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

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Fukushima Daiichi NPS - Timeline

March 2011	Time (JST)	Major events affecting worker exposures
11th	14:46	EARTHQUAKE (Magnitude 9.0)
	15:35	TSUNAMI, 15 m wave height *Loss of almost all electricity on-site; loss of all safety systems including access control & recording* *Widespread destruction of on-site infrastructure* *Loss of most electronic personal dosemeters*
12th	02:45	Strong likelihood of reactor pressure vessel failure, Unit 1
	15:36	Hydrogen explosion, Unit 1 *Some workers remained in main control room for several days* *Presumed to have inhaled radioactive material due to lack of PPE*
13th	am	Likely damage to reactor pressure vessel, Unit 3 *KI tablets provided for FDNPS emergency workers*
14th	11:01	Hydrogen explosion, Unit 3
15th	~06:00	Hydrogen explosion, Unit 4
15th	07:38	Start of major discharge of radioactive material from Unit 2

FDNPS – Fukushima Daiichi Nuclear Power Station

Initial actions and control measures

a. Declaration of **Level 7 event** on International Nuclear Event Scale (INES)

b. Emergency dose[1] limit for workers raised from 100 to **250 mSv** (TEPCO[2]: 200 mSv)

c. Start of **distribution of KI** tablets for about 2000 workers engaged on emergency work - from 13 March 2011

d. Sharing of electronic personal dosemeters (one per team) – during March 2011

e. Introduction of: physical barriers, limits on working time, personal protective equipment (PPE)

f. Start of reliable ***in vivo* measurements of ^{131}I in the thyroid** for workers with the highest exposures – from mid-April 2011.

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

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

Report:
http://www.unscear.org/unscear/en/publications/2013_1.html

UNSCEAR Committee

UNSCEAR Secretariat

- **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

Increased to 160 workers by October 2013

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

External dose

Monthly dose range (mSv)	TEPCO	Contractors	Total
>250	0	0	0
200 - <250	0	0	0
150 - <200	6	3	9
100 - <150	20	8	28
50 - <100	105	58	163
20 - <50	292	182	474
10 - <20	598	331	929
<10	673	1697	2370
Total	1694	2279	3973
Max. (mSv)	182.33	199.42	199.42
Average (mSv)	19.41	9.07	13.48

Note: External doses are those received during March 2011

Internal dose

Monthly dose range (mSv)	TEPCO	Contractors	Total
>250	5	0	5
200 - <250	1	0	1
150 - <200	1	0	1
100 - <150	6	0	6
50 - <100	37	21	58
20 - <50	186	99	285
10 - <20	398	249	647
<10	1038	1837	2875
Total	1672	2206	3878
Max. (mSv)	590.00	98.53	590.00
Average (mSv)	11.97	5.12	8.07

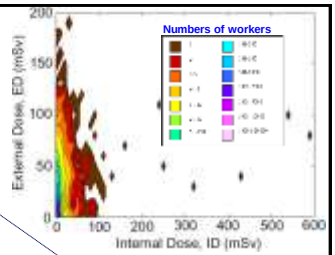
Note: Internal doses are those resulting from intakes received during March 2011

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**.

Doses for individual FDNPS workers



Numbers of Fukushima workers with a specified combination of internal dose (ID) and external dose (ED)

Reported doses for the 5 workers with the highest cumulative effective doses for the period March 2011 to April 2012

Cumulative external dose (mSv)	Cumulative internal dose (mSv)	Total dose (mSv)
89	590	679
106	540	646
44	433	477
33	328	361
110	242	352

Comparison with Chernobyl worker doses

FDNPS workers			Chernobyl workers		
Period	Number of workers	Average dose (mSv) [a]	Period	Number of workers	Average dose (mSv) [a]
March 2011	3973	21	1986-1990	530 000	120
March 2011 – October 2012	24 832	12			
			1986-1990	219 [b]	~8000

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 ^{131}I:^{137}Cs 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

Delay in starting ^{131}I in thyroid measurements - II

➔ Shorter-lived radionuclides (^{132}Te, ^{132}I, ^{133}I, ^{136}Cs) would have been undetectable in the body at the time of measurement.

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

Estimated releases to atmosphere

Time period in 2011 (JST)		*Duration (h)*	*Activity released (Bq)*			
Start	*End*		*^{132}Te*	*^{131}I*	*^{132}I*	*^{133}I*
12 March 05:00	12 March 09:30	4.5	1.79E+14	1.67E+14	1.79E+14	2.15E+14
12 March 09:30	12 March 15:30	6	1.04E+14	1.02E+14	1.04E+14	1.13E+14
12 March 15:30	12 March 16:00	0.5	1.49E+15	1.50E+15	1.49E+15	1.51E+15
12 March 16:00	13 March 23:00	31	2.26E+15	2.60E+15	2.26E+15	1.70E+15
12 March 23:00	14 March 11:00	12	3.08E+14	4.32E+14	3.08E+14	1.44E+14
14 March 11:00	14 March 11:30	0.5	1.01E+15	1.50E+15	1.01E+15	4.15E+14
14 March 11:30	14 March 21:30	10	1.48E+14	2.30E+14	1.48E+14	5.46E+13
14 March 21:30	15 March 00:00	2.5	1.98E+15	3.25E+15	1.98E+15	6.40E+14
15 March 00:00	15 March 07:00	7	1.62E+15	2.45E+15	1.62E+15	4.19E+14
15 March 07:00	15 March 10:00	3	5.01E+15	9.00E+15	5.01E+15	1.33E+15
15 March 10:00	15 March 13:00	3	1.30E+14	2.40E+14	1.30E+14	3.24E+13
15 March 13:00	15 March 17:00	4	8.40E+15	1.60E+16	8.40E+15	1.94E+15

Derived from Table B5, UNSCEAR 2013 Report, Vol. 1, Annex A (data for radiocaesium omitted)

Contributions to thyroid absorbed dose from shorter-lived radionuclides

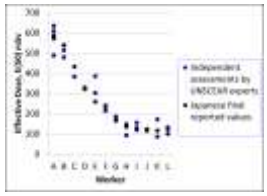
Scenario	Intake period
A	05:00 to 09:30 JST, 12 March 2011
B	05:00 JST, 2 March 2011 - 00:00 JST, 1 May 2011
C	05:00 JST, 12 March 2011 - 17:00 JST, 15 March 2011

Scenario	Fractional contribution to total thyroid absorbed dose from each radionuclide						
	^{132}Te	^{131}I	^{132}I	^{133}I	^{134}Cs	^{136}Cs	^{137}Cs
A	0.02	0.78	0.01	0.20	0.00	0.00	0.00
B	0.00	0.98	0.00	0.01	0.00	0.00	0.00
C	0.01	0.94	0.00	0.04	0.00	0.00	0.00

Evaluation of reported internal doses - I

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

Results:



Short-lived radionuclides not included

Main conclusions

1. **Good agreement** between independent assessments and reported values
2. Assessed internal doses were **largely due to ^{131}I 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

Results
See Appendix D, UNSCEAR report for detailed results

Main conclusions

1. Internal doses were **largely due to ^{131}I intakes** (98%)
2. **TEPCO reported values confirmed as reliable** where a positive measurement of ^{131}I in thyroid was made
3. Reliability not confirmed where the ^{131}I 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.)

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 ^{131}I in thyroid monitoring)

Self Defense Force (military) – external dose

Location	Number of workers in dose band			
	<10 mSv	10-20 mSv	20-50 mSv	50-100 mSv
On-site	132	3	8	4
Off-site	8 453	5	-	-

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*"

WHO (2013). Health risk assessment from the nuclear accident after the 2011 Great East Japan earthquake and tsunami based on a preliminary dose assessment. WHO, Geneva. 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)

Scenario	Effective dose (mSv)			Comments / assumptions
	Total	External	Internal	
1	5	5	-	Total dose , E < 10 mSv; **~ 69% of workers** - Any internal dose is due to $^{134/137}$Cs inhalation, and so is homogeneous - Therefore, organ doses = effective dose
2	30	24	6	Total dose , 10 <E <100 mSv; **~ 30% of workers** Internal dose is all due to ^{131}I inhalation
3	200	200	-	External doses, E >100 mSv; **160 workers** - Any internal dose is due to $^{134/137}$Cs inhalation - Therefore, organ doses = effective dose - Representative of maximum doses in group
4	700	100	600	Committed effective dose >100 mSv; **12 workers** - Internal dose is all due to ^{131}I inhalation - Representative of maximum doses in group

E – effective dose

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

Scenario	Red bone marrow (mGy)	Thyroid (mGy)	Colon (mGy)
1	5	5	5
2	24	138	24
3	200	200	200
4	104	11 800	103

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:

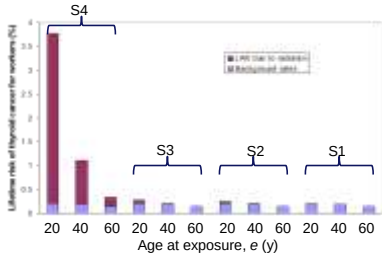
$$LAR_c(e,D) = \int_{a=e}^{\infty} \left[\mu_c(a \mid e, D) - \mu_c(a)\right] S(a \mid e)\, da$$

where: $\mu_c(a \mid e, D)$ 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)*

$S(a \mid e)$ 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

Lifetime attributable risk (LAR)



Etherington G, Zhang W, Harrison JD and Walsh L (2014). Worker doses and potential health effects resulting from the accident at the Fukushima nuclear power plant in 2011. International Journal of Radiation Biology **90** (11), 1088 – 1094.

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, they 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

UNSCEAR 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

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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 ^{134}Cs and ^{137}Cs 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 ^{131}I intake.

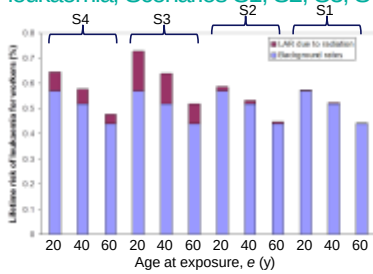
Scenario 2 is representative of typical exposures of workers that meet its inclusion criterion.

Scenario 3 is broadly representative of the *maximum* exposure of workers that meet its inclusion criterion.
The contribution to E(50) from ^{131}I 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 ^{131}I intake.

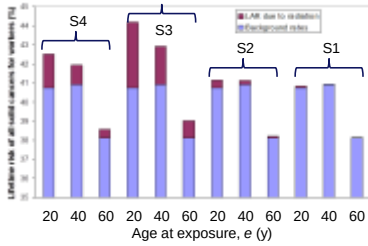
Scenario 4 is broadly representative of the *maximum* exposure of workers that meet its inclusion criterion.

E(50) – committed effective dose

LAR – leukaemia, Scenarios S1, S2, S3, S4



LAR – all solid cancers, Scenarios S1, S2, S3, S4



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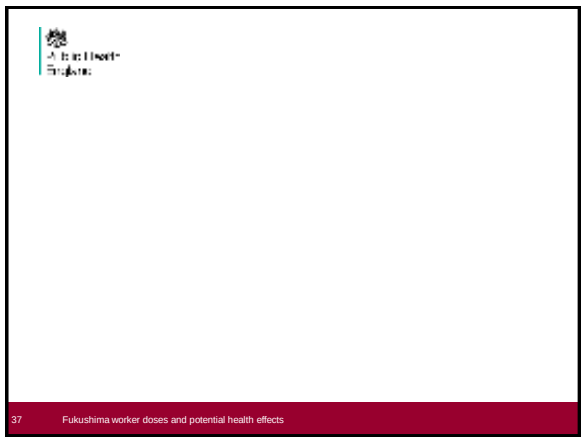
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Fukushima worker doses and potential health effects