Dosimetry and risks to health for Fukushima workers

EURADOS Annual Meeting AM2015
Winter School “The Fukushima Daiichi nuclear accident - the role of dosimetry in assessing the consequences”
12 February 2015, Dubrovnik, Croatia

George Etherington¹, Jean-René Jourdain², Wei Zhang¹, John Harrison¹

¹Centre for Radiation, Chemical and Environmental Hazards
Public Health England (PHE)
Chilton, Didcot, Oxon., OX11 0RQ, UK
²IRSN - Institut de Radioprotection et de Sûreté Nucléaire
B.P. 17 F-92265 Fontenay-aux-Roses France

Fukushima worker doses and potential health effects

(1) “Dose” means “effective dose” (external) or “committed effective dose” (internal) unless otherwise stated
(2) TEPCO - Tokyo Electric Power Company, the FDNPS operator

Fukushima Daiichi NPS - Timeline

- Declaration of Level 7 event on International Nuclear Event Scale (INES)
- Emergency dose¹ limit for workers raised from 100 to 250 mSv (TEPCO²: 200 mSv)
- Start of distribution of KI tablets for about 2000 workers engaged on emergency work - from 13 March 2011
- Sharing of electronic personal dosemeters (one per team) – during March 2011
- Introduction of physical barriers, limits on working time, personal protective equipment (PPE)
- Start of reliable in vivo measurements of ¹³¹I in the thyroid for workers with the highest exposures – from mid-April 2011.
The UNSCEAR assessment
Aim: to provide the UN General Assembly with an assessment of the levels of exposure and radiation risks due to the Fukushima nuclear accident

Data, quality assurance, Radionuclide releases, dispersion, deposition, Pathways, public doses, non-human biota, Workers doses, Health implications

The worker assessment
Scope: workers who were involved in the emergency response and clean-up operations before 31 October 2012
a. Review of reported effective doses and absorbed doses to organs
b. Assessment of the reliability of reported doses (using information on exposures provided from Japan)
c. Projected risks to health
d. Observed health effects

Assessment of the reliability of reported doses
Re-assessment or review of ~ 25,000 individual worker dose assessments would not have been possible. Therefore:

Two-stage approach
- Review of methodologies for monitoring and dosimetry used in Japan
- Independent individual dose assessments for selected workers
- Comparison with reported doses for those workers
Published dose statistics

Numbers of FDNPS workers with doses in each dose band, March 2011 (TEPCO, 2011, 2013)

<table>
<thead>
<tr>
<th>Monthly dose range (mSv)</th>
<th>TEPCO</th>
<th>Contractors</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;250</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>200 – &lt;250</td>
<td>0</td>
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<tr>
<td>150 – &lt;200</td>
<td>6</td>
<td>0</td>
<td>6</td>
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<tr>
<td>100 – &lt;150</td>
<td>8</td>
<td>0</td>
<td>8</td>
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<tr>
<td>50 – &lt;100</td>
<td>15</td>
<td>8</td>
<td>23</td>
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<tr>
<td>50 – &lt;50</td>
<td>200</td>
<td>105</td>
<td>305</td>
</tr>
<tr>
<td>&gt;250</td>
<td>10</td>
<td>8</td>
<td>18</td>
</tr>
<tr>
<td>200 – &lt;250</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>150 – &lt;200</td>
<td>5</td>
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<td>6</td>
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<td>100 – &lt;150</td>
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<td>0</td>
<td>6</td>
</tr>
<tr>
<td>50 – &lt;100</td>
<td>37</td>
<td>21</td>
<td>58</td>
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<tr>
<td>&gt;250</td>
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<tr>
<td>50 – &lt;100</td>
<td>37</td>
<td>21</td>
<td>58</td>
</tr>
</tbody>
</table>

Increased to 160 workers by October 2013

Max. (mSv)

>250

Average (mSv)

>250

Numbers of FDNPS workers with doses in each dose band, March 2011 (TEPCO, 2011, 2013)

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<td>1</td>
<td>6</td>
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<td>6</td>
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<td>6</td>
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<td>58</td>
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<tr>
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<td>37</td>
<td>21</td>
<td>58</td>
</tr>
</tbody>
</table>

Max. (mSv)

>250

Average (mSv)

>250

Doses for female workers

Nineteen women who had worked at FDNPS before the accident (five of whom were not occupationally exposed) received an effective dose of more than 1 mSv following the accident;

The two highest doses to female workers resulting from the accident were assessed to have been 7 mSv and 18 mSv.
### Comparison with Chernobyl worker doses

<table>
<thead>
<tr>
<th>Period</th>
<th>FDNPS workers</th>
<th></th>
<th>Chernobyl workers</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of workers</td>
<td>Average dose (mSv)</td>
<td>Period</td>
<td>Number of workers</td>
</tr>
<tr>
<td>March 2011</td>
<td>3973</td>
<td>21</td>
<td>1986-1990</td>
<td>530 000</td>
</tr>
<tr>
<td>March 2011 – October 2012</td>
<td>24 832</td>
<td>12</td>
<td>1986-1990</td>
<td>219 (b)</td>
</tr>
</tbody>
</table>

Notes:  
(a) Average value of total (external + internal) effective dose during the period  
(b) Recovery operation workers

### Review of methods: external dosimetry

*Instrumentation, technical standards and calibration methods used appear to meet generally-accepted requirements for individual monitoring*

**Potentially significant issue:** Use of shared dosemeters  
*In the absence of information on the extent to which the conditions described (below) were met for individual workers, some reservations remained about the reliability of the external dosimetry performed before 1 April 2011*

**TEPCO conditions:**  
- Dose for the task was less than 10 mSv  
- The workplace environmental dose rate was known  
- Variations in dose rate with location at the site of the task to be performed were not large  
- Members of an operational group were always together at the work site

### Review of methods: internal contamination monitoring & dosimetry

*The measurement systems, calibration phantoms and methods, and quality control procedures were adequate for conducting in vivo measurements during a radiation emergency*

**Software (was) appropriate for assessing intakes, … committed effective doses and absorbed doses**

**Most significant issue:**  
Delay in commencing reliable in vivo measurements of $^{131}$I in the thyroid  
- mid-April 2011 – for some workers  
- mid- to late-May 2011 for most workers  

$^{131}$I half-life = 8 d
Delay in starting $^{131}$I in thyroid measurements - I

$^{131}$I was not measurable in the thyroid of many workers

Two estimation methods were used:

1. “Environmental ratio” method
   - environmental measurements of time-dependent $^{137}$Cs/$^{131}$I ratio were used
   - $^{131}$I intake estimated from $^{137}$Cs intake determined from a whole-body measurement
   - “… judged that estimates derived using this method had very large uncertainties”

2. “Minimum Detectable Activity” (MDA) method
   - $^{131}$I in thyroid assumed equal to MDA
   - “… judged to provide a reliable estimate of the upper limit on $^{131}$I intake, but could not be taken to provide a reliable estimate of the true intake”

But the affected workers were in general likely to have received lower doses

Estimated releases to atmosphere

<table>
<thead>
<tr>
<th>Time period in 2011 (JST)</th>
<th>Duration</th>
<th>$^{132}$Te</th>
<th>$^{131}$I</th>
<th>$^{132}$I</th>
<th>$^{133}$I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>End</td>
<td>(h)</td>
<td>$^{132}$Te</td>
<td>$^{131}$I</td>
<td>$^{132}$I</td>
</tr>
<tr>
<td>12 March 09:00</td>
<td>12 March 09:30</td>
<td>4.5</td>
<td>1.79E+14</td>
<td>1.79E+14</td>
<td>1.79E+14</td>
</tr>
<tr>
<td>12 March 09:30</td>
<td>12 March 15:30</td>
<td>6</td>
<td>1.04E+14</td>
<td>1.02E+14</td>
<td>1.04E+14</td>
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<tr>
<td>12 March 15:30</td>
<td>12 March 16:00</td>
<td>0.5</td>
<td>4.90E+15</td>
<td>4.59E+15</td>
<td>4.90E+15</td>
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<tr>
<td>12 March 16:00</td>
<td>12 March 23:00</td>
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<td>2.26E+15</td>
<td>2.26E+15</td>
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<td>13 March 01:00</td>
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<td>4.32E+15</td>
<td>4.08E+15</td>
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<tr>
<td>13 March 01:00</td>
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<td>1.16E+15</td>
<td>1.01E+15</td>
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<td>1.16E+15</td>
<td>1.01E+15</td>
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<tr>
<td>13 March 16:00</td>
<td>13 March 23:00</td>
<td>7</td>
<td>1.62E+15</td>
<td>1.70E+15</td>
<td>1.62E+15</td>
</tr>
<tr>
<td>13 March 23:00</td>
<td>14 March 00:00</td>
<td>7</td>
<td>1.62E+15</td>
<td>1.70E+15</td>
<td>1.62E+15</td>
</tr>
<tr>
<td>14 March 00:00</td>
<td>14 March 07:00</td>
<td>7</td>
<td>1.62E+15</td>
<td>1.70E+15</td>
<td>1.62E+15</td>
</tr>
<tr>
<td>14 March 07:00</td>
<td>14 March 14:00</td>
<td>7</td>
<td>1.62E+15</td>
<td>1.70E+15</td>
<td>1.62E+15</td>
</tr>
<tr>
<td>14 March 14:00</td>
<td>14 March 21:00</td>
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<td>1.62E+15</td>
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<td>1.62E+15</td>
</tr>
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<td>1.70E+15</td>
<td>1.62E+15</td>
</tr>
<tr>
<td>15 March 07:00</td>
<td>15 March 14:00</td>
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<td>1.62E+15</td>
<td>1.70E+15</td>
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<td>7</td>
<td>1.62E+15</td>
<td>1.70E+15</td>
<td>1.62E+15</td>
</tr>
<tr>
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<td>7</td>
<td>1.62E+15</td>
<td>1.70E+15</td>
<td>1.62E+15</td>
</tr>
</tbody>
</table>

Assessment of potential additional contributions to internal dose:

(a) Workers at FDNPS during the period 12-19 March 2011

Estimated additional contribution to committed effective dose in range 6-45%, relative to dose from $^{131}$I intake

(typical value ~20%)

(b) Workers who commenced work after 19 March

No significant additional contribution

Derived from Table B5, UNSCEAR 2013 Report, Vol. 1, Annex A (data for radiocaesium omitted)
Contributions to thyroid absorbed dose from shorter-lived radionuclides

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Intake period</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>05:00 to 09:30 JST, 12 March 2011</td>
</tr>
<tr>
<td>B</td>
<td>05:00 JST, 2 March 2011 - 00:00 JST, 1 May 2011</td>
</tr>
<tr>
<td>C</td>
<td>05:00 JST, 12 March 2011 - 17:00 JST, 15 March 2011</td>
</tr>
</tbody>
</table>

Fractional contribution to total thyroid absorbed dose from each radionuclide

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Fractional contribution to total thyroid absorbed dose from each radionuclide</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>131I  0.02  132I  0.78  133I  0.01  134Cs  0.20  136Cs  0.00  137Cs  0.00</td>
</tr>
<tr>
<td>B</td>
<td>131I  0.00  132I  0.98  133I  0.00  134Cs  0.01  136Cs  0.00  137Cs  0.00</td>
</tr>
<tr>
<td>C</td>
<td>131I  0.01  132I  0.94  133I  0.00  134Cs  0.04  136Cs  0.00  137Cs  0.00</td>
</tr>
</tbody>
</table>

Evaluation of reported internal doses - I

Independent assessments for 12 of the 13 workers with internal doses > 100 mSv

Main conclusions:
1. Good agreement between independent assessments and reported values
2. Assessed internal doses were largely due to 131I intakes (99%)
3. Worker A – thyroid absorbed dose ~ 12 Gy
4. Sufficient information available to provide absorbed doses to organs for health risk assessment (thyroid, red bone marrow, colon)

Evaluation of reported internal doses - II

Independent assessments for 42 randomly-selected workers:
- 3 dose ranges (0-5, 5-20, 20-100 mSv)
- Equal numbers of TEPCO workers and contractors
- Comprehensive information from TEPCO, less so from contractors

Main conclusions:
1. Internal doses were largely due to 131I intakes (98%)
2. TEPCO reported values confirmed as reliable where a positive measurement of 131I in thyroid was made
3. Reliability not confirmed where the 131I in thyroid measurement was below detection limit
4. Unable to confirm reliability of values reported by contractors for their workers. (However, some discrepancies were resolved after a 2013 re-assessment of doses reported in Japan. Further information would be needed to evaluate reliability.)

Results
See Appendix D, UNSCEAR report for detailed results
Reported doses for other groups of workers

13 police
- Reported external doses < 10 mSv
- Reported internal doses < 1 mSv

Municipal workers – “insufficient information”

249 firefighters
- Maximum reported external dose = 30 mSv
- Maximum reported internal dose = 1 mSv (but no reliable 131I in thyroid monitoring)

Self Defense Force (military) – external dose
- Maximum reported external dose = 30 mSv
- Maximum reported internal dose = 1 mSv

Health Risk Assessment (HRA)

"(UNSCEAR’s) estimates of doses were based on a considerably expanded database and were generally within the dose ranges estimated by WHO"

"(UNSCEAR’s) assumptions underpinning its estimates of health implications are generally well aligned with those of WHO"


http://apps.who.int/iris/bitstream/10665/78218/1/9789241505130_eng.pdf

WHO HRA Scenarios

A simple scenario approach was adopted (because individual dosimetric data were not available at the time of the WHO assessment)
Estimation of absorbed dose to organs in the 1st year

Risk of leukaemia, thyroid cancer, and “all solid cancers combined” were assessed using organ doses to red bone marrow, thyroid and colon.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Red bone marrow (mGy)</th>
<th>Thyroid (mGy)</th>
<th>Colon (mGy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>138</td>
<td>24</td>
</tr>
<tr>
<td>3</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>4</td>
<td>104</td>
<td>11 800</td>
<td>103</td>
</tr>
</tbody>
</table>

Lifetime attributable risk (LAR)

The LAR specifies the probability of premature incidence (up to age 89 y) of a cancer attributable to radiation exposure in a representative member of the population.

Formal definition:

The lifetime risk of a cancer \( c \) that has been caused by exposure \( D \) at age \( e \) is:

\[
LAR(e, D) = \int_0^\infty \left[ \mu_c(a | \epsilon, D) - \mu_c(a | \epsilon) \right] S(a | e) da
\]

where:

- \( \mu_c(a | \epsilon, D) \) is the annual risk of incidence from cancer \( c \) at age \( a \) given an exposure \( D \) at age \( e \) (based on the LSS cohort, Japanese A-bomb survivors)
- \( S(a | e) \) is the probability that a member of the unexposed population who is alive and cancer-free at age-at-exposure \( e \) will survive cancer-free to age \( a \).

Risk of thyroid cancer: Scenarios S1, S2, S3, S4

Will increased thyroid cancer rates be observed?

Scenario S4
LAR (for 20 y old worker) – 3.5%
BUT, only 13 workers are represented by S4
⇒ An increase in thyroid cancer cases is unlikely to be observed

Scenario S2
About 7,500 workers are represented by S2
BUT, LAR (for 20 y old worker) ~ 0.04%
⇒ Predicted excess of one case
⇒ Baseline incidence of ~ 5 cases; so excess unlikely to be observed

Non-cancer risks
1. No acute health effects or deaths that could be attributed to radiation exposure have been observed
2. Thirteen workers were estimated to have received absorbed doses to the thyroid in the range of 2 to 12 Gy from inhalation of $^{131}$I. UNSCEAR considers that hypothyroidism is possible in the more exposed workers in this group, but the likelihood is low.
3. UNSCEAR considers that risks for circulatory disease due to radiation exposure among the workers who were most exposed are very low.
4. UNSCEAR considers that there is insufficient information on exposures of the eye lens of workers from beta radiation to reach an informed judgement on the risk of cataracts

Summary and Conclusions
1. The highest reported total effective dose for a worker was 679 mSv (590 mSv internal, 89 mSv external).
2. For the workers with the highest internal doses, the major contribution to committed effective dose was the thyroid dose resulting from inhalation of $^{131}$I.
3. No radiation-related deaths have been reported among FDNPP workers since the accident.
4. For Scenario 4 (13 workers), LAR values for thyroid cancer up to 3.5% were estimated; a radiation-related increase in thyroid cancer incidence is unlikely to be observed because of the small number of workers.
5. For Scenarios 2 & 3, a radiation-related increase in thyroid cancer incidence is unlikely to be observed because of the variability in baseline rates of cancer incidence.
6. For Scenario 1, any elevated radiation-related cancer risk is insignificant.
7. Non-cancer risks are low.
Lessons learnt – a personal view

1. Monitoring systems and equipment need to be resilient to a major (catastrophic) accident.
2. The reliability of monitoring in the event of a major accident needs to be considered (i.e. “Would we be confident of the results of monitoring?”)
3. Individual monitoring of workers needs to be carried out promptly. Once early data is lost, it can’t be reconstructed with confidence.
4. If capacity is severely reduced, monitoring of a limited number of workers is better than no monitoring.
5. Site operators should consider whether their contractors are capable of implementing a reliable monitoring programme in the event of a major accident.
6. The maintenance of capabilities for urine monitoring in the event of an accident (e.g. for $^{90}$Sr or Pu intakes) should be considered.

UNSCAR Fukushima follow-up

Phase I (2015-2016)
monitor developments; evaluate published information; conduct systematic reviews; conduct ad hoc analyses as appropriate; provide an annual review for submission to UNSCEAR.

Phase II (2017-2020?)
Develop a plan to update UNSCEAR 2013 Report; for workers, consider the uncertainties in dose and risk estimates.

Acknowledgements

The contributions of the following independent experts are acknowledged:

UNSCAR assessment
- Dr Makoto Akashi (NIRS, Japan)
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- Dr Dunstana Melo (IRD, Brazil)
- Dr Melanie Rickard (CNSC-CCSN, Canada)
- Dr Sergeii Romanov (SUBI, Russia)
- Dr Bertrand Theriault (CNSC-CCSN, Canada)

WHO assessment
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- Dr Lynn Anspaugh (Univ. of Utah, USA)
- Dr Nick Gehl (PHL, UK)
- Dr Dominique Laurier (IRSN, France)
- Dr Linda Walsh (BfS, Germany)
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- Dr Bertrand Theriault (CNSC-CCSN, Canada)

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George Etherington¹, Jean-René Jourdain², Wei Zhang¹, John Harrison¹

¹Centre for Radiation, Chemical and Environmental Hazards
Public Health England (PHE)
Chilton, Didcot, Oxon., OX11 0RQ, UK

²IRSN - Institut de Radioprotection et de Sûreté Nucléaire
B.P. 17, F-92265 Fontenay aux Roses, France

Additional slides

PHE’s evaluation of the WHO scenarios

Scenario 1 specifies a total effective dose of 5 mSv (as a “reasonably conservative” value). Any E(50) assumed to be due to ¹³⁴Cs and ¹³⁷Cs intakes. A value of 2.5 mSv is more representative. E(50) contributes only about 6% of the total effective dose, but it is likely that the main contribution to E(50) is from ¹³¹I intake.

Scenario 2 is representative of typical exposures of workers that meet its inclusion criterion.

Scenario 3 is broadly representative of the maximum exposure of workers that meet its inclusion criterion.

The contribution to E(50) from ¹³¹I intake is assumed to be zero. While the contribution of E(50) to total effective dose is generally small (13%), it is likely that the main contribution to E(50) is from ¹³¹I intake.

Scenario 4 is broadly representative of the maximum exposure of workers that meet its inclusion criterion.

E(50) – committed effective dose


References


