimation of exposures based on the identification of 18 evacuation patterns for residents from the area within 20 kilometres of the Fukushima Daiichi nuclear power plant (patterns 1–12) and for residents from the "deliberate evacuation area" (patterns 13–18). As this report was being finalized, first estimated doses for 1727 residents in Kawamata town, Namie town and Iitate village were published by Fukushima prefecture, indicating external dose estimations in a dose band of 0–15 mSv. New data for 9747 residents became available, indicating estimated external doses of less than 1 mSv for 57.8% of the residents, with a maximum external dose of 23 mSv (*44*, *45*). This external dose estimation is not directly comparable to the characteristic effective doses estimated in this report for these example locations because:

- input data includes modelling by SPEEDI and dose rate maps;
- it is based on an actual survey among residents that provided more detailed information about the timing of the implementation of protective measures;
- it includes residents from inside and outside the 20 kilometre zone;
- it includes external exposure pathways which in these locations are the major contributors to the effective dose, and it excludes the internal exposure pathways (inhalation and ingestion) which are less relevant in these locations.

4.7 Main sources of uncertainty and limitations

An earlier section has summarized the key assumptions made in the assessment, with an indication of where conservative but realistic assumptions have been made, although in some places it has been necessary to adopt a cautious position because of the lack of information. The assessment has been based on the best data available to the International Expert Panel at the time of the assessment. Several methods and assumptions have been used to assess doses, and for validation purposes the assessment results have been compared with human monitoring data. However, a quantitative uncertainty analysis has not been possible due to the early nature of this study and the lack of statistical input distributions. As a result of these multiple approaches, the panel considers the assessment to be as robust as possible at this time.

While estimated doses are presented mostly in order-of-magnitude dose bands of characteristic individual doses for each region considered, it cannot be expected that doses to all individuals within each region will necessarily lie within the order-of-magnitude dose bands presented here. Considerable variations occur in the results of environmental monitoring (e.g. in levels of radionuclides on the ground) within a region. In general, dose rates decline with increasing distance from the nuclear power plant, but in the north-westerly direction some increase is observed with distance, reflecting the significance of precipitation in the area at the time of radioactive cloud passage. In addition, other factors will vary from one individual to another (e.g. human behaviour patterns and precise locations). The main sources of uncertainty in the dose estimates are summarized below.

4.7.1 Estimating time-integrated air concentrations based on deposition measurements

Where measurements of concentrations in air are not available, it is theoretically possible to estimate activity concentrations in air from the measured activity on the ground. However, there is no simple and consistent relationship between activity concentration in air and either the amount of activity that is deposited on the ground or the external dose rates. Much depends on the radionuclide and its chemical form. For example, the chemical form of iodine influences the deposition rates, and thus the assumption about the chemical form of iodine (i.e. particulate or vapour) has a significant influence on the inhalation dose assessment. The effect of precipitation is also very important as it can significantly enhance the deposition of radionuclides and again lead to differences in the ratio of concentration in air and in the deposit.

For the reasons mentioned above, the estimated doses based on these data are associated with significant uncertainties. However, it is of interest to note that the approach based on dispersion modelling, when applied to the area of Japan outside the Fukushima prefecture (for validation purposes), gives similar predicted doses to those based on deposition measurements. In this approach, the deposition levels are predicted from modelled air concentrations stemming from a source term, taking into account dry and wet deposition processes and actual weather in the area at the time. Hence, although there are still significant uncertainties in this approach they are to some extent of a different origin from those in the measurement-based approach, giving some confidence in the doses estimated on the basis of both approaches.

4.7.2 Assumed radionuclide composition in Japanese locations

Measurements show great variability in the radionuclide composition in different locations in Japan, such as in the ratio between ^{131}I and ^{137}Cs in ground deposits. For the dose assessment in Japan, two alternative assumptions in the radionuclide composition have been used in approaches A and B (see Annex 6, Table A6.1) in conjunction with measured levels of deposited activity. This will have some impact on the doses predicted to arise from external and inhalation pathways, but the use of two alternative radionuclide compositions in this assessment provides reassurance that the impact of this uncertainty has not been overlooked. Since the chemical form of iodine (i.e. particulate or vapour) has significant influence on the inhalation dose, the inhalation dose estimates in the assessment cautiously assumed that the iodine was in elemental vapour form.

4.7.3 Location factor

The assessment assumes a location factor that represents the degree of shielding from external radiation provided by wooden housing, which may be regarded as a cautious value. However, the use of a less cautious number would only reduce the total dose from external irradiation by no more than a factor of two (*35*).

4.7.4 Use of ICRP dose coefficients for Japan

As mentioned in the previous section, in this study both effective and thyroid doses were assessed using the dose coefficients recommended by ICRP. These estimates use the ICRP values of the inhalation and ingestion dose coefficients. They assume generic anatomical and physiological human data based on the reference person as defined by ICRP, and as such are not intended to be the inhabitants of any particular region. The use of these dose coefficients may result in some overestimation of equivalent doses to the thyroid for Japanese individuals because the high iodine content of the Japanese diet (e.g. from sea fish, shellfish and seaweed) may reduce the uptake of radioactive iodine by the thyroid. The panel was not aware of thyroid dose coefficients developed specifically for the Japanese or for a population with an iodine-rich diet. However, not all diets in Japan are rich in iodine (*46*), so protection afforded by high levels of natural iodine may not apply to all. It has also been noted that iodine-rich food does not in itself appear effective as a countermeasure after a release of radioactive iodine (*47*).

4.7.5 Source term

The definition of what radionuclides were released and the timing of the release, together with information on chemical form, particle size and release height/energy, must be regarded as highly uncertain. In the assessment, this uncertainty is linked to another, discussed above, which is how the released radionuclides deposit during precipitation and how this changes over distance from the release. However, source terms are applied in this assessment only to estimate doses in the world beyond Japan, and the majority of these estimated doses are below the low level of dose used here as a cut-off value in the presentation of results. Hence an underestimation or an overestimation in the source terms used would have little or no effect on the majority of the doses presented.

4.7.6 Dispersion modelling

The panel is aware that, internationally, the use of complex dispersion models, such as the one used in this assessment to estimate the global dispersion arising from the Fukushima accident, generally results in model estimates substantially lower than measurements at far distances. This is thought to arise from either a complex situation regarding wet deposition or from inaccuracies in the current source term estimates, or from a combination of these factors. The estimates of the NAME III model around the northern hemisphere for Xe-133 are also in good agreement with measurements, suggesting that the global dispersion modelling is fundamentally correct. Comparison between the estimates of the NAME model of time-integrated activity concentrations in air and measured air concentrations for ^{131}I and ^{137}Cs taken in various parts of the world in March and April has indicated an increasing trend with distance from the release site for the estimates to be lower than the measurements. Unlike ^{133}Xe, ^{131}I and ^{137}Cs are radionuclides that deposit, lending support to the possibility that the discrepancy may in part be linked to the modelling of deposition processes, although the possibility of some inaccuracy in the magnitude and temporal variability of the source terms cannot be eliminated. On the timescale of this preliminary study it is an issue that cannot be resolved.

4.7.7 Ingestion doses in Japan

The estimation of ingestion doses in Japan incorporated into the total doses (as presented in Tables 3 and 4), is generally considered to be conservative on the basis of the assumptions listed in Section 2.6.

5. Summary and conclusions

The radiation doses in this report represent a preliminary assessment of doses for the first year after the Fukushima accident based on data available to the panel up to September 2011. Doses are provided for different populations by age and geographical location.

Effective doses and equivalent doses to the thyroid have been estimated for three age groups: 1-year-old infants, 10-year-old children, and adults. These age groups were chosen to enable the characterization of the radiological impact on younger and more sensitive populations. The estimated doses are those received by a characteristic person living in the region or location of interest, and are mostly reported as bands of one order of magnitude, providing a level of accuracy commensurate with the preliminary nature of the assessment. The bands do not indicate the range of doses in the population in the area, which would have required distributions of input data not available to the panel within the time frame of this assessment[1].

In general, the doses assessed are the committed doses for residents staying in a given region or location during the full first year after the accident. However, in a few locations in the most affected part of Fukushima prefecture, doses were calculated for the first four months after the accident as relocation took place at some time during the first few months.

On the basis of the input data used for this assessment, extrapolation of doses beyond the first year was not performed because of uncertainties that may influence long-term exposure, including future protective and remedial actions, that will further reduce radiation exposure (*48*, *49*). The experience of the Chernobyl accident was that about 30% of the lifetime dose was delivered during the first year and about 70% during the first 15 years (*31*). On the basis of environmental activity concentration data, it can be expected that the fraction of the lifetime dose beyond the first year will be lower for the Fukushima Daiichi nuclear power plant accident than for the Chernobyl accident, due to the greater influence of the shorter-lived ^{134}CS (half-life two years) compared to ^{137}CS (half-life 30 years).

In summary, the key features of the assessed doses are as follows.

For the estimated effective doses:

- In Fukushima prefecture the estimated effective doses are within a dose band of 1–10 mSv, except in two of the example locations where the effective doses are estimated to be within a dose band of 10–50 mSv.
- In prefectures neighbouring Fukushima, the estimated effective doses are within a dose band of 0.1–10 mSv, and in all other prefectures the effective doses are estimated to be within a dose band of 0.1–1 mSv.

1. The Independent Expert Panel worked from June to November 2011.

- 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 most affected regions the external dose from groundshine is important, but with increasing distance from the site the ingestion of food becomes the main contributor.

For the estimated thyroid doses:

- 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 estimated thyroid doses to infants are within a dose band of 100–200 mSv.
- In the rest of Fukushima prefecture the estimated thyroid doses are within a dose band of 1–10 mSv to adults and 10–100 mSv to children and infants.
- In the rest of Japan the estimated thyroid doses are within a dose band of 1–10 mSv.
- 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 most affected regions, inhalation from the cloud and the external dose from groundshine are important, but with increasing distance from the site the ingestion of food becomes the main contributor.

It can be concluded that the estimated effective doses outside Japan from the Fukushima Daiichi nuclear power plant accident are below (and often far below) the dose levels regarded by the international radiological protection community as very small. An annual dose of 0.01 mSv (10 μSv) corresponds to the radiological criterion for exemption of materials from need of regulatory control and for clearance of materials from any further control, as established in the International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources (*38*). This level of dose is comparable to the average population dose resulting from 1.5 days of exposure to natural background radiation/natural sources of radiation (*37*).

It can also be concluded that low effective doses are estimated in much of Japan. To put this into context, and keeping in mind that dose limits do not apply in emergency exposure situations, it could be noted that estimated effective doses outside Fukushima and neighbouring prefectures are below the annual limit for public exposure in planned exposure situations (1 mSv) (*10*,*38*).

In the Fukushima prefecture and in neighbouring prefectures the estimated effective doses are below the internationally agreed reference level for public exposure due to radon in dwellings (annual effective dose of about 10 mSv (*39*)), except in two locations in the most affected part of Fukushima prefecture where the effective doses were estimated to be within a dose band of 10–50 mSv. To put this into context, the ICRP recommends reference levels for planned residual dose in emergency exposure situations (the dose that remains after protective actions have been taken) in the band of 20–100 mSv annual or acute effective dose (*48*).

In view of the time frame of the assessment, a number of assumptions were taken to calculate the doses, which mostly provide conservative estimates. In particular the panel was aware of some protective measures taken by the Government of Japan in relocating residents of certain areas (i.e. in the "deliberate evacuation area"). Because of lack of the necessary detailed information, it has been assumed that the relocation of residents in these areas took place at least four months after the accident, whereas a proportion of the population was relocated earlier. Therefore, the doses estimated in the example locations considered for the most affected areas of Fukushima prefecture may be overestimated.

Moreover, the protective effects of sheltering may not also have been fully taken into account due to lack of more detailed information. This being said, the dominant contributors to the total effective dose in these locations were the inhalation[2] and external exposure pathways. While evacuation prior to the arrival of the radioactive cloud would be effective in reducing inhalation and external exposure from cloudshine, relocation after the radioactive release (e.g. at two months instead of four months as assumed) would not significantly reduce the overall dose as the early exposure pathways would remain unchanged.

For prefectures far away from Fukushima included under the scenario for the rest of Japan, food appears to be the main exposure source. In these locations, food was not monitored and it assumed that consumers only ate food coming from Fukushima and neighbouring prefectures. The doses are therefore clearly overestimated.

Comparison between the estimated doses for Japan in this report and those estimated from direct measurements of radionuclides in Japanese residents and travellers returning from Japan gives confidence that the estimated doses in this report do not underestimate the actual doses in Japan. The doses estimated from in vivo human measurements are similar, and in some cases lower, than those estimated in the assessment using environmental data, although a direct correlation between the quantities cannot be made. As discussed, cautious assumptions have been made where data are lacking. However, the panel considers that the doses presented here are unlikely to be very significantly overestimated.

The Independent Expert Panel considers that the dose estimates are robust on the basis of knowledge and information on hand at the time of the study. The data used as input to this assessment are considered by the panel to be the most appropriate available on the timescale required (September 2011) and to be fit-for-purpose.

The long-term priority in radiological protection after a nuclear accident is to protect people with the highest exposures, and to reduce all individual exposures associated with the event to as low as reasonably achievable (*30*). This requires the knowledge of the dose distribution for the subsequent optimization of protection.

It has been reported that a number of remedial actions have been taken by the Government of Japan, municipal authorities and residents to lower radiation exposure (*49*). At

2. Since protection from inhalation exposure due to being indoors for a proportion of the time has not generally been taken into account in this assessment, the early doses from inhalation are likely to be somewhat overestimated.

the time of publication of this report, additional protective and remedial actions are being implemented[3]. Such measures that will further lower exposure can be accounted for in future studies, such as the upcoming two-year UNSCEAR assessment.[4]

In addition to the UNSCEAR study, a major initiative initiated in the Fukushima prefecture will inform future more detailed dose assessments. This unprecedented initiative, the Fukushima Health Survey, includes a survey to determine the whereabouts of every prefectural resident from the time of the March 11 nuclear accident onwards (a so-called "record of movement") and to provide the basis for estimating the level of radiation exposure, which will assist in future health effect assessments.

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3. Remedial actions have been planned by the Government of Japan through the Act on Special Measures concerning the Handling of Environment Pollution by Radioactive Materials Discharged by the NPS Accident Associated with the Tohoku District -Off the Pacific Ocean Earthquake That Occurred on March 11, 2011 (Act No. 110 of 2011), and through the Guidelines for Decontamination in a Specific Area for Decontamination (Decontamination Roadmap) (January 26, 2012, Ministry of the Environment). Moreover, additional protective actions have been taken such as the establishment of stricter New Standard Limits for Radionuclides in Foods (April 1, 2012, Ministry of Health Labour and Welfare).

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Glossary

Absorbed dose
Mean energy imparted by ionizing radiation to an irradiated medium per unit mass, expressed in grays (Gy). Amount of energy absorbed by that organ or tissue divided by its weight. The international unit of absorbed dose is the gray (Gy), which is equal to one joule per kilogram.

Activity: *see* radioactivity.

Alpha particles
Two neutrons and two protons bound as a single particle that is emitted from the nucleus of certain radioactive isotopes in the process of decay or disintegration; a positively charged particle indistinguishable from the nucleus of a helium atom.

Activity median aerodynamic diameter (AMAD)
The value of aerodynamic diameter such that 50% of the airborne activity in a specified aerosol is associated with particles smaller than the AMAD, and 50% of the activity is associated with particles larger than the AMAD.

Atmospheric dispersion
The spreading of radionuclides in air resulting mainly from physical processes affecting the velocity of different molecules in the medium.

Atom
The smallest particle of an element that cannot be divided or broken up by chemical means. It consists of a central core of protons and neutrons, called the nucleus, and of electrons which revolve in orbits in the region surrounding the nucleus.

Background radiation
Amount of radiation to which a population is exposed from natural sources, such as terrestrial radiation due to naturally occurring radionuclides in the soil, cosmic radiation originating in outer space, and naturally occurring radionuclides deposited in the human body.

Becquerel
In the International System, a unit of activity equal to one disintegration per second.

Beta particles
A negatively charged particle emitted from the nucleus of an atom, with mass equal to those of an electron.

Biodistribution
Result of the transfer of compounds of interest in the body.

Clearance
The removal by the regulatory body of regulatory control from radioactive material or radioactive objects within notified or authorized practices.

Committed dose
The lifetime dose expected to result from a radionuclide intake.

Consumption level
Amount of food ingested per day, per person.

Cloud
Mass of air and vapour in the atmosphere carrying radioactive material released from a nuclear explosion.

Cloudshine
Gamma radiation from radionuclides in an airborne radioactive plume (i.e. radioactive cloud).

Deposition: *see* deposition density.

Deposition density
Activity of a radionuclide per unit area of ground. Reported in the International System as becquerels per square meter (Bq/m^2) or curies per square meter.

Deterministic effects
Health effects, the severity of which varies with dose and for which typically there is a threshold below which they will not occur (e.g. acute radiation syndrome). Deterministic effects are also referred to as "tissue reactions" or non-stochastic effects.

Deterministic approach/analysis
Approach or analysis using single numerical values (taken to have a probability of 1), leading to a single value for the result. In the context of exposure assessment this is typically used with either 'best estimate' or 'conservative' values, based on expert judgment and knowledge of the phenomena being modeled. Contrasting/opposite terms: probabilistic analysis or stochastic analysis.

Dose
A general term denoting the quantity of radiation or energy absorbed in a target.

Dose assessment
Assessment of the dose(s) to an individual or group of people.

Dose coefficients
Factors used to convert the amount of incorporated radioactive substances (radionuclide intake) to the dose in tissues/organs, and/or the whole body dose. These factors (also called "dose conversion factors") may depend on the radionuclide, the incorporation route (e.g. inhalation, ingestion), the chemical compound and the age of the person. Usually expressed as dose per unit intake (e.g. sieverts per becquerel (e.g. sieverts per becquerel, Sv/Bq).

Dose conversion factor: *see* dose coefficients.

Dose limit
In planned exposure situations, the value of the individual effective dose or equivalent that is not to be exceeded. Dose limits do not apply to existing exposure situation or emergency exposure situations.

Dose rate
Absorbed dose delivered per unit time.

Effective dose
Sum of the products of absorbed dose to each organ multiplied by a radiation weighting factor and a tissue weighting factor that takes into account the radiosensitivity of tissues and organs.

Environmental monitoring
The measurement of external dose rates due to sources in the environment or of radionuclide concentrations in environmental media.

Equivalent dose
Absorbed dose averaged over a tissue or organ, further applying a radiation weighting factor that varies by radiation type and is related to the density of ionization created.

Evacuation
The rapid, temporary removal of people from an area to avoid or reduce short-term radiation exposure in an emergency.

Exemption
The determination by a regulatory body that a source or practice need not be subject to some or all aspects of regulatory control on the basis that the exposure and the potential exposure due to the source or practice are too small to warrant the application of those aspects or that this is the optimum option for protection irrespective of the actual level of the doses or risks.

Exposure
The state or condition of being subject to irradiation from a source that is outside the body (i.e. external exposure) or within the body (i.e. internal exposure).

Exposure pathway
A route by which radiation or radionuclides can reach humans and cause exposure.

External exposure: *see* exposure.

Fallout (nuclear)
Minute radioactive particles that descend slowly from the atmosphere after a nuclear explosion.

Food self-sufficiency
The food self-sufficiency ratio is calculated as the domestic food production divided by the food supply for domestic consumption.

Gamma rays
Short-wavelength electromagnetic radiation (i.e. photons) of nuclear origin; similar to X-radiation but emitted at very specific energies characteristic of the decaying atoms.

Ground deposition: *see* deposition density.

Groundshine
Gamma radiation from radionuclides deposited on the ground.

Half-life
The time taken for the quantity of a specified material (e.g. a radionuclide) in a specified place to decrease by half as a result of any specified process or processes that follow similar exponential patterns to radioactive decay. The radioactive half-life for a radionuclide is the time required for the activity to decrease, by a radioactive decay process, by half. The biological half-life is the time taken for the quantity of a material in a specified tissue, organ or region of the body to halve as a result of biological processes. The effective half-life is the time taken for the activity of a radionuclide in a specified place to halve as a result of all relevant processes (e.g. radioactive decay, biological half-life).

Ingestion
Consumption of a substance by a living organism.

Inhalation
Movement of air from the external environment, through the airways, and into the pulmonar alveoli.

Inhalation rate
Number of breaths taken within a given amount of time, typically one minute.

Intake
The activity of a radionuclide taken into the body (by inhalation or ingestion or through the skin) in a given time period or as a result of a given event.

Internal exposure: *see* exposure.

Ionization
Process by which a neutral atom or molecule acquires a positive or negative charge.

Ionizing radiation
For the purposes of radiation protection, radiation capable of producing ion pairs in biological material(s).

Kerma (kinetic energy released in matter)
Unit of exposure that represents the kinetic energy transferred to charged particles per unit mass of irradiated medium when indirectly ionizing (uncharged) particles, such as photons or neutrons, traverse the medium. If all of the kinetic energy is absorbed "locally", the kerma is equal to the absorbed dose. The quantity (K) is expressed in µGy/h at 1 m.

Location factor
The ratio of the dose rate in air at a point inside a settlement to a similar value above a plot of undisturbed soil.

Natural background: *see* background radiation.

Noble gas
An inert radioactive gas that does not readily enter into chemical combination with other elements. Examples are helium, argon, krypton, xenon and radon.

Occupancy factor:
A typical fraction of the time for which a location is occupied by an individual or group.

Radioactive decay
The decrease in the amount of any radioactive material with the passage of time due to the spontaneous emission from the atomic nuclei of either alpha or beta particles, often accompanied by gamma radiation.

Radioactive material
The "scientific" meaning of radioactive, as in radioactive substance, refers only to the presence of radioactivity, and gives no indication of the magnitude of the hazard involved. In its “regulatory” meaning, it refers to a material designated in national law or by a regulatory body as being subject to regulatory control because of its radioactivity.

Radioactivity (also called "activity")
The amount of radioactivity of a radionuclide defined as the mean number of decays per unit time. The unit of activity in the International System (SI) is the reciprocal second (s^{-1}), termed the becquerel (Bq).

Radionuclide
Radioactive species of an atom characterized by the constitution of its nucleus.

Reference level
In an emergency exposure situation or an existing exposure situation, the level of dose , risk or activity concentration above which it is not appropriate to plan to allow exposures to occur and below which optimization of protection and safety would continue to be implemented.

Relocation
Non-urgent movement of people from a contaminated area to avoid chronic exposure. It is a longer-term protective action that may be a continuation of the urgent protective action of evacuation. It may be permanent relocation (sometimes termed resettlement) if it continues for more than a year or two and return is not foreseeable; otherwise it is temporary relocation.

Remedial action: *see* remediation.

Remediation
Any measures that may be carried out to reduce the radiation exposure from existing contamination of land areas through actions applied to the contamination itself (the source) or to the exposure pathways to humans.

Risk
Hazard, danger or chance of harmful consequences associated with exposures or potential exposures. It relates to quantities such as the probability that specific deleterious consequences may arise and to the magnitude and character of such consequences. It refers to detrimental health effects of exposure to radiation (including the likelihood of

such effects occurring) as well as to any other safety-related risks, including those to ecosystems in the environment, that might arise as a direct consequence of exposure to radiation.

Sheltering
An urgent protective action, used during nuclear emergencies to provide shielding against external exposure and to reduce the intake of airborne radionuclides by inhalation by using a structure for protection from an airborne plume and/or deposited radionuclides (e.g. recommending people to stay indoors).

Shielding
Physical barriers that provide protection against exposure to radiation. Radiation shielding (see also Shielding factor) is the reduction of radiation by interposing a physical barrier (i.e. a shield) of absorbing material between any radioactive source and a person, work area or radiation-sensitive device.

Shielding factor
A measure of the effectiveness of the shield expressed as the ratio between the radiation level at a location behind a shield on which radiation is incident and the radiation level at the same location without the presence of the shield.

Sievert
The SI unit of equivalent dose and effective dose, equal to 1 J/kg.

Source
Anything that may cause radiation exposure by emitting ionizing radiation or by releasing radioactive substances or material, and that can be treated as a single entity for protection and safety purposes.

Source term
The amount and isotopic composition of material released (or postulated to be released) from a facility. Used in modeling releases of radionuclides to the environment, particularly in the context of accidents at nuclear installations or releases from radioactive waste in repositories.

Threshold (or "threshold dose")
Minimal absorbed radiation dose that will produce a detectable degree of any given effect.

Organ dose
The mean absorbed dose in a specified tissue or organ of the human body. Sometimes called tissue dose.

Tissue reactions: *see* deterministic effects.

X-rays (or X-radiation)
Penetrating electromagnetic radiation (i.e. photons) whose wavelength is shorter than that of visible light. It is usually produced by bombarding a metallic target with fast electrons in a high vacuum. In nuclear reactions, it is customary to refer to photons originating in the nucleus as gamma-radiation and those originating in the extranuclear part of the atom as X-radiation.

Abbreviations

Ag	silver
AMAD	Activity Median Aerodynamic Diameter
BfS	Bundesamt für Strahlenschutz (Federal Office of Radiation Protection), Germany
BSS	Basic Safety Standards
Co	cobalt
Cs	caesium
FAO	Food and Agriculture Organization
GEMS	Global Environmental Monitoring System
HPA	Health Protection Agency
I	iodine
IAEA	International Atomic Energy Agency
IARC	International Agency for Research on Cancer
ICRP	International Commission on Radiological Protection
INES	International Nuclear Event Scale
INFOSAN	International Food Safety Authorities Network
IRH	Institute of Radiation and Hygiene, Russia
IRSN	Institut de Radioprotection et Sureté Nucléaire, France
LOD	Limit Of Detection
LOQ	Limit Of Quantification
Mn	manganese
NAME	Numerical Atmospheric dispersion Modelling Environment
NIRS	National Institute of Radiological Sciences, Japan
Sb	antimony
SPEEDI	System for Prediction of Environmental Emergency Dose Information
Te	tellurium
TEPCO	Tokyo Electric Power Company
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WHO	World Health Organization
Xe	xenon

Annex 1. Declaration of interests statement

The independent experts who participated in the meetings of the International Expert Panel on the initial evaluation of radiation exposure from the nuclear accident after the 2011 Great East Japan Earthquake and Tsunami were asked to inform WHO if at any time a conflict of interest, whether actual or potential, could be perceived in their work and they were required to sign a conflict-of-interest statement. There was no conflict of interest for any Panel members who contributed to the preparation of this document.

Annex 2. Examples of doses from different sources of exposure

Table A2.1 Annual average effective dose from naturally-occurring sources

Source	Worldwide average annual effective dose (mSv)	Typical range (mSv)
External exposure		
Cosmic rays	0.39	0.3–1 [a]
Terrestrial radiation: Outdoors	0.07	0.3–1 [b]
Indoors	0.41	
Internal exposure		
Inhalation (mainly radon)	1.26	0.2–10 [c]
Ingestion (food and drinking-water)	0.29	0.2–1 [d]
Total	**2.4**	**1–13**

[a] Range from sea level to high ground elevation.
[b] Depending on radionuclide composition of soil and building material.
[c] Depending on indoor accumulation of radon gas.
[d] Depending on radionuclide composition of foods and drinking water.

Adapted from United Nations. Sources and effects of ionizing radiation. UNSCEAR 2008 Report to the General Assembly with scientific annexes. Vol 1 Annex B Exposures of the public and workers from various sources of radiation. United Nations, New York 2010.

Table A2.2 Examples of typical effective doses from diagnostic radiological medical procedures

Source of exposure	Effective dose
Dental X-ray	0.005 mSv
Chest X-ray (single PA film)	0.02 mSv
Skull X-ray	0.06 mSv (*)
Mammography	0.4 mSv
Lumbar spine X-ray	1 mSv
Head CT scan	2 mSv
Chest CT scan	8 mSv
Abdomen and pelvis CT scan	15 mSv

(*) As an example, this level of dose is comparable to the typical effective dose resulting from external exposure to cosmic rays received during a transatlantic flight.

Annex 3. Input parameters for the dose assessment

1. Inhalation dose coefficients

Table A3.1 Effective inhalation dose coefficients for members of the public: adults, children, and infants

Radionuclide	Radionuclide form	Lung absorption type	Committed effective dose coefficient – adult (Sv/Bq)	Committed effective dose coefficient – 10-year-old child (Sv/Bq)	Committed effective dose coefficient – 1-year-old infant (Sv/Bq)
^{103}Ru	Particulate aerosol	M	$2.4\ 10^{-9}$	$3.5\ 10^{-9}$	$8.4\ 10^{-9}$
^{106}Ru	Particulate aerosol	M	$2.8\ 10^{-8}$	$4.1\ 10^{-8}$	$1.1\ 10^{-7}$
^{127m}Te	Particulate aerosol	M	$7.4\ 10^{-9}$	$1.1\ 10^{-8}$	$2.6\ 10^{-8}$
^{129m}Te	Particulate aerosol	M	$6.6\ 10^{-9}$	$9.8\ 10^{-9}$	$2.6\ 10^{-8}$
^{131m}Te	Particulate aerosol	M	$9.4\ 10^{-10}$	$1.9\ 10^{-9}$	$5.8\ 10^{-9}$
^{132}Te	Particulate aerosol	M	$2.0\ 10^{-9}$	$4.0\ 10^{-9}$	$1.3\ 10^{-8}$
^{131}I	Elemental vapour	F	$2.0\ 10^{-8}$	$4.8\ 10^{-8}$	$1.6\ 10^{-7}$
	Particulate aerosol	F	$7.4\ 10^{-9}$	$1.9\ 10^{-8}$	$7.2\ 10^{-8}$
^{132}I	Elemental vapour	F	$3.1\ 10^{-10}$	$6.4\ 10^{-10}$	$2.3\ 10^{-9}$
	Particulate aerosol	F	$9.4\ 10^{-11}$	$2.2\ 10^{-10}$	$9.6\ 10^{-10}$
^{133}I	Elemental vapour	F	$4.0\ 10^{-9}$	$9.7\ 10^{-9}$	$4.1\ 10^{-8}$
	Particulate aerosol	F	$1.5\ 10^{-9}$	$3.8\ 10^{-9}$	$1.8\ 10^{-8}$
^{135}I	Elemental vapour	F	$9.2\ 10^{-10}$	$2.1\ 10^{-9}$	$8.5\ 10^{-9}$
	Particulate aerosol	F	$3.2\ 10^{-10}$	$7.9\ 10^{-10}$	$3.7\ 10^{-9}$
^{134}Cs	Particulate aerosol	F	$6.6\ 10^{-9}$	$5.3\ 10^{-9}$	$7.3\ 10^{-9}$
^{137}Cs	Particulate aerosol	F	$4.6\ 10^{-9}$	$3.7\ 10^{-9}$	$5.4\ 10^{-9}$
^{137m}Ba	–	–	–	–	–
^{140}Ba	Particulate aerosol	M	$5.1\ 10^{-9}$	$7.6\ 10^{-9}$	$2.0\ 10^{-8}$
^{141}Ce	Particulate aerosol	M	$3.2\ 10^{-9}$	$4.6\ 10^{-9}$	$1.1\ 10^{-8}$
^{144}Ce	Particulate aerosol	M	$3.6\ 10^{-8}$	$5.5\ 10^{-8}$	$1.6\ 10^{-7}$

Source: ICRP database of dose coefficients: workers and members of the public (v2.0.1).
Note: For the purposes of the assessment it has been assumed that the iodine was in elemental vapour form.
Data are for particle sizes of AMAD = 1.0 micron unless stated otherwise.

Table A3.2 Thyroid inhalation dose coefficients for members of the public: adults, children, and infants

Radionuclide	Radionuclide form	Lung absorption type	Committed thyroid dose coefficient: adult (Sv/Bq)	Committed thyroid dose coefficient: 10-year-old child (Sv/Bq)	Committed thyroid dose coefficient: 1-year-old infant (Sv/Bq)
^{103}Ru	Particulate aerosol	M	$1.9\ 10^{-10}$	$3.4\ 10^{-10}$	$1.0\ 10^{-9}$
^{106}Ru	Particulate aerosol	M	$2.7\ 10^{-9}$	$4.8\ 10^{-9}$	$1.5\ 10^{-8}$
^{127m}Te	Particulate aerosol	M	$8.6\ 10^{-10}$	$2.0\ 10^{-9}$	$9.8\ 10^{-9}$
^{129m}Te	Particulate aerosol	M	$1.0\ 10^{-9}$	$2.5\ 10^{-9}$	$1.2\ 10^{-8}$
^{131m}Te	Particulate aerosol	M	$2.7\ 10^{-9}$	$6.6\ 10^{-9}$	$2.5\ 10^{-8}$
^{132}Te	Particulate aerosol	M	$4.3\ 10^{-9}$	$1.1\ 10^{-8}$	$5.3\ 10^{-8}$
^{131}I	Elemental vapour	F	$3.9\ 10^{-7}$	$9.5\ 10^{-7}$	$3.2\ 10^{-6}$
	Particulate aerosol	F	$1.5\ 10^{-7}$	$3.7\ 10^{-7}$	$1.4\ 10^{-6}$
^{132}I	Elemental vapour	F	$3.6\ 10^{-9}$	$8.9\ 10^{-9}$	$3.8\ 10^{-8}$
	Particulate aerosol	F	$1.4\ 10^{-9}$	$3.4\ 10^{-9}$	$1.6\ 10^{-8}$
^{133}I	Elemental vapour	F	$7.6\ 10^{-8}$	$1.9\ 10^{-7}$	$8.0\ 10^{-7}$
	Particulate aerosol	F	$2.8\ 10^{-8}$	$7.4\ 10^{-8}$	$3.5\ 10^{-7}$
^{135}I	Elemental vapour	F	$1.5\ 10^{-8}$	$3.8\ 10^{-8}$	$1.6\ 10^{-7}$
	Particulate aerosol	F	$5.7\ 10^{-9}$	$1.5\ 10^{-8}$	$7.0\ 10^{-8}$
^{134}Cs	Particulate aerosol	F	$6.3\ 10^{-9}$	$5.1\ 10^{-9}$	$6.3\ 10^{-9}$
^{137}Cs	Particulate aerosol	F	$4.4\ 10^{-9}$	$3.5\ 10^{-9}$	$4.4\ 10^{-9}$
^{137m}Ba	–	–	–	–	–
^{140}Ba	Particulate aerosol	M	$2.7\ 10^{-10}$	$5.0\ 10^{-10}$	$1.4\ 10^{-9}$
^{141}Ce	Particulate aerosol	M	$3.8\ 10^{-11}$	$7.2\ 10^{-11}$	$2.3\ 10^{-10}$
^{144}Ce	Particulate aerosol	M	$1.8\ 10^{-9}$	$2.9\ 10^{-9}$	$9.0\ 10^{-9}$

Source: ICRP database of dose coefficients: workers and members of the public (v2.0.1).
Note: For the purposes of the assessment it has been assumed that the iodine was in elemental vapour form.
Data are for particle sizes of AMAD = 1.0 micron unless stated otherwise.

2. Ingestion dose coefficients

Table A3.3 Effective ingestion dose coefficients for members of the public: adults, children and infants

Radionuclide	Committed effective dose coefficient: adult (Sv/Bq)	Committed effective dose coefficient: 10-year-old child (Sv/Bq)	Committed effective dose coefficient: 1-year-old infant (Sv/Bq)
^{103}Ru	$7.3\ 10^{-10}$	$1.5\ 10^{-9}$	$4.6\ 10^{-9}$
^{106}Ru	$7.0\ 10^{-9}$	$1.5\ 10^{-8}$	$4.9\ 10^{-8}$
^{127m}Te	$2.3\ 10^{-9}$	$5.2\ 10^{-9}$	$1.8\ 10^{-8}$
^{129m}Te	$3.0\ 10^{-9}$	$6.6\ 10^{-9}$	$2.4\ 10^{-8}$
^{131m}Te	$1.9\ 10^{-9}$	$4.3\ 10^{-9}$	$1.4\ 10^{-8}$
^{132}Te	$3.8\ 10^{-9}$	$8.3\ 10^{-9}$	$3.0\ 10^{-8}$
^{131}I	$2.2\ 10^{-8}$	$5.2\ 10^{-8}$	$1.8\ 10^{-7}$
^{132}I	$2.9\ 10^{-10}$	$6.2\ 10^{-10}$	$2.4\ 10^{-9}$
^{133}I	$4.3\ 10^{-9}$	$1.0\ 10^{-8}$	$4.4\ 10^{-8}$
^{135}I	$9.3\ 10^{-10}$	$2.2\ 10^{-9}$	$8.9\ 10^{-9}$
^{134}Cs	$1.9\ 10^{-8}$	$1.4\ 10^{-8}$	$1.6\ 10^{-8}$
^{137}Cs	$1.3\ 10^{-8}$	$1.0\ 10^{-8}$	$1.2\ 10^{-8}$
^{137m}Ba	–	–	–
^{140}Ba	$2.6\ 10^{-9}$	$5.8\ 10^{-9}$	$1.8\ 10^{-8}$
^{141}Ce	$7.1\ 10^{-10}$	$1.5\ 10^{-9}$	$5.1\ 10^{-9}$
^{144}Ce	$5.2\ 10^{-9}$	$1.1\ 10^{-8}$	$3.9\ 10^{-8}$

Source: ICRP database of dose coefficients: workers and members of the public (v2.0.1).

Table A3.4 Thyroid ingestion dose coefficients for members of the public: adults, children and infants

Radionuclide	Committed thyroid dose coefficient: adult (Sv/Bq)	Committed thyroid dose coefficient: 10-year-old child (Sv/Bq)	Committed thyroid dose coefficient: 1-year-old infant (Sv/Bq)
^{103}Ru	$6.7\ 10^{-11}$	$1.3\ 10^{-10}$	$4.1\ 10^{-10}$
^{106}Ru	$1.4\ 10^{-9}$	$2.8\ 10^{-9}$	$8.7\ 10^{-9}$
^{127m}Te	$3.1\ 10^{-9}$	$7.7\ 10^{-9}$	$3.4\ 10^{-8}$
^{129m}Te	$4.6\ 10^{-9}$	$1.1\ 10^{-8}$	$5.1\ 10^{-8}$
^{131m}Te	$1.8\ 10^{-8}$	$4.5\ 10^{-8}$	$1.5\ 10^{-7}$
^{132}Te	$3.1\ 10^{-8}$	$7.5\ 10^{-8}$	$3.2\ 10^{-7}$
^{131}I	$4.3\ 10^{-7}$	$1.0\ 10^{-6}$	$3.6\ 10^{-6}$
^{132}I	$3.4\ 10^{-9}$	$8.3\ 10^{-9}$	$3.5\ 10^{-8}$
^{133}I	$8.2\ 10^{-8}$	$2.0\ 10^{-7}$	$8.6\ 10^{-7}$
^{135}I	$1.6\ 10^{-8}$	$3.9\ 10^{-8}$	$1.7\ 10^{-7}$
^{134}Cs	$1.8\ 10^{-8}$	$1.4\ 10^{-8}$	$1.6\ 10^{-8}$
^{137}Cs	$1.3\ 10^{-8}$	$9.7\ 10^{-9}$	$1.1\ 10^{-8}$
^{137m}Ba	–	–	–
^{140}Ba	$8.7\ 10^{-11}$	$4.2\ 10^{-10}$	$8.3\ 10^{-10}$
^{141}Ce	$3.0\ 10^{-13}$	$8.6\ 10^{-13}$	$4.5\ 10^{-12}$
^{144}Ce	$1.2\ 10^{-11}$	$2.2\ 10^{-11}$	$6.8\ 10^{-11}$

Source: ICRP database of dose coefficients: workers and members of the public (v2.0.1).

3. Inhalation rates

The inhalation rates applied are the average rates over a day from the ICRP model of the respiratory tract and include time spent sleeping, at home and at work, and hence they are suitable for someone exposed for 24 hours a day. For time spent at work, the inhalation rate is modelled on the male sedentary worker.

Table A3.5 Inhalation rates for adults, children and infants (average over a day)

Age group	Inhalation rate (m^3/d)	Inhalation rate (m^3/s)
Adult (sedentary worker)	22.18	$2.57\ 10^{-4}$
Child (10-year-old)	15.28	$1.77\ 10^{-4}$
Infant (1-year-old)	5.20	$6.02\ 10^{-5}$

Source: Human respiratory tract model for radiological protection. ICRP Publication 66, Ann. ICRP 24 (1-3), 1994.

4. External dose per unit deposit

External dose coefficients per unit deposit for members of the public (adults, children and infants) were used for both effective dose and thyroid dose. The values were data used in the European decision support system RODOS, and are taken from Jacob P et al (see Source below tables). The values shown in Tables A3.6 and A3.7 were applied in this assessment.

Table A3.6 External dose coefficients per unit deposit for members of the public: adults, children and infants (effective dose, exposure over 1 year)

Radionuclide	Effective dose coefficient: adult (Sv per Bq/m²)	Effective dose coefficient: 10-year-old child (Sv per Bq/m²)	Effective dose coefficient : 1-year-old infant (Sv per Bq/m²)
^{103}Ru	1.5 10^{-9}	1.6 10^{-9}	2.0 10^{-9}
^{106}Ru	3.0 10^{-9}	3.3 10^{-9}	4.0 10^{-9}
^{127m}Te	2.1 10^{-11}	2.5 10^{-11}	4.4 10^{-11}
^{129m}Te	1.8 10^{-10}	2.0 10^{-10}	2.5 10^{-10}
^{131m}Te	1.3 10^{-10}	1.5 10^{-10}	1.8 10^{-10}
^{132}Te	6.5 10^{-10}	7.2 10^{-10}	8.6 10^{-10}
^{131}I	2.5 10^{-10}	2.7 10^{-10}	3.3 10^{-10}
^{132}I	1.7 10^{-11}	1.9 10^{-11}	2.3 10^{-11}
^{133}I	4.2 10^{-11}	4.5 10^{-11}	5.7 10^{-11}
^{135}I	3.2 10^{-11}	3.5 10^{-11}	4.2 10^{-11}
^{134}Cs	2.7 10^{-8}	3.0 10^{-8}	3.6 10^{-8}
^{137}Cs	1.2 10^{-8}	1.2 10^{-8}	1.6 10^{-8}
^{137m}Ba	#	#	#
^{140}Ba	2.8 10^{-9}	3.0 10^{-9}	3.6 10^{-9}
^{141}Ce	1.8 10^{-10}	2.0 10^{-10}	2.5 10^{-10}
^{144}Ce	6.4 10^{-10}	7.1 10^{-10}	8.5 10^{-10}

Source: Jacob P et al. *Calculation of organ doses from environmental gamma rays using human phantoms and Monte-Carlo methods. Part 2: Radionuclides distributed in air or deposited on the ground.* (GSF-Report 12/90). Neuherberg, GSF National Research Center on Environment and Health, 1990.

^{137m}Ba is already included in the dose factor of mother nuclide ^{137}Cs.

Table A3.7 External dose coefficients per unit deposit for members of the public: adults, children and infants (thyroid dose, exposure over 1 year)

Radionuclide	Thyroid dose coefficient: adult (Sv per Bq/m^2)	Thyroid dose coefficient: 10-year-old child (Sv per Bq/m^2)	Thyroid dose coefficient : 1-year-old infant (Sv per Bq/m^2)
^{103}Ru	1.6 10^{-9}	1.8 10^{-9}	1.9 10^{-9}
^{106}Ru	3.3 10^{-9}	3.6 10^{-9}	3.9 10^{-9}
^{127m}Te	1.8 10^{-11}	2.4 10^{-11}	3.7 10^{-11}
^{129m}Te	2.0 10^{-10}	2.2 10^{-10}	2.4 10^{-10}
^{131m}Te	1.4 10^{-10}	1.6 10^{-10}	1.8 10^{-10}
^{132}Te	7.1 10^{-10}	7.8 10^{-10}	8.8 10^{-10}
^{131}I	2.7 10^{-10}	2.8 10^{-10}	3.3 10^{-10}
^{132}I	1.9 10^{-11}	2.1 10^{-11}	2.3 10^{-11}
^{133}I	4.5 10^{-11}	5.1 10^{-11}	5.4 10^{-11}
^{135}I	3.5 10^{-11}	4.0 10^{-11}	4.3 10^{-11}
^{134}Cs	2.9 10^{-8}	3.2 10^{-8}	3.6 10^{-8}
^{137}Cs	1.2 10^{-8}	1.4 10^{-8}	1.6 10^{-8}
^{137m}Ba	#	#	#
^{140}Ba	3.0 10^{-9}	3.4 10^{-9}	3.7 10^{-9}
^{141}Ce	1.9 10^{-10}	2.1 10^{-10}	2.5 10^{-10}
^{144}Ce	6.8 10^{-10}	7.5 10^{-10}	8.5 10^{-10}

Source: Jacob P et al. *Calculation of organ doses from environmental gamma rays using human phantoms and Monte-Carlo methods. Part 2: Radionuclides distributed in air or deposited on the ground.* (GSF-Report 12/90). Neuherberg, GSF National Research Center on Environment and Health, 1990.

^{137m}Ba is already included in the dose factor of mother nuclide ^{137}Cs.

5. Dose reduction factor: external dose from radioactive material in air

A dose reduction factor to represent the saving in external dose from radioactive material in the air due to being indoors has been applied in the assessment, based on an assumed location factor and building occupancy factor.

Table A3.8 Dose reduction factor for external dose from radioactive material in air (from http://radioactivity.mext.go.jp/en/1750/2011/04/1305904_0424e.pdf)

Cloud gamma location factor (indoors)	0.4
Occupancy factor	66%
Cloud gamma dose reduction factor	0.60 [0.66 x 0.4 + (1 - 0.66) x 1]

Table A3.9 Dose reduction factor for external dose from ground deposits (from http://radioactivity.mext.go.jp/en/1750/2011/04/1305904_0424e.pdf)

Deposited gamma location factor (indoors)	0.4
Occupancy factor	66%
Deposited gamma dose reduction factor	0.60 [0.66 x 0.4 + (1 - 0.66) x 1]

Annex 4. Source term for use in dispersion-based calculations

The assessment of doses outside Japan, which was based on atmospheric dispersion modelling, required an assumed source term as input data. As defined here, a source term is the amount of each radionuclide released (or postulated to be released), and the timing of the releases of each radionuclide. Using both environmental monitoring data and computer simulation based on atmospheric dispersion modelling of radioactive materials, the Japan Atomic Energy Agency (JAEA) provided estimates of the source term of iodine and caesium discharged from the Fukushima Daiichi nuclear power plant into the atmosphere.

In this report, two source terms have been used to assess doses to countries outside Japan.

Source term S_1, was based on Bannai, 2011 and revised to take account of the corrections (to ^{132}I, ^{133}I, ^{135}I, ^{131m}Te and ^{132}Te), as reported by personal communication with Yuji Otake, representative from the Ministry of Foreign Affairs of Japan (MOFA)[1]. The source term is a function of time and spans the period 12–18 March 2011. The basis for the source term was operational records, observed parameters and the chronology of events at the site.

Source term S_2, was based on

- releases of ^{131}I and ^{137}Cs: based on Chino et al, 2011 revised to account for the greater detail given in the report by the Government of Japan, 2011, and further revised in agreement with Dr Chino's suggested changes to duration of the release;
- releases of ^{133}Xe: based on Bannai, 2011;
- releases of ^{134}Cs: based on a ^{137}Cs/^{134}Cs scaling factor derived from Bannai, 2011 and applied to the Chino et al, 2011 ^{137}Cs source term.

Source term S_2 spans a longer period from 12 March to 6 April 2011. Chino et al, 2011 estimated release rates using a "reverse estimation method" by coupling environmental monitoring data with atmospheric dispersion simulations. This involved dividing measured air concentrations of ^{131}I and ^{137}Cs into modelled ones at sampling points and using this ratio to scale the modelled source term.

1. Personal communication and subsequent press release of the Government of Japan, on 20 October 2011, of which the English translation is: http://translate.google.co.uk/translate?sl=auto&tl=en&js=n&prev=_t&hl=en&ie=UTF-8&layout=2&eotf=1&u=http%3A%2F%2Fwww.meti.go.jp%2Fpress%2F2011%2F10%2F20111020001%2F20111020001.html

Table A4.1 Source terms S_1 and S_2 (Bq)

	Source Term S_1	Source Term S_2
^{140}Ba	3.13E+15	–
^{134}Cs	1.76E+16	1.13E+16
^{137}Cs	1.53E+16	9.66E+15
^{141}Ce	1.77E+13	–
^{144}Ce	1.15E+13	–
^{131}I	1.59E+17	1.24E+17
^{132}I	1.30E+13	–
^{133}I	4.21E+16	–
^{135}I	2.27E+15	–
^{103}Ru	7.50E+09	–
^{106}Ru	2.14E+09	–
^{127m}Te	1.09E+15	–
^{129m}Te	3.33E+15	–
^{131m}Te	4.95E+15	–
^{132}Te	8.80E+16	–
^{133}Xe	1.13E+19	1.13E+19

Other relevant information

Other elements are relevant to the source term – particularly the elevation of the release and the particle size of the dispersing material. In the absence of specific information, a release spread along the vertical from 0 metres to 100 metres has been assumed. No information on the size distribution of the particles released was available. It was assumed that all particles were 1 µm AMAD for all non-noble gas radionuclides (i.e. every radionuclide other than ^{133}Xe). ^{133}Xe was modelled as a gas. Deposition velocities of $1\ 10^{-2}$ m s^{-1} for isotopes of iodine (elemental iodine vapour) and $1\ 10^{-3}$ m s^{-1} for all other depositing radionuclides were applied.

References to Annex 4

Additional Report of the Japanese Government to the IAEA. The accident at TEPCO's Fukushima nuclear power stations, second report., September 2011 (http://www.meti.go.jp/english/earthquake/nuclear/iaea/iaea_110911.html, accessed 30 March 2012).

Bannai T. *Regarding the evaluation of the conditions on reactor cores of Units 1, 2 and 3 related to the accident at Fukushima Dai-ichi nuclear power station*. Tokyo Electric Power Co. Inc. Tokyo, Nuclear and Industrial Safety Agency, 2011.

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Stohl A et al. Xenon-133 and caesium-137 releases into the atmosphere from the Fukushima Dai-ichi nuclear power plant: determination of the source term, atmospheric dispersion, and deposition. *Atmospheric Chemistry and Physics*, 2011, 11:28319–28394 (http://www.atmos-chem-phys.net/12/2313/2012/acp-12-2313-2012.pdf, accessed 130 May 2012).

Annex 5. Example of input monitoring data from Japan

This annex lists some of the basic input data used in the dose assessment for three settlements – Iitate, Katsurao and Namie – in the deliberate evacuation area. The doses were estimated on the basis of the average values (for each settlement) of monitoring data for the surface activity density of ^{137}Cs.

Figure A5.1 Monitoring sites of data used as input for dose assessment for Iitate, Katsurao and Namie. GDR: Gamma Dose Rates

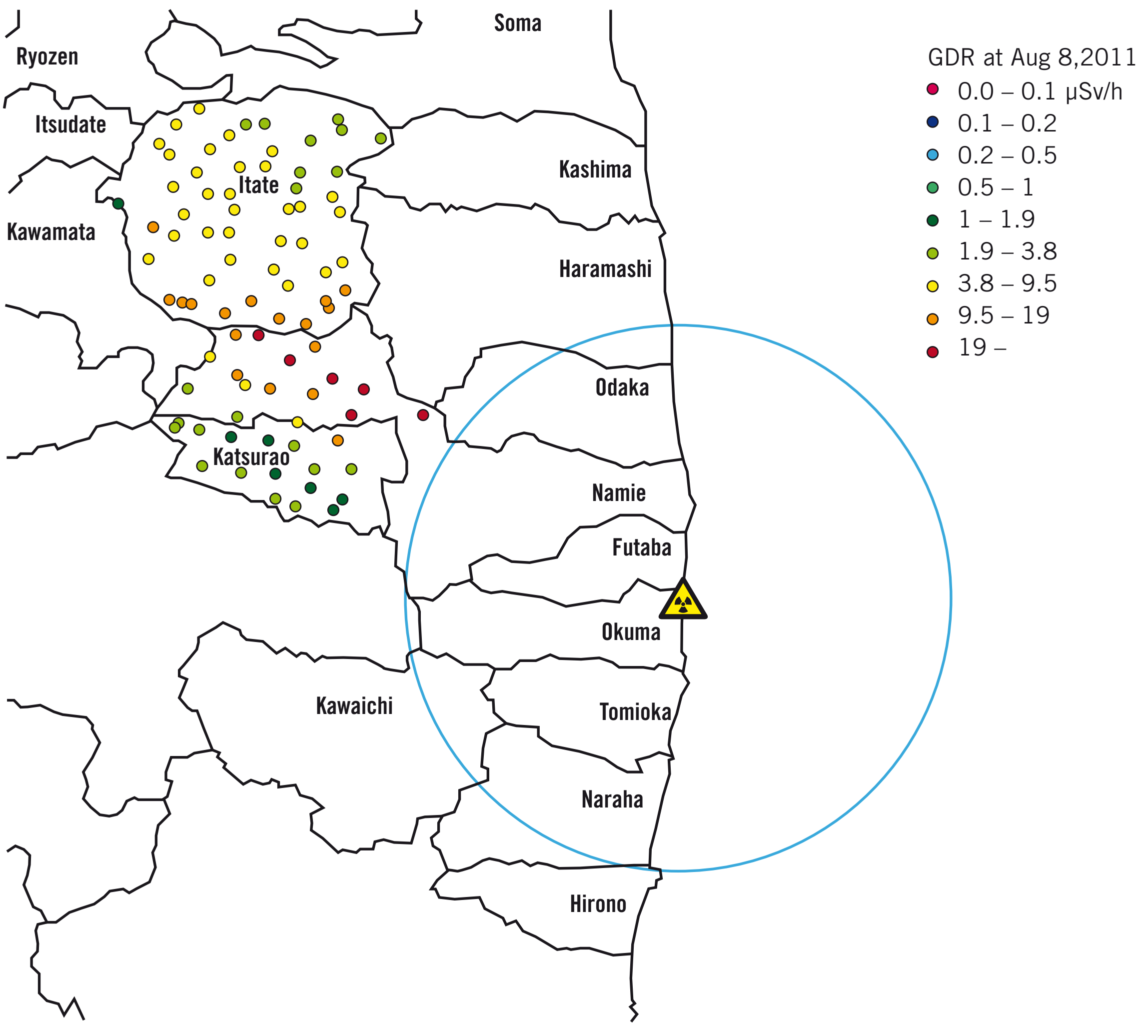

Table A5.1 Monitoring data for the surface activity density of ^{137}Cs used as input for dose assessment for IItate town

Latitude	Longitude	A_{Cs137} (Bq/m^2)
37.613556	140.80025	979939
37.603028	140.785278	1592481
37.607583	140.766556	1345789
37.60975	140.731111	455527
37.615917	140.708056	664481
37.625389	140.810528	1354264
37.618917	140.797056	597467
37.628806	140.773111	1274462
37.618417	140.749361	993816
37.63305	140.720871	851040
37.618611	140.703556	1087038
37.619306	140.694944	965700
37.644583	140.808778	621607
37.638056	140.798167	1527598
37.639389	140.763472	956600
37.645744	140.735016	740202
37.646611	140.680667	715162
37.656444	140.783167	254377
37.658028	140.768472	1289455
37.664222	140.732806	753436
37.664028	140.721028	881912
37.661361	140.697194	281150
37.677417	140.806861	345334
37.681222	140.780194	794992
37.679147	140.773328	484259
37.679194	140.738	956620
37.675694	140.70425	738168
37.668056	140.683806	490616
37.688111	140.80225	500720
37.693472	140.777528	370842
37.693642	140.757438	848547
37.690611	140.733944	379905

Latitude	Longitude	A_{Cs137} (Bq/m^2)
37.689806	140.720083	1038643
37.694472	140.6975	403758
37.6845	140.659333	273571
37.704389	140.80575	390523
37.704111	140.780194	634331
37.707972	140.758528	945709
37.707	140.741139	485533
37.70425	140.713139	804183
37.715694	140.694722	739814
37.726783	140.834833	142509
37.731917	140.808278	335451
37.725028	140.787278	327865
37.717518	140.76332	302717
37.728611	140.734028	616293
37.720194	140.720972	420757
37.722528	140.688139	751964
37.738703	140.805588	116758
37.737083	140.756972	299710
37.736	140.745083	549939
37.746778	140.713889	587715
37.735528	140.697833	880765
Average		**701000**

Source: extracted from http://www.mext.go.jp/b_menu/shingi/chousa/gijyutu/017/shiryo/__icsFiles/afieldfile/2011/09/02/1310688_1.pdf.

Table A5.2 Monitoring data for the surface activity density of ^{137}Cs used as input for dose assessment for Namie town

Latitude	Longitude	A_{Cs137} (Bq/m²)
37.541861	140.862222	1303029
37.542806	140.815583	3144837
37.537765	140.780232	1571278
37.541611	140.739917	286147
37.560528	140.823806	5663908
37.556833	140.789722	2085925
37.560806	140.761056	1756064
37.561583	140.744472	1155541
37.559917	140.707361	184303
37.566826	140.802109	2531915
37.579306	140.774472	1979903
37.569333	140.738972	906899
37.581167	140.721583	991959
37.58825	140.790556	1582173
37.596056	140.754111	7901503
37.596806	140.738222	1675721
Average		**2170000**

Source: extracted from http://www.mext.go.jp/b_menu/shingi/chousa/gijyutu/017/shiryo/__icsFiles/afieldfile/2011/09/02/1310688_1.pdf.

Table A5.3 Monitoring data for the surface activity density of ^{137}Cs used as input for dose assessment for Katsurao

Latitude	Longitude	A_{Cs137} (Bq/m^2)
37.48	140.803417	201006
37.481917	140.777861	363009
37.48575	140.807722	158117
37.49375	140.787917	224726
37.488	140.764833	131903
37.506972	140.815056	406894
37.506833	140.79075	299681
37.504111	140.764444	393280
37.504694	140.742639	190366
37.508944	140.716222	220665
37.52575	140.806	1236706
37.522333	140.77775	310008
37.526306	140.76075	384797
37.52875	140.735222	57320
37.533111	140.714	267997
37.537222	140.701444	134859
37.535	140.698417	191129
Average		**304000**

Source: extracted from http://www.mext.go.jp/b_menu/shingi/chousa/gijyutu/017/shiryo/__icsFiles/afieldfile/2011/09/02/1310688_1.pdf.

Annex 6. Models for external and inhalation doses in Japan (Approach A and Approach B)

In the assessment of external and inhalation doses in Japan, two approaches were developed to calculate the effective and thyroid doses for three age groups. This annex describes the mathematical models and input data used in the calculations.

1. Model for external dose from nuclides deposited on soil

1.1 Effective dose

Approach A: the effective dose E_i^{dep} and effective dose rate $\dot{E}_i^{dep}(t)$ of the population group i from deposited radionuclides were calculated by means of computational model developed after the Chernobyl accident (*1–4*):

$$E_i^{dep} = \int \dot{E}_i^{dep}(t)\,dt \qquad \dot{E}_i^{dep}(t) = \dot{K}_{air}(t)\cdot k_i \cdot RF_i \tag{1}$$

$$\dot{K}_{air}(t) = r(t)\cdot A_{Cs137}\cdot \sum_m \left(\frac{A_m}{A_{Cs137}}\right)\cdot \dot{d}_m^{dep}\cdot \exp(-\lambda_m \cdot t) \tag{2}$$

where:

- the summation index *m* is for deposited radionuclides;
- λ_m is the decay constant of radionuclide *m*;
- $\dot{d}_m^{dep}$ is the dose rate coefficient from surface activity density to kerma rate in free air $\dot{K}_{air}(t)$ for height of 1 m above ground due to initial distribution of radionuclide *m* in the ground (*5* [Table 1]);
- A_m is the surface activity density of radionuclide *m* on the ground;
- RF_i is a reduction factor for population group *i* (assumed to be 0.6 for all population groups in Japan, Table A3.9 in Annex 3);
- k_i is a conversion factor from kerma in free air to the effective dose, independent of location and time after the accident: 0.75 Sv Gy^{-1} for adults, 0.80 Sv Gy^{-1} for children (10 years) and 0.90 Sv Gy^{-1} for infants (1 year) (*6*);
- *r(t)* is a time dependent attenuation function[1] that accounts for radionuclide penetration in the soil (*2–4*).

Approach B differs from approach A in:

- using dose coefficients per unit deposit (5, see Table A3.6 in Annex 3) instead of dose rate coefficients and conversion factors k_i ;
- using slightly different nuclide ratios A_m / A_{Cs137} (see Table A6.1);

1. This attenuation function r(t) represents the influence of the radionuclide migration into the soil on the gamma dose rate and was fitted in the form: $r(t) = p_1 \cdot \exp\left(-\frac{\ln 2}{T_1}\cdot t\right) + p_2 \cdot \exp\left(-\frac{\ln 2}{T_2}\cdot t\right)$ where p_1=0.34, p_2=0.66, T_1=1.5 years and T_2=50 years.

- not accounting for shielding effect from radionuclide penetration in soil (parameter $r(t)$; this leads to approximately 5% higher doses in the first year).

1.2 Thyroid dose

Approach A: the thyroid dose of the population group i from deposited radionuclides was taken equal to the value of effective dose since the values of conversion coefficients from kerma in free air to effective dose does not differ by more than 10% for selected age groups (*6*).

Approach B: the thyroid dose of the population group i from deposited radionuclides was calculated in the same way as the effective dose but using the appropriate coefficients per unit deposit for thyroid dose (*5*, see Table A3.7 in Annex 3).

2. Model for external dose from radioactive cloud

2.1 Effective dose

Approach A: the effective dose E_i^{cloud} of the population group *i* from radioactive cloud was calculated as follows:

$$E_i^{cloud} = A_{Cs137} \cdot k_i \cdot RF_i \cdot \sum_m \left(\frac{A_m / A_{Cs137}}{V_{bm}}\right) \cdot d_m^{cloud} \qquad (3)$$

where:

- V_{bm} is bulk deposition velocity of radionuclide *m* for particular weather and surface conditions;
- d_m^{cloud} is dose rate coefficient from semi-infinite volume source in air to kerma in free air for height of 1 m above ground due to uniform distribution of radionuclide *m* in the air (*5*);
- RF_i is an anthropogenic reduction factor for population group *i* (assumed to be 0.6 for Japan, Table A3.8 in Annex 3);

The remaining symbols and parameter values are the same as above.

In the absence of firm meteorological data, different sets of radionuclide deposition velocities were applied depending on the surface activity density of ^{137}Cs:

In Approach A two cases are distinguished:

- in areas of predominantly wet deposition, with A_{Cs137} > 30 kBq m^{-2}
  $V_{b\,^{131}I}$ = 0.07 m s^{-1} and V_{bm} = 0.01 m s^{-1} for all other radionuclides;
- in areas of predominantly dry deposition, with A_{Cs137} < 30 kBq m^{-2}
  $V_{b\,^{131}I}$ = 0.01 m s^{-1} and V_{bm} = 0.001 m s^{-1} for all other radionuclides.

Approach B differs from Approach A only in:

- applying an average bulk deposition velocity V_{bm} of 0.07 m s^{-1} for all radionuclides and in all areas (assuming predominantly wet deposition);

- using effective dose coefficients per unit air concentration [*5*] instead of dose rate coefficients in air and conversion factors k_i;
- using slightly different nuclide ratios A_m / A_{Cs137} (see Table A6.1).

2.2 Thyroid dose

Approach A: the thyroid dose of the population group *i* from radioactive cloud was taken equal to the value of effective dose as in the case of deposited radionuclides.

Approach B: the thyroid dose of the population group *i* from radioactive cloud was calculated in the same way as the effective dose but using the appropriate coefficients per unit air concentration for thyroid dose (*5*).

3. Model for internal dose from inhalation

3.1 Effective dose

Approach A: the effective dose E_i^{inh} of the population group i from inhalation of radioactive materials was calculated according to:

$$E_i^{inh} = A_{Cs137} \cdot I_i \cdot \sum_m \left(\frac{A_m / A_{Cs137}}{V_{bm}}\right) \cdot d_{mi}^{inh} \qquad (4)$$

where:

- V_{bm} is the bulk deposition velocity of radionuclide *m*;
- I_i is the breathing rate for population group (Table A3.5 in Annex 3);
- d_{mi}^{inh} is the effective dose inhalation coefficient for population group *i* and radionuclide *m* (Tables A3.1 in Annex 3).

The remaining symbols and parameter values are the same as above.

No protection is assumed due to being indoors for a proportion of the time.

Approach B differs from approach A only in:

- using different sets of radionuclide deposition velocities (as in the case of dose assessment from the radioactive cloud);
- using slightly different nuclide ratios A_m / A_{Cs137} (see Table A6.1).

3.2 Thyroid dose

Thyroid equivalent dose was also calculated by equation (*4*); however, a different set of dose coefficient values was applied (see Table A3.2 in Annex 3).

4. Input data

The doses via the three pathways were estimated on the basis of soil deposition data as follows:

4.1 Surface activity density of ^{137}Cs (A_{Cs137})

For the surface activity density of ^{137}Cs, the input data A_{Cs137} was:

- In the deliberate evacuation area and in most affected parts of the Fukushima prefecture, the input data were the average values of ^{137}Cs surface activity density in a particular settlement (15 settlements in total) (*7*, *8*).
- In the less contaminated parts of the Fukushima prefecture and in the neighbouring prefectures of Chiba, Gunma, Ibaraki, Miyagi, Saitama, Tochigi, Tokyo and Yamagata, the input data were ^{137}Cs surface activity densities based on maps (*9*).
- For other Japanese prefectures with ^{137}Cs surface activity density above 500 Bq m^{-2}, external doses from deposition were estimated on the basis of measurements of ground deposition at monitoring posts (one point per prefecture) (*10*).
- For prefectures of Japan with ^{137}Cs surface activity density less than 500 Bq m^{-2}, the value of surface activity density of 500 Bq m^{-2} was conservatively used. In this case the first year external dose was equal to 0.01 mSv.

4.2 Surface activity density of other nuclides (A_m)

The dose assessment based on gamma dose rate measurements or on measurements of ^{137}Cs on the ground required an assumption about the nuclide composition. The relative isotopic composition of deposit A_m / A_{Cs137} was assessed on the basis of soil contamination measurements for the reference date of 15 March (the day when the major deposition northwest of the nuclear power plant began).

Approach A: Relative isotopic composition of deposit (see Table A6.1) was assessed on the basis of soil measurements according to the reports (*11*,*12*).

Approach B: Except for the short-lived radionuclide ^{132}Te, all other ratios were derived as average values from the results of soil sampling in the Fukushima prefecture (*13*). For ^{132}Te, the ratio was derived from in situ gamma spectrometric measurements in the Fukushima prefecture performed by an IAEA team in March 2011. It has been recognized that, for some areas to the south of the Fukushima Daiichi nuclear power plant, the ^{131}I to ^{137}Cs ratio in the soil might have been significantly higher than the average value given here, but this has not been explicitly considered in the assessment.

Table A6.1 Assumed relative isotopic composition of deposit (on 15 March 2011)

Radionuclide	Approach A (*13*)	Approach B (*11*,*12*)
^{131}I	7.8	11.7
^{132}I	7.6	–
^{132}Te	7.6	8.0
^{134}Cs	0.92	0.94

Radionuclide	Approach A (*13*)	Approach B (*11,12*)
^{136}Cs	0.16	0.2
^{137}Cs	1	1
^{140}Ba	–	0.1
^{110m}Ag	–	0.01
^{129m}Te	–	1.5

Source: Dose readings and estimates of the Ministry of Education, Culture, Sports, Science and Technology, at: http://radioactivity.mext.go.jp/en/1750/2011/04/1305904_0424e.pdf, accessed 30 March 2012.

References to Annex 6

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3. Golikov V, Balonov M, Erkin V, Jacob P. Model validation for external doses due to environmental contamination by the Chernobyl accident. *Health Physics*, 1999, 77(6):654–661.
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6. Golikov V et al. Evaluation of conversion coefficients from measurable to risk quantities for external exposure over contaminated soil by use of physical human phantoms. *Radiation and Environmental Biophysics*, 2007, 46(4):375–382.
7. Data from the Ministry of Education, Culture, Sports, Science and Technology (http://www.mext.go.jp/b_menu/shingi/chousa/gijyutu/017/shiryo/__icsFiles/afieldfile/2011/09/02/1310688_1.pdf, accessed 13 May 2012) (in Japanese).
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11. *Synthèse des informations disponibles sur la contamination radioactive de l'environnement terrestre japonais provoquée par l'accident de Fukushima Daiichi*. Paris, L'Institut de Radioprotection et de Sûreté Nucléaire, 13 juillet 2011.

12. Iitate Village Area Radioactive Contamination Investigation Team: IMANAKA Tetsuji (Representative), Research Reactor Institute, Kyoto University, ENDO Satori Hiroshima University, Graduate School of Engineering, SHIZUMA Kiyoshi Hiroshima University, Graduate School of Engineering, SUGAI Masuro Kokugakuin University, OZAWA Shoji Nihon University, College of Bioresources Sciences. *Interim report on radiation survey in Iitate village area conducted on March 28th and 29th*. 4 April 2011 (http://www.rri.kyoto-u.ac.jp/NSRG/seminar/No110/Iitate-interim-report110404.pdf, accessed 13 May 2012).

13. *Readings of soil monitoring around Fukushima NPP.* Ministry of Education, Culture, Sports, Science and Technology (http://radioactivity.mext.go.jp/en/ accessed 13 May 2012).

Annex 7. Models for external and inhalation doses outside Japan (Approach C)

1. Model for external dose from radionuclides deposited on soil

The effective dose E_i^{dep} for the population age group *i* from deposited radionuclides, in Sv, was calculated as follows:

$$E_i^{dep} = RF \sum_m A_m \cdot \dot{de}_{m,i}^{dep}$$

where:

- A_m is the total surface activity density of radionuclide *m* on the ground, in Bq m^{-2}, estimated by the NAME model;
- $\dot{de}_{m,i}^{dep}$ is the effective external dose coefficient per unit deposit of radionuclide *m* for age group *i*, in Sv per Bq m^{-2};
- RF is the dose reduction factor (assumed to be 0.6 for Japan, see Table A3.9 in Annex 3);
- m is the summation index over the radionuclides considered.

The thyroid dose T_i^{dep} for the population age group i from deposited radionuclides, in Sv, was calculated as follows:

$$T_i^{dep} = RF \sum_m A_m \cdot \dot{de}_{m,i}^{dep}$$

where:

- $\dot{de}_{m,i}^{dep}$ is the thyroid external dose coefficient per unit deposit of radionuclide *m* for age group *i*, in Sv per Bq m^{-2}.

The remaining symbols and parameter values are the same as above.

2. Model for external dose from radioactive cloud

The external doses from exposure to the radioactive cloud are estimated within the NAME model. NAME uses a combination of a Lagrangian particle approach, which sums the contribution to dose at each receptor point from each individual model particle, and a semi-infinite cloud model, which assumes that all the air in a hemisphere around the person is uniformly contaminated to a radius sufficient to account for the range of the radiation in air. The approaches are summarized in the reference (*1*).

The estimated doses were modified by the dose reduction factor (assumed to be 0.6 for Japan, see Table A3.9 in Annex 3).

3. Model for internal dose from inhalation

The effective dose E_i^{inh} of population age group *i* from inhalation of radioactive materials was calculated according to:

$$E_i^{inh} = I_i \cdot \sum_m T_m \cdot de_{mi}^{inh}$$

where:

- T_m is the time-integrated activity concentration in air during cloud passage of radionuclide *m* in Bq y m^{-3}, estimated by the NAME model;
- I_i is the breathing rate for age group *i* in m^3 y^{-1} (from Table A3.5 in Annex 3);
- de_{mi}^{inh} is the effective inhalation dose coefficient for age group *i* and radionuclide *m* in Sv Bq^{-1} (from Table A3.1 in Annex 3).

The thyroid dose T_i^{inh} of population age group *i* from inhalation of radioactive materials was calculated according to:

$$T_i^{inh} = I_i \cdot \sum_m T_m \cdot dt_{mi}^{inh}$$

where:

- dt_{mi}^{inh} is the thyroid inhalation dose coefficient for age group *i* and radionuclide *m* in Sv Bq^{-1} (from Table A3.1 in Annex 3).

The remaining symbols and parameter values are the same as above.

No protection is assumed due to being indoors for a proportion of the time.

References to Annex 7

1. Bedwell P et al. *Cloud gamma modelling in the UK Met Office's NAME III model*. Proceedings of the 13th Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes (HARMO13), 1–4 June 2010, Paris, France, H13–17.

Annex 8. Model for ingestion doses in Japan (Approach D)

1. Model for dose calculation

Both the effective and the thyroid doses were calculated by using the same approaches.

The effective dose E_i^{ing} of the population group *i* from ingestion of radioactive materials was calculated according to:

$$E_i^{ing} = \sum_{T=1}^{5} E_{Ti}^{ing} + 7\ E_{6i}^{ing}$$

and the monthly dose E_{Ti}^{ing} for month T is described by

$$E_{Ti}^{ing} = \sum_f F_{if} \sum_m C_{mfT} d_{mi}^{ing}$$

where

- the summation index m is for deposited radionuclides ^{134}Cs, ^{137}Cs and ^{131}I;
- the summation index f is for food groups;
- the summation T represents the month;
- the summation is done over the first five months, and the calculation for the sixth month is summed seven times to achieve the estimated first-year dose;
- F_{if} is the food consumption per month for population *i* and food group *f* (Table A8.1);
- C_{mfT} is the concentration of radionuclide *m* for food group *f* and month *T* (based on Table A8.2);
- d_{mi}^{ing} is the effective dose coefficient from ingestion for population group *i* and radionuclide *m* (Table A3.3 in Annex 3).

The thyroid dose was calculated using a similar equation, but replacing d_{mi}^{ing} by the thyroid dose coefficient from ingestion for population group *i* and radionuclide *m* (Table A3.4 in Annex 3).

Because the panel did not have the full distribution of food consumption, a deterministic approach was chosen with three scenarios detailed for each of the two following locations:

- Locations in Fukushima prefectures:
  1. Mean consumption * median radioactivity concentration
  2. Mean consumption * mean radioactivity concentration
  3. Mean consumption * 90th percentile radioactivity concentration.
- Locations in Japanese prefectures excluding Fukushima prefecture:
  4. Mean consumption * median radioactivity concentration
  5. 97.5th percentile consumption * median radioactivity concentration
  6. 97.5th percentile consumption * mean radioactivity concentration.

Food consumption (g/pers/day)

- Mean, standard deviation and 97.5th percentile were systematically extracted for each of the three age groups.
- Due to the lack of information regarding the mean consumption of one-year-old children, the mean consumption of children aged 1–6 years was used.

Radioactivity concentration (Bq/kg food)

- Mean, median, 90th percentile and maximum were systematically calculated for each of nine main food categories, each of the two locations (Fukushima prefecture and other prefectures) and each of the six months.
- Analytical results for food categories other than the nine main ones (e.g. spices, tea) were not used.

2. Input data

Food consumption data (g/pers/day)

The food consumption data are based on the 2009 National Health and Nutrition survey. The data were provided by the Japanese National Institute for Health and Nutrition, a national institution recognized by WHO.[1] It is given by age groups (see Table A8.1).

Table A8.1 Food consumption for the food groups considered in the assessment

	Per capita whole population						Consumers only
Age (years)	1–6		7–14		20 and over		15 and over
Food group (g/pers/day)	Mean	SD	Mean	SD	Mean	SD	97.5th percentile
Eggs	27	28	35	32	35	35	122
Fish and shellfish	36	40	53	52	87	80	275
Fruit	109	117	95	124	115	142	543
Meat	62	48	102	69	79	74	270
Milk	199	171	307	182	97	129	500
Mushrooms	8	15	13	19	17	29	121
Vegetables	140	95	244	121	290	171	696
Wheat/wheat products	71	72	107	98	100	109	396

1. According to the regulations for collaboration with national institutions recognized by WHO (accessible at http://apps.who.int/gb/bd/).
2. Food radioactivity concentration data (Bq/kg food)

Food radioactivity concentration data (Bq/kg food)

The food radioactivity concentration data was provided by Japan to INFOSAN,[3] a joint initiative of WHO and the FAO. This global network comprises 177 member states, including Japan.

Data on radioactivity concentration of ^{131}I, ^{134}Cs and ^{137}Cs were sorted into nine types of foodstuffs and tabulated with the following information:

- about 31 000 analytical results;
- food name;
- place of sampling (prefecture);
- date of sampling.

No information about analytical method/LOD[4] was provided.

3. For further information on the International Food Safety Authorities Network (INFOSAN), see: http://www.who.int/foodsafety/fs_management/infosan/en/.

4. LOD: limit of detection.

Table A8.2 Summary of radioactivity concentration for the first four months for ^{131}I in food (Bq/kg) (nd: not detected = < 10 Bq /kg)

		Fukushima				
	Month	N samples	Median	Mean	90th	Max
Food			Bq/kg	Bq/kg	Bq/kg	Bq/kg
Cereals excluding rice	1	no data	no data	no data	no data	no data
Eggs	1	17.00	nd	15.77	34.40	45.00
Fish and other sea-foods	1	13.00	13.00	1374.05	1660.00	12000.00
Fruits	1	40.00	nd	60.54	67.70	1400.00
Meats	1	42.00	nd	10.31	nd	19.00
Milks	1	150.00	34.00	207.86	372.00	5300.00
Mushrooms	1	89.00	16.00	290.21	332.00	12000.00
Vegetables	1	293.00	66.00	990.03	2480.00	22000.00
Cereals excluding rice	2	no data	no data	no data	no data	no data
Eggs	2	11.00	nd	nd	nd	nd
Fish and other sea-foods	2	28.00	nd	216.77	354.00	3900.00
Fruits	2	16.00	nd	10.34	nd	20.00
Meats	2	38.00	nd	nd	nd	nd
Milks	2	46.00	nd	10.34	nd	18.50
Mushrooms	2	92.00	nd	28.18	56.70	440.00
Vegetables	2	428.00	nd	17.32	18.30	750.00
Cereals excluding rice	3	no data	no data	no data	no data	no data
Eggs	3	no data	no data	no data	no data	no data
Fish and other sea-foods	3	164.00	nd	16.27	nd	820.00
Fruits	3	70.00	nd	nd	nd	nd
Meats	3	28.00	nd	nd	nd	nd
Milks	3	68.00	nd	nd	nd	nd
Mushrooms	3	26.00	nd	nd	nd	nd
Vegetables	3	543.00	nd	22.01	nd	2200.00
Cereals excluding rice	4	58.00	nd	nd	nd	nd
Eggs	4	11.00	nd	nd	nd	nd
Fish and other sea-foods	4	370.00	nd	nd	nd	nd
Fruits	4	201.00	nd	nd	nd	nd
Meats	4	296.00	nd	nd	nd	nd
Milks	4	63.00	nd	nd	nd	nd
Mushrooms	4	60.00	nd	nd	nd	nd
Vegetables	4	723.00	nd	10.11	nd	47.00

All prefectures				
N samples	Median	Mean	90th	Max
	Bq/kg	Bq/kg	Bq/kg	Bq/kg
no data	no data	no data	no data	no data
18.00	10	15.45	32.80	45.00
98.00	nd	351.64	911.00	12000.00
89.00	nd	38.69	59.75	1400.00
45.00	10	10.30	10.00	19.00
239.00	20.00	166.30	300.00	5300.00
96.00	nd	269.78	300.00	12000.00
1013.00	56.00	852.54	2080.00	54100.00
no data	no data	no data	no data	no data
12.00	nd	nd	nd	nd
192.00	nd	52.45	19.00	3900.00
44.00	nd	10.12	nd	20.00
40.00	nd	nd	nd	nd
135.00	nd	9.20	nd	18.50
159.00	nd	20.43	26.60	440.00
1016.00	nd	16.52	22.50	750.00
5.00	nd	nd	nd	nd
7.00	nd	nd	nd	nd
339.00	nd	13.22	nd	820.00
112.00	nd	nd	nd	nd
37.00	nd	nd	nd	nd
156.00	nd	nd	nd	nd
36.00	nd	nd	nd	nd
1164.00	nd	15.70	nd	2200.00
158.00	nd	nd	nd	nd
21.00	nd	nd	nd	nd
566.00	nd	nd	nd	nd
264.00	nd	nd	nd	nd
610.00	nd	nd	nd	nd
197.00	nd	nd	nd	nd
71.00	nd	nd	nd	nd
1435.00	nd	10.05	nd	47.00

Notes:

- When more than 50% of samples were below the limit of detection, the median is reported as “not detected” (nd) in the tables.
- When more than 90% of samples were below the limit of detection, the 90th percentile is reported as “not detected” (nd) in the tables.
- When all the samples were below the limit of detection, the mean and the maximum are reported as “not detected” (nd) in the tables.

Table A8.3 Summary of radioactivity concentration for the first 6 months for ^{134}Cs and ^{137}Cs in food for all prefectures

		^{134}Cs				
	Month	N samples	Median	Mean	90th	Max
Food			Bq/kg	Bq/kg	Bq/kg	Bq/kg
Cereals excluding rice	1	no data	no data	no data	no data	no data
Eggs	1	17	nd	nd	nd	nd
Fish and other sea-foods	1	14	nd	533	268	6200
Fruits	1	44	nd	19	19	170
Meats	1	24	nd	10	11	19
Milks	1	167	nd	11	nd	210
Mushrooms	1	89	nd	166	198	6400
Rice	1	no data	no data	no data	no data	no data
Vegetables	1	359	17	855	1720	41000
Cereals excluding rice	2	no data	no data	no data	no data	no data
Eggs	2	11	nd	nd	nd	nd
Fish and other sea-foods	2	35	71	409	944	7100
Fruits	2	16	nd	13	19	37
Meats	2	22	42	58	124	187
Milks	2	71	nd	11	nd	105
Mushrooms	2	97	51	194	474	3600
Rice	2	no data	no data	no data	no data	no data
Vegetables	2	481	nd	65	170	2600
Cereals excluding rice	3	2	nd	nd	nd	nd
Eggs	3	no data	no data	no data	no data	no data
Fish and other sea-foods	3	174	65	134	327	1400
Fruits	3	72	75	107	289	360
Meats	3	12	14	43	123	124
Milks	3	81	nd	nd	nd	nd
Mushrooms	3	26	68	237	680	1300
Rice	3	no data	no data	no data	no data	no data
Vegetables	3	550	nd	44	77	1500
Cereals excluding rice	4	102	nd	18	20	310
Eggs	4	14	nd	nd	nd	nd
Fish and other sea-foods	4	382	36	95	190	2100
Fruits	4	213	20	39	89	330
Meats	4	185	nd	49	59	1510
Milks	4	82	nd	nd	nd	nd
Mushrooms	4	60	nd	65	191	820
Rice	4	no data	no data	no data	no data	no data
Vegetables	4	849	nd	19	nd	1300

^{137}Cs			
Median	Mean	90th	Max
Bq/kg	Bq/kg	Bq/kg	Bq/kg
no data	no data	no data	no data
nd	nd	nd	nd
nd	544	281	6300
nd	19	31	170
nd	10	11	18
nd	11	nd	210
nd	169	210	6600
no data	no data	no data	no data
17	864	1820	41000
no data	no data	no data	no data
nd	nd	nd	nd
62	421	964	7300
nd	13	19	46
39	63	134	208
nd	15	nd	106
54	204	518	3600
no data	no data	no data	no data
nd	68	170	2800
nd	nd	nd	nd
no data	no data	no data	no data
69	145	367	1500
89	115	326	400
22	50	119	146
nd	nd	nd	nd
67	254	730	1400
no data	no data	no data	no data
nd	46	83	1600
nd	19	25	320
nd	nd	nd	nd
39	106	210	2300
20	42	93	370
nd	54	63	1730
nd	nd	nd	nd
nd	73	231	950
no data	no data	no data	no data
nd	20	nd	1500

		^{134}Cs				
	Month	N samples	Median	Mean	90th	Max
Food			Bq/kg	Bq/kg	Bq/kg	Bq/kg
Cereals excluding rice	5	79	nd	19	42	120
Eggs	5	5	13	nd	nd	nd
Fish and other sea-foods	5	294	30	66	180	830
Fruits	5	337	nd	25	23	1500
Meats	5	1293	nd	21	29	630
Milks	5	5	76	nd	9	nd
Mushrooms	5	72	nd	59	88	2200
Rice	5	592	nd	10	nd	27
Vegetables	5	405	nd	12	nd	390
Cereals excluding rice	6	114	nd	12	nd	150
Eggs	6	18	nd	nd	nd	nd
Fish and other sea-foods	6	798	12	42	89	1000
Fruits	6	558	nd	68	37	13000
Meats	6	4334	nd	13	nd	615
Milks	6	161	nd	9	nd	15
Mushrooms	6	495	nd	68	76	8900
Rice	6	2145	nd	11	nd	301
Vegetables	6	1121	nd	14	nd	943

^{137}Cs			
Median	Mean	90th	Max
Bq/kg	Bq/kg	Bq/kg	Bq/kg
nd	21	48	150
nd	nd	nd	nd
34	75	190	940
nd	28	28	1700
nd	24	35	710
nd	8	nd	nd
nd	68	136	2400
nd	10	nd	33
nd	12	nd	410
nd	13	nd	170
nd	nd	nd	nd
13	50	110	1200
nd	80	51	13000
nd	14	nd	790
nd	9	nd	20
nd	82	100	11000
nd	11	nd	367
nd	15	11	1100

Table A8.4 Summary of radioactivity concentration for the first 6 months for ^{134}Cs and ^{137}Cs in food for Fukushima prefecture

	^{134}Cs					
	Month	N samples	Median	Mean	90th	Max
Food			Bq/kg	Bq/kg	Bq/kg	Bq/kg
Cereals excluding rice	1	no data	no data	no data	no data	no data
Eggs	1	17	nd	nd	nd	nd
Fish and other sea-foods	1	13	nd	574	272	6200
Fruits	1	40	nd	20	21	170
Meats	1	24	nd	10	11	19
Milks	1	150	nd	12	nd	210
Mushrooms	1	89	nd	166	198	6400
Rice	1	no data	no data	no data	no data	no data
Vegetables	1	290	23	1022	2320	41000
Cereals excluding rice	2	no data	no data	no data	no data	no data
Eggs	2	11	nd	nd	nd	nd
Fish and other sea-foods	2	28	97	510	1330	7100
Fruits	2	15	nd	13	20	37
Meats	2	22	42	58	124	187
Milks	2	44	nd	nd	nd	nd
Mushrooms	2	92	59	204	504	3600
Rice	2	no data	no data	no data	no data	no data
Vegetables	2	428	nd	72	180	2600
Cereals excluding rice	3	no data	no data	no data	no data	no data
Eggs	3	no data	no data	no data	no data	no data
Fish and other sea-foods	3	164	68	142	330	1400
Fruits	3	70	79	110	291	360
Meats	3	12	14	43	123	124
Milks	3	64	nd	nd	nd	nd
Mushrooms	3	26	68	237	680	1300
Rice	3	no data	no data	no data	no data	no data
Vegetables	3	516	nd	46	115	1500
Cereals excluding rice	4	58	nd	21	28	310
Eggs	11	nd	nd	nd	nd	nd
Fish and other sea-foods	4	364	38	100	200	2100
Fruits	4	201	21	41	91	330
Meats	4	138	nd	56	65	1510
Milks	4	55	nd	nd	nd	nd
Mushrooms	4	60	nd	65	191	820
Rice	4	no data	no data	no data	no data	no data
Vegetables	4	718	nd	19	nd	1300

^{137}Cs			
Median	Mean	90th	Max
Bq/kg	Bq/kg	Bq/kg	Bq/kg
no data	no data	no data	no data
nd	nd	nd	nd
nd	585	284	6300
nd	20	32	170
nd	10	11	18
nd	12	nd	210
nd	169	210	6600
no data	no data	no data	no data
19	1032	2330	41000
no data	no data	no data	no data
nd	nd	nd	nd
98	524	1360	7300
nd	13	21	46
39	63	134	208
nd	nd	nd	nd
63	214	528	3600
no data	no data	no data	no data
nd	75	193	2800
no data	no data	no data	no data
no data	no data	no data	no data
77	153	377	1500
89	118	330	400
22	50	119	146
nd	nd	nd	nd
67	254	730	1400
no data	no data	no data	no data
nd	48	108	1600
nd	23	27	320
nd	nd	nd	nd
42	111	220	2300
22	44	99	370
nd	62	77	1730
nd	nd	nd	nd
nd	73	231	950
no data	no data	no data	no data
nd	21	nd	1500

	^{134}Cs					
	Month	N samples	Median	Mean	90th	Max
Food			Bq/kg	Bq/kg	Bq/kg	Bq/kg
Cereals excluding rice	5	64	nd	21	52	120
Eggs	5	11	nd	nd	nd	nd
Fish and other sea-foods	5	261	38	74	190	830
Fruits	5	290	nd	27	24	1500
Meats	5	83	nd	30	59	412
Milks	5	40	nd	nd	nd	nd
Mushrooms	5	71	nd	60	89	2200
Rice	5	37	nd	10	nd	11
Vegetables	5	327	nd	13	nd	390
Cereals excluding rice	6	108	nd	13	nd	150
Eggs	6	11	nd	nd	nd	nd
Fish and other sea-foods	6	491	26	60	120	1000
Fruits	6	463	nd	80	50	13000
Meats	6	1024	nd	14	12	610
Milks	6	50	nd	nd	nd	nd
Mushrooms	6	338	nd	84	72	8900
Rice	6	1189	nd	11	11	220
Vegetables	6	781	nd	16	17	940

^{137}Cs			
Median	Mean	90th	Max
Bq/kg	Bq/kg	Bq/kg	Bq/kg
nd	23	58	150
nd	nd	nd	nd
42	83	200	940
nd	31	31	1700
nd	34	66	496
nd	nd	nd	nd
nd	69	140	2400
nd	10	nd.4	12
nd	13	nd	410
nd	13	nd.3	170
nd	nd	nd	nd
32	72	140	1200
nd	94	60	15000
nd	15	14	790
nd	nd	nd	nd
nd	102	96	11000
nd	12	12	250
nd	17	17	1100

3. Assumptions

- For calculations, results below limits of quantification were replaced by 10 Bq/kg.
- Dose coefficients (for converting Bq into mSv) were standard ICRP values based on the default chemical form.
- Total effective dose and thyroid dose were calculated for six months and extrapolated to one year.

For children of 1 and 10 years of age, the 97.5th percentiles for consumption were not available and the average +2 standard deviation value of the two highest contributing food categories, which were fish and vegetables, plus the mean of other food categories were used as a surrogate. The calculated values were compared with the 97.5th percentile of consumption of children less than 15 years of age reported in the Japanese national survey and consistency between them was confirmed.

For fish, the calculated high consumption at 1 and 10 years of age and the reported high consumption of children less than 15 years are respectively 116, 157 and 177 g d^{-1}.

For vegetables, the calculated high consumption at 1 and 10 years of age and the reported high consumption of children below 15 are respectively 330, 486 and 500 g d^{-1}.

Annex 9. Model for ingestion doses outside Japan (Approach E)

1. Model for dose estimation

The effective dose E_i^{ing} of the population age group *i* from ingestion of radioactive materials was calculated according to:

$$E_i^{ing} = \sum_f F_f \sum_m A_m c_{mf} de_{mi}^{ing}$$

where

- the summation index *m* is for deposited radionuclides;
- the summation index *f* is for food categories;
- F_f is the annual food consumption rate for food category *f* (Table A9.1);
- A_m is the surface activity density of radionuclide *m* on the ground;
- C_{mf} is the radionuclide concentration factor for food category *f* of radionuclide *m* (based on Table A9.2 and Table A9.3 in Annex 9);
- de_{mi}^{ing} is the effective ingestion dose coefficient for population age group *i* and radionuclide *m* (Table A3.3 in Annex 3).

Note that the food consumption F_f is based on average consumption weighted for total population and so represents the average over all age groups. For this reason, the same consumption was applied to all age groups.

The estimates of surface activity densities were derived from the NAME model (*1*), and the radionuclide concentration factors were derived from the food chain model FARMLAND (*2*).

The thyroid dose T_i^{ing} for the population age group *i* from deposited radionuclides, in Sv, was calculated as follows:

$$T_i^{ing} = \sum_f F_f \sum_m A_m c_{mf} dt_{mi}^{ing}$$

where

- dt_{mi}^{ing} is the thyroid ingestion dose coefficient for population age group *i* and radionuclide *m* (Table A3.4 in Annex 3).

The remaining symbols and parameter values are the same as above.

2. Input data

Food consumption

The food consumption for the assessment of food doses in the rest of the world excluding Japan (used in conjunction with the source term and dispersion-based part of the assessment) were selected from the WHO GEMS data (*3*). Cluster diet G was selected

and the details are shown below in Table A9.1. The food consumption is based on average consumption weighted for total population and so represents the average over all age groups. For this reason, the same consumption was applied to all age groups.

Table A9.1 Food consumption for the world outside Japan

Food category	Average consumption for cluster diet G (kg per person per year)
Cereals	225.2
Green vegetables	114.2
Root vegetables	43.7
Orchard fruit	53.1
Soft fruit	1.0
Milk	15.3
Beef	2.5
Lamb	0.7

Source: WHO GEMS/Food consumption cluster diets, August 2006 (3).

Note: The precision to which these numbers are quoted is based on the precision of the source data.

Food radioactivity concentration

Activity concentrations in food per unit deposit were used in conjunction with the source term and dispersion-based part of the assessment. A subset of the radionuclides has been considered for the radionuclides making the most significant contribution to the dose.

Food concentration factors have been taken from the food chain model FARMLAND. These data are based on unit deposition (per Bq m^{-2}) in early summer which is considered to be cautious. The FARMLAND factors are representative of United Kingdom annual average conditions (somewhere between “wet” and “dry” deposition). The radionuclides included below are those which are, in general, potentially of significance for the ingestion dose pathway. However, in the case of the Fukushima release, most of these will make only very small contributions as the great majority of the ingestion dose will derive from the radionuclides of iodine and caesium.

Table A9.2 Time-integrated activity concentration factors in food to 1 year

Radionuclide	Cereals (Bq y /kg per Bq m^{-2})	Green vegetables (Bq y /kg per Bq m^{-2})	Root vegetables (Bq y /kg per Bq m^{-2})	Orchard fruit (Bq y /kg per Bq m^{-2})
^{103}Ru	1.78 10^{-6}	2.27 10^{-3}	2.54 10^{-6}	1.05 10^{-6}
^{106}Ru	2.88 10^{-5}	2.91 10^{-3}	1.49 10^{-5}	2.05 10^{-5}
^{127m}Te	3.54 10^{-3}	3.24 10^{-3}	3.21 10^{-3}	1.99 10^{-3}
^{129m}Te	3.55 10^{-4}	2.52 10^{-3}	1.47 10^{-3}	1.67 10^{-4}
^{131m}Te	2.02 10^{-12}	6.37 10^{-4}	1.11 10^{-5}	6.28 10^{-14}
^{131}I	2.06 10^{-7}	1.25 10^{-3}	1.79 10^{-4}	1.79 10^{-3}
^{132}I	2.25 10^{-32}	2.26 10^{-5}	3.70 10^{-43}	8.59 10^{-34}
^{133}I	1.73 10^{-19}	1.94 10^{-4}	9.13 10^{-10}	5.53 10^{-9}
^{135}I	3.58 10^{-27}	6.42 10^{-5}	1.36 10^{-35}	2.08 10^{-28}
^{134}Cs	1.09 10^{-2}	3.66 10^{-3}	5.57 10^{-3}	6.43 10^{-3}
^{137}Cs	1.32 10^{-2}	3.74 10^{-3}	6.23 10^{-3}	7.85 10^{-3}
^{140}Ba	1.56 10^{-7}	1.52 10^{-3}	4.04 10^{-7}	1.28 10^{-7}
^{144}Ce	1.68 10^{-5}	2.87 10^{-3}	1.35 10^{-6}	9.98 10^{-6}

Source: data from implementation of the FARMLAND model (2) by the UK's Health Protection Agency.

Table A9.3 Time-integrated activity concentration factors in food to 1 year

Radionuclide	Soft fruit (Bq y /kg per Bq m^{-2})	Milk (Bq y /kg per Bq m^{-2})	Beef (Bq y /kg per Bq m^{-2})	Lamb (Bq y /kg per Bq m^{-2})
^{103}Ru	1.02 10^{-4}	7.74 10^{-7}	1.01 10^{-4}	1.63 10^{-4}
^{106}Ru	1.75 10^{-4}	1.76 10^{-6}	6.16 10^{-4}	6.33 10^{-4}
^{127m}Te	2.59 10^{-2}	5.74 10^{-4}	4.85 10^{-3}	6.79 10^{-3}
^{129m}Te	1.38 10^{-2}	3.69 10^{-4}	2.37 10^{-3}	4.09 10^{-3}
^{131m}Te	1.17 10^{-4}	1.20 10^{-4}	1.82 10^{-4}	2.42 10^{-4}
^{131}I	3.86 10^{-8}	1.84 10^{-3}	7.84 10^{-4}	1.00 10^{-3}
^{132}I	0.00 10^{0}	5.18 10^{-7}	1.15 10^{-7}	5.23 10^{-8}
^{133}I	4.10 10^{-21}	1.20 10^{-4}	3.51 10^{-5}	2.15 10^{-5}
^{135}I	0.00 10^{0}	9.77 10^{-6}	2.48 10^{-6}	1.21 10^{-6}
^{134}Cs	3.42 10^{-2}	9.86 10^{-3}	4.76 10^{-2}	4.36 10^{-2}
^{137}Cs	3.58 10^{-2}	1.12 10^{-2}	5.52 10^{-2}	4.59 10^{-2}
^{140}Ba	1.75 10^{-4}	2.74 10^{-4}	7.59 10^{-5}	1.20 10^{-4}
^{144}Ce	1.56 10^{-4}	1.61 10^{-4}	5.08 10^{-5}	5.41 10^{-5}

Source: data from implementation of the FARMLAND model (2) by the UK's Health Protection Agency.

3. Assumptions

The FARMLAND results applied in the assessment assume that the release occurred in early summer. This is a cautious assumption for many regions of the northern hemisphere for an accident occurring in mid-March, but it was chosen because agricultural practices around the world vary; in some southerly regions more food production and harvesting may have occurred than in more northerly regions.

References to Annex 9

1. Jones AR et al. The UK Met Office's next-generation atmospheric dispersion model, NAME III. In: Borrego C, Norman A-L, eds. *Air pollution modeling and its application XVII (Proceedings of the 27th NATO/CCMS International Technical Meeting on Air Pollution Modelling and its Application).* New York, NY, Springer, 2007 (pages 580–589).

2. Brown J, Simmonds JR. *FARMLAND: a dynamic model for the transfer of radionuclides through terrestrial foodchains*. (NRPB-R273). Chilton, UK National Radiological Protection Board, 1995.

3. *Global Environmental Monitoring System. Food contamination monitoring and assessment programme. GEMS/Food consumption cluster diets*. Geneva, World Health Organization, 2006 (http://www.who.int/foodsafety/chem/gems/en/index1.html, accessed 13 May 2012).

PRELIMINARY DOSE ESTIMATION

The earthquake and tsunami in Japan on 11 March 2011 led to releases of radioactive material into the environment from the Tokyo Electric Power Company's Fukushima Daiichi nuclear power station. This report provides a preliminary estimation of the anticipated scale of doses received by members of the public around the world for the first year after the accident.
It represents the first international effort to assess global radiation doses from the Fukushima Daiichi nuclear power plant accident considering all major exposure pathways.

Public Health and Environment Department (PHE)
Health Security and Environment Cluster (HSE)
World Health Organization (WHO)
Avenue Appia 20 – CH-1211 Geneva 27
Switzerland
www.who.int/phe

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