Dose Assessment of External Exposure

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NIRS

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Exposure to External Radiation

Dose depends on the absorbed energy at the exposure
Relationship among Quantities

**Physical Quantities**
- Fluence: $\Phi$
- Kerma: $K$
- Absorbed dose: $D$

**Operational Quantities**
- Ambient dose equivalent: $H^*(d)$
- Directional dose equivalent: $H'(d,\Omega)$
- Personal dose equivalent: $H_p(d)$

**Protection Quantities**
- Absorbed Dose: $D_T$
- Equivalent Dose: $H_T$
- Effective Dose: $E$

Calibration and calculation

Quantities of monitoring
Responses of equipment
Effective Dose (ICRP Publ. 103)

Radionuclide Intake & External Exposure

Male phantom Absorbed Doses, $D_T^M$

Female phantom Absorbed Doses, $D_T^F$

Equivalent doses, $H_T^M$

Equivalent doses, $H_T^F$

Sex-averaged equivalent doses, $H_T$

Effective dose, $E$

Reference Male

$W_R$

Reference Female

$W_T$

Reference Person
Phantom

MIRD phantom

Voxel phantom
ICRP Publication 110 (2009)

Adult Reference Computational Phantoms (Adult male and female)

Files of CD:
- Array of Organ ID numbers
- List of individually segmented structures
- List of the media, their elemental compositions, and densities
- Mass ratios of bone constituents
- Mass ratios of blood in various body tissues
External Exposure: Measurement of Organ Dose

Measurement: Organ Doses (physical quantity)
Effective Dose (protection quantity)

Phantom

Example:

Dosimeters (glass)

Measurement by using an anthropomorphic phantom and dosimeters such as glasses or TLDs
External Exposure: Environmental Monitoring

Measurement: Ambient Dose Equivalent (operational quantity)

Ionization Chamber
Expanded and Aligned Field, ICRU sphere (diameter: 30cm)

GM

Scintillation

\[
d=1\text{cm} : 1\text{cm dose equivalent} \\
(\text{For estimation of effective dose})
\]

\[
d=70\mu\text{m} : 70\mu\text{m dose equivalent} \\
(\text{For estimation of equivalent dose of skin})
\]
External Exposure: Personal Monitoring

Measurement: Personal Dose Equivalent (operational quantity)

Glass Badge

Quixel Badge

30 cm × 30 cm × 15 cm ICRU Slab Phantom

d=1cm: 1cm dose equivalent
(For estimation of effective dose)

d=70μm: 70μm dose equivalent
(For estimation of equivalent dose of skin)
External Exposure: Simulation

(Referred from ICRP Publ. 74)
External Exposure: Simulation

(Referred from ICRP Publ. 116)
External Exposure - Fukushima -
“Fukushima Health Management Survey” has been performed by Fukushima prefectural government and Fukushima Medical University after the accident.

- **Basic Survey**
  - Subject: All residents in Fukushima
  - Method: Survey sheet
  - Contents: Behaviors after 11 March 2011

- **Health Management file**
  - Record of the results of health check
  - Information on radiation

- **Database**
  - Use for the health management and therapy
  - Knowledge for the next generation

- **Thyroid Examination**
  - Subject: All residents of 18yrs and under
  - Contents: Ultrasound examination

- **Health Check**
  - Subject: evacuation area residents, persons who need the check based on the basic survey
  - Contents: general issues, differential white blood count

- **Survey on the mental health and lifestyle**

- **Survey for the expectant and nursing mothers**

- **Consultation, Support**

- **Flow-up**

- **Therapy**
Estimation of External Exposure

The external exposures of the residents in Fukushima prefecture have been estimated by using external exposure calculation system developed by NIRS.

Behaviors of the residents

Dose rate maps

Coefficients (shield, age, etc.)

External exposure (effective dose)
Data on the behavior of the residents in the survey sheet are digitized and anonymized, and inputted into the NIRS calculation system for estimating external doses.

**Period:** March 12, 2011 – July 11, 2011

**Items:** Behaviors of each day in the period
- indoor, moving, outdoor places, from and to where

**Data:** Digitized and anonymized in Fukushima Medical Univ. and sent to NIRS
Dose Rate Maps

- **Data used**
  - March 12 - 14: Results of SPEEDI (effective dose rates)
  - After March 16: Monitoring data by MEXT (Ambient dose equivalent rates -> effective dose rates)
  - March 15: Used dose rate map of March 16 based on the monitoring data (because of insufficient data)
  - Conservative estimation except south and southwest area of the NPP, Only about 11 μSv underestimation for the south and southwest area of the NPP

- **Size of meshes**
  - Almost 2 km \( \times \) 2 km corresponding to the size divided the second mesh defined by Geospatial Information Authority of Japan (The SPEEDI mesh size 1 km \( \times \) 1km was reconstructed to 2 km \( \times \) 2km).

- **Averaged dose rate calculation**
  - Interpolate discrete data using a software

- **Excluded background dose rate**
  - Subtracted background effective dose rate before accident
Dose Quantities in Radiation Protection: Conversion to effective dose for adult

Physical Quantities

Absorbed Dose, $D$ [Gy, J/kg], etc.

Equivalent Dose $H_T$ [Gy, J/kg]

Effective Dose $E$ [Sv]

Operational Quantities

Ambient Dose Equivalent, $H^{*}(10)$ [Sv]

Personal Dose Equivalent, $H_p(10)$ [Sv], etc.

MEXT monitoring data

Protection Quantities

Operational Quantities > Protection Quantities (avoiding underestimation)

<table>
<thead>
<tr>
<th>Nuclide, $X$</th>
<th>Xe-133</th>
<th>Te-129m</th>
<th>Te-132</th>
<th>I-131</th>
<th>I-132</th>
<th>Cs-134</th>
<th>Cs-137</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_x$</td>
<td>0.44</td>
<td>0.58</td>
<td>0.48</td>
<td>0.53</td>
<td><strong>0.59</strong></td>
<td>0.58</td>
<td>0.57</td>
</tr>
</tbody>
</table>
The background before the accident is based on the reported data by Fukushima prefectural government (6 cities and 1 town).

**Background effective dose rate in the normal situation:** 0.03 μSv/h

**Air Kerma Rates**

<table>
<thead>
<tr>
<th>Fukushima city</th>
<th>Koriyama city</th>
<th>Shirakawa city</th>
<th>Aizuwa kamats city</th>
<th>Minamiaizu town</th>
<th>Minamisoma city</th>
<th>Taira in Iwaki city</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.04</td>
<td>0.04-0.06</td>
<td>0.04-0.05</td>
<td>0.04-0.05</td>
<td>0.02-0.04</td>
<td>0.05</td>
<td>0.05-0.06</td>
</tr>
</tbody>
</table>

- The conversion coefficients from air kerma to effective dose were calculated by using the same method of the conversion from ambient dose equivalent to effective dose \( \Rightarrow 0.75 \) [Sv/Gy].
- Adopted \( 0.04 \times 0.75 = 0.03 \) μSv/h as the background effective dose rate in the normal situation.
Examples of the Dose Rate Maps

March 12 → March 13 → March 14 → March 15

April 14 → May 14 → June 14 → July 11
Calculate effective doses based on the behavior data and dose rate maps (indoor + outdoor + moving)

March 12-14: factors of cloud shine, After: factors of ground shine

### Buildings or houses

<table>
<thead>
<tr>
<th>Building Type</th>
<th>March 12-14</th>
<th>March 15 or later</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoor or moving</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Indoor: one or two story wood frame house</td>
<td>0.9</td>
<td>0.4</td>
</tr>
<tr>
<td>Indoor: one or two story concrete house or building</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>Indoor: three or more story concrete building</td>
<td>0.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

### Calculation Formula

\[
\text{Effective Dose} = \left( \frac{\text{Effective dose rate in the concerned day in the resion (μSv/h)}}{\text{Hours of indoor (h)}} \times \text{Dose reduction coefficient} \right) + \left( \frac{\text{Effective dose rate in the concerned day in the resion after moving (μSv/h)}}{\text{Hours of outdoor (h)}} \right) \times 2
\]
Calculation of Cumulated Effective Dose: Body size correction with age coefficients

As the age is lower, the conversion coefficient per gamma ray is higher, because the volume of the upper layer of the body increases as the body size is bigger. Hence, effective dose per ambient dose equivalent is higher as the age is lower.

The effective dose for infants and children can be calculated based on the ratio to adults.

Conversion coefficients for each age group were estimated by using a linear function.

\[ y = -0.0144x + 1.27 \]

<table>
<thead>
<tr>
<th>Nuclide, ( X )</th>
<th>Age</th>
<th>0</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe-133</td>
<td>1.30</td>
<td>1.23</td>
<td>1.16</td>
<td>1.11</td>
<td>1.01</td>
<td></td>
</tr>
<tr>
<td>Te-129m</td>
<td>1.29</td>
<td>1.21</td>
<td>1.15</td>
<td>1.10</td>
<td>1.03</td>
<td></td>
</tr>
<tr>
<td>Te-132</td>
<td>1.36</td>
<td>1.26</td>
<td>1.19</td>
<td>1.13</td>
<td>1.06</td>
<td></td>
</tr>
<tr>
<td>I-131</td>
<td>1.33</td>
<td>1.24</td>
<td>1.18</td>
<td>1.12</td>
<td>1.05</td>
<td></td>
</tr>
<tr>
<td>I-132</td>
<td>1.29</td>
<td>1.21</td>
<td>1.15</td>
<td>1.11</td>
<td>1.04</td>
<td></td>
</tr>
<tr>
<td>Cs-134</td>
<td>1.29</td>
<td>1.21</td>
<td>1.16</td>
<td>1.11</td>
<td>1.04</td>
<td></td>
</tr>
<tr>
<td>Cs-137</td>
<td>1.30</td>
<td>1.21</td>
<td>1.16</td>
<td>1.10</td>
<td>1.04</td>
<td></td>
</tr>
<tr>
<td>Max.</td>
<td>1.36</td>
<td>1.26</td>
<td>1.19</td>
<td>1.13</td>
<td>1.06</td>
<td></td>
</tr>
</tbody>
</table>
For grasping the exposure levels of the external doses of the residents, 18 evacuation patterns were assumed by NIRS before using the survey data of the residents.

<table>
<thead>
<tr>
<th>Evacuations</th>
<th>The places from where the residents started to evacuate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>18 patterns were made referring actual evacuation information</strong></td>
<td>The places from where the residents started to evacuate were 2 kinds;</td>
</tr>
<tr>
<td><strong>Assumption of moving</strong></td>
<td><strong>• the public area such as town office</strong></td>
</tr>
<tr>
<td>• 10km/h for the moving inside the prefecture</td>
<td><strong>• the places where the doses were highest until when they evacuated</strong></td>
</tr>
<tr>
<td>• 30km/h for those from Fukushima to other prefectures.</td>
<td></td>
</tr>
<tr>
<td>• After April: the ordinary traffic conditions</td>
<td></td>
</tr>
<tr>
<td><strong>Assumption of outdoor</strong></td>
<td></td>
</tr>
<tr>
<td>the residents behaved:</td>
<td></td>
</tr>
<tr>
<td>• 4 hours until the evacuations</td>
<td></td>
</tr>
<tr>
<td>• 2hours in their evacuated places</td>
<td></td>
</tr>
</tbody>
</table>
Restrict area, Deliberate evacuation area, and Evacuation-prepared area in case of emergency

1. Within 20km
   - all area: Tomioka town, Okuma town, Futaba town
   - a part: Naraha town, Namie town, Tamura city, Minami-soma city, Hirono town, Kawauchi village, Katsurao village

2. Deliberate evacuation area
   - all area: Iitate village
   - a part: Namie town, katsurao village, Minamisoma city Kawamata town
From the area within 20km

- Futaba Town Office (ID: 3,4)
- Okuma Town Office (ID: 2)
- Tomioka Town Office (ID: 1)
- Kawauchi Village Office (ID: 1)
- Big Palette Fukushima (ID: 3,4)
- Funabiki Shugyo-kaizen Center (ID: 2)
- Kawamata Elementary School (ID: 3,4)
- Saitama Super Arena (ID: 3,4)

Fukushima Prefecture

Former Kisai High School (ID: 2)
From the area within 20km

Fukushima Prefecture
From the area within 20km:

- ID: 9
  Date City Office
  3/15

- ID: 10
  Ono Town
  Office
  3/12

- ID: 11
  Kawauchi Village
  Elementary School
  3/16

- ID: 12
  Big Palette Fukushima
  3/16

- ID: 8
  Denso East
  3/12

- ID: 9
  Minami Soma City
  (Evacuation Area)

- ID: 12
  Katsurao Village
  (Evacuation Area)

- ID: 8
  Tamura City
  (Evacuation Area)

- ID: 11
  Kawauchi Village
  (Evacuation Area)

- ID: 10
  Hirono Town
  (Evacuation Area)
From the deliberate evacuation area

Fukushima Prefecture
18 model cases: results

From the area within 20km

From deliberate evacuation area

Representative Place

mSv

Pattern number
“Fukushima Health Management Survey” has been performed by Fukushima prefectural government and Fukushima Medical University after the accident.

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Use for the health management and therapy
Knowledge for the next generation

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- Contents: general issues, differential white blood count

**Survey on the mental health and lifestyle**
Survey for the expectant and nursing mothers

**Consultation, Support**
**Flow-up**

**Fukushima Health Management Survey**
**Grasp the doses**
**Grasp the health condition**

**Therapy**
 Estimated External Doses as of 2013 July 31 (including radiation workers)

445,015 persons including radiation workers

- < 1 mSv: 65.8%
- < 2 mSv: 94.7%
- < 5 mSv: 99.6%
- Max.: 66 mSv

Referred from the report of Fukushima prefecture (in Japanese)
Estimated External Doses as of 2013 July 31 (excluding radiation workers)

435,788 persons excluding radiation workers

- < 1mSv: 65.9%
- < 2mSv: 94.8%
- < 5mSv: 99.8%
- Max.: 25mSv

Referred from the report of Fukushima prefecture (in Japanese)
Estimated External Doses as of 2013 July 31 (excluding radiation workers)

Data of each area

Number of the residents

mSv

Referred from the report of Fukuhsima prefecture (in Japanese)
Estimated External Doses as of 2013 July 31 (excluding radiation workers)

Data of each age group

Referred from the report of Fukuhsima prefecture (in Japanese)
Uncertainties

Algorism

Parameters

Dose rate maps
  Source terms, Codes, Measurements, Lack of the data, Mapping, etc.
Evacuation activities of the residents
  Insufficient or imprecise data in the survey sheets
Coefficients in the calculations
  Dose quantities, age, body sizes, etc.

The estimated doses show not precise exposures but dose levels of the residents
The local governments in Fukushima prefecture have been distributing personal dosemeters for the residents.

**Fukushima city:**
Nov 2012 ~ Jan 2013
for the children (0-15y)

<table>
<thead>
<tr>
<th>Dose (mSv)</th>
<th>No. of Residents</th>
<th>Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.1</td>
<td>2,888</td>
<td>17.8</td>
</tr>
<tr>
<td>&lt;0.5</td>
<td>13,127</td>
<td>80.9</td>
</tr>
<tr>
<td>&lt;1.0</td>
<td>203</td>
<td>1.25</td>
</tr>
<tr>
<td>&lt;1.5</td>
<td>2</td>
<td>0.012</td>
</tr>
<tr>
<td>&lt;2.0</td>
<td>2</td>
<td>0.012</td>
</tr>
<tr>
<td>&lt;2.5</td>
<td>1</td>
<td>0.006</td>
</tr>
<tr>
<td>Sum</td>
<td>16,223</td>
<td>100</td>
</tr>
</tbody>
</table>

Referred from the website of Fukushima city (in Japanese)

**Date city:**
Jul 2012 ~ Mar 2013
for the all residents

<table>
<thead>
<tr>
<th>Specific Spots Recommended for Evacuation</th>
<th>Effective Dose (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of residents</td>
<td>Average of 3 months</td>
</tr>
<tr>
<td>2,396</td>
<td>0.8</td>
</tr>
<tr>
<td>Other Area</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Referred from the report of Date city (in Japanese)
Minamisoma city:  
Jun 2012 ~ Nov 2012  
for the residents (pregnant women, 0-18y children)

Referred from the report of Minamisoma city (in Japanese)  
Recent Data on Environmental Radioactivity Levels

Airborne monitoring: Air dose rates map of the evacuation-directed zones (Air dose rates at the height of 1m above the ground surface, as of March 11, 2013)

[Map image]

Environmental Radioactivity Levels:

Example:
Iitate village on 26 Aug. 2013 at 15:30

[Map image]

Referred from the report of Nuclear Regulation Authority

Referred from the website of Nuclear Regulation Authority (in Japanese)
http://radioactivity.nsr.go.jp/map/ja/area.html
Decontamination
The “Act on Special Measures Concerning the Handling of Radioactive Pollution” was enacted in August 2011, in response to the unprecedented situation of radioactive pollution after the accident at TEPCO’s Fukushima Daiichi Nuclear Power Station.

With the “Basic Principles” and related orders for handling radioactive pollution established by the end of the year, the Act came fully into force on January 1, 2012.

Thus, a new policy framework for the off-site decontamination has been arranged, under which decontamination works have been steadily implemented under the responsibility of the national government.

Referral:
Special Decontamination Area

Area designation by the Minister of the Environment

- 11 Municipalities in (former) restricted zone or planned evacuation zone

Formulation of decontamination plan by the Minister of the Environment

- Specify principle and goal for implementation of measures for decontamination
- Consult with the heads of related administrative bodies
- Hear the opinions of the heads of local government

Implementation of measures for decontamination by the National Government

- Implemented by the Ministry of the Environment in cooperation with relevant ministers

Referred from the web of Ministry of the Environment
Intensive Contamination Survey Area

Designation of an intensive survey area by the Minister of the Environment

- Areas where the dose rate is over 0.23 μSv/h (equivalent to over 1mSv/y of additional dose).
- 104 municipalities in 8 prefectures (Iwate, Miyagi, Fukushima, Ibaraki, Tochigi, Gunma, Saitama and Chiba).

Surveys and measurement of the contamination status by the heads of the municipalities, etc.

Implementation of decontamination and other measures by the heads of the municipalities, in accordance with their decontamination plans

Formulation of decontamination plans by the heads of the municipalities, etc.

Organizations responsible for taking measures
- Land under national control: National Government
- Land under prefectural control: Prefectural governor
- Land under municipal control: Head of the municipality
- Land under independent control: independent administrative agency
- Other land: Head of the municipality

Decontamination policy for special decontamination area

Policy in FY 2012 and 2013

Area 1: <20mSv/yr
Aiming for reducing additional exposure dose less than 1mSv/yr as long-term goal.

Area 2: 20-50mSv/yr
Aiming for reducing exposure dose in residential and farmland area less than 20mSv/yr by the end of FY 2013.

Area >50mSv/yr
Demonstration projects will be implemented. Lessons learned will be reflected into future decontamination policy.

Policy after FY 2014

• Aiming for reducing additional exposure dose less than 1mSv/yr as long-term goal.
• Check and evaluate two-year decontamination results, consider proper actions, and revise implementation plans as needed.

Refereed from the web of Ministry of the Environment
## Progress in the Special Decontamination Area

<table>
<thead>
<tr>
<th>Progress Status</th>
<th>Preliminary Decontamination</th>
<th>Full Scale Decontamination Work</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Plan</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temporary Storage Site</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Decontamination Work</td>
</tr>
<tr>
<td>on full-scale decontamination work/on plan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tamura city</td>
<td>2012 Apr. 13</td>
<td>secured</td>
</tr>
<tr>
<td>Naraha town</td>
<td>2012 Apr. 13</td>
<td>secured</td>
</tr>
<tr>
<td>Kawauchi village</td>
<td>2012 Apr. 13</td>
<td>secured</td>
</tr>
<tr>
<td>Iitate village</td>
<td>2012 May 24</td>
<td>partially secured</td>
</tr>
<tr>
<td>Kawamata town</td>
<td>2012 Aug. 10</td>
<td>partially secured</td>
</tr>
<tr>
<td>Katsurao village</td>
<td>2012 Sep. 28</td>
<td>partially secured</td>
</tr>
<tr>
<td>Okuma town</td>
<td>2012 Dec. 28</td>
<td>secured</td>
</tr>
<tr>
<td>Minami-Soma city</td>
<td>2012 Apr. 18</td>
<td>partially secured</td>
</tr>
<tr>
<td>Tomioka town</td>
<td>2013 Jun. 26</td>
<td>partially secured</td>
</tr>
<tr>
<td>Prepared to order</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Namie town</td>
<td>2012 Nov. 21</td>
<td>under coordination process</td>
</tr>
<tr>
<td>Plans not yet formulated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Futaba town</td>
<td>2012 Nov. 21</td>
<td>under coordination process</td>
</tr>
</tbody>
</table>

Example: Tamura city
## Progress in Intensive Contamination Survey Area

<table>
<thead>
<tr>
<th>In Fukushima pref. (As of the end of Jan. 2013)</th>
<th>Ordering Ratio</th>
<th>Implementation Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public facility, etc.</td>
<td>more than 90%</td>
<td>approx. 75%</td>
</tr>
<tr>
<td>Residence</td>
<td>approx. 80%</td>
<td>approx. 60%</td>
</tr>
<tr>
<td>Road</td>
<td>approx. 75%</td>
<td>approx. 61%</td>
</tr>
<tr>
<td>Farmland &amp; meadow</td>
<td>approx. 80%</td>
<td>approx. 62%</td>
</tr>
<tr>
<td>Forest (living area)</td>
<td>nearly 20%</td>
<td>less than 10%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>School, nursery school</td>
<td>almost ordered</td>
<td>more than 80%</td>
</tr>
<tr>
<td>Park, sports facility</td>
<td>approx. 80%</td>
<td>approx. 60%</td>
</tr>
<tr>
<td>Residence</td>
<td>approx. 40%</td>
<td>approx. 20%</td>
</tr>
<tr>
<td>Public facility, etc.</td>
<td>approx. 70%</td>
<td>approx. 70%</td>
</tr>
<tr>
<td>Road</td>
<td>approx. 60%</td>
<td>approx. 60%</td>
</tr>
<tr>
<td>Farmland &amp; meadow</td>
<td>approx. 70%</td>
<td>approx. 30%</td>
</tr>
<tr>
<td>Forest (living area)</td>
<td>Partially ordered</td>
<td>Partially implemented</td>
</tr>
</tbody>
</table>

Plans are as of the end of FY2012.

Referred from the web of Ministry of the Environment
External Exposure

Estimation

- Measurement
  - Protection quantity
    - Effective dose (E), Equivalent dose: Anthropomorphic phantom, dosemeters
  - Operational quantity
    - Personal dose equivalent Hp(d): Personal dosemeters
    - Ambient dose equivalent H*(d): Survey meters etc.
    *In general, H_p(10), H*(10) > E
- Calculation (Simulation)
  - MIRD type phantoms
  - Voxel phantoms

Fukushima (as of July 31, 2013)

- Based on the dose rate maps and the data of the behaviors
- < 1mSv: 65.9%, < 2mSv: 94.8%, < 5mSv: 99.8%, Max: 25mSv
  (Excluding radiation workers)
- Decontaminations have been being performed