The internal and external dosimetry challenges from past experience: *Fukushima Daiichi accident*

Toshikazu Suzuki

Technical advisor of Chiyoda Technol Corporation
Technical advisor of TEPCO
16 hours after the accident, we flew to the local headquarter called “off-site center” from NIRS
8:10, March 12
Experts from NIRS were dispatched to the "Off-site center", which was located 4.5km from FDNPS.
The function of the Fukushima off-site center (OFC) that had the role as the center for emergency response measures in case of nuclear accident had been almost paralyzed on 12\textsuperscript{th} March 2011.

Although the emergency power supply had been restored, the multiplex communication network was completely destroyed due to the earthquake.

135 telephones and data communication terminals were quite useless except five satellite phones.
Radioactive plume

It was calm outside and the air dose rate was around 0.06μSv/h. Any anomaly was not found in the gamma-ray spectrum.

However, the leakage of radioactive material from the PCV of unit 1 had already begun because of the meltdown which had occurred 16 hours before.

Around 12:30pm on the day, Xe-133, Xe-135, Te-132, I-131, I-132, I-133 and Cs-136 were observed in the spectrum. This was the first moment when the radioactive plume had been observed at OFC.
Immediately after that, surface contamination check by a pancake GM survey meter was started for the workers returning from FDNPS at the entrance.

The screening level was decided temporary as 13000cpm which meant approx. 40Bq/cm².

At this point, the contamination of the tire or the shoe sole was already difficult to decontaminate.
Self –Defense Force personnel –from the sky-

84 personnel were engaged in discharging water operation for the cooling of the spent fuel pool (SPF) by CH-47JA helicopter on 17th March.

Air dose rate at 300ft. above the Unit 3 was approx. 90mSv/h.

Lead sheets were spread over the place where the pilot and the mechanic were located.

The opening under the aircraft was sealed up with a transparent, acrylic board to prevent radioactive substance from flowing in.

The crew wore a lead protective suit under the protective combat suit with a full-face mask, and took iodine tablets in advance.
Self - Defense Force personnel - dose evaluated -

Through four times of flight in this mission external exposure of all personnel was below 1mSv

Internal contamination of them all was below the detection limit, which was measured by chair-type WBC installed in central military hospital.
Self–Defense Force personnel on the ground

The other 84 personal were engaged in SPF cooling operation from the ground side by using water cannon truck.

At 11:01am on March 14th three vehicles were rolled in the hydrogen explosion with six CNBC personnel.
Self-Defense Force personnel -situation-

90 minutes before the hydrogen explosion they took potassium iodine (130mg)

Their equipment was APD, TLD, Tyvek® suit on the battle suit and full-face mask with charcoal filter

The blast of the hydrogen explosion directly pierced through their Tyvek® suit and the battle suit

Surface contamination level at the distance of 10cm was 1.0mSv/h when they reached the OFC by walk

For the quick decontamination their Tyvek suit was cut by a medical scissors, during this treatment the APD sounded. As the alarm setting value was 20mSv, their external exposure was evaluated as 20mSv
Eight months later, their clothes were still highly contaminated by Cs-134 and Cs-137. The maximum contamination level was 1800 Bq/cm².
Their medical treatment and internal dose evaluation was executed at the NIRS soon.

Because of the remaining high surface contamination and the gamma-ray pile-up, the quantification by WBC was difficult at the early stage.

Recorded at 21:56 on 14 Mar. 2011 by 4 - 8"φx4" NaI(Tl) bed type WBC

The first day

Four days later
Self –Defense Force personnel -internal contamination-
whole body counting

For this measurement,
NIRS’s main WBC ;
6 channels of high volume Ge detector
and 4 channels of Lung monitor using
Canberra’s LEGe detector
could not be used because of its high sensitivity and evasion of cross-contamination

( MDA is below 10Bq to Cs-137)
Self–Defense Force personnel -internal contamination- whole body counting

For the emergency screening, four channel open air WBC was adopted, which was always energized to keep the stability.

The calibration was carried out by using ANSI 13.35 BOMAB phantoms.

In order to compensate the contribution of ambient background and shielding effect of human body, K-40 water BOMAB phantom was applied.

8”φx4” shielded NaI(Tl) scintillator
Because high surface contamination had remained, in-vitro measurements were not able to be used in the first stage.

Urine diluted five times was measured by Ge detector for 60 minutes in U8 container.

A large amount of radio iodine was observed in the urine.
There was an incorporation to the thyroid gland though the full-face mask with charcoal filter was worn.

The personnel was not using glasses, and the possibility of the leakage from the temple was few.

It is thought this was caused by the filtering efficiency (99.9%) of the charcoal filter, considering large specific activity of I-131 (4.6E15 Bq/g)
The maximum exposure among the six personnel was:

- Effective dose: $20mSv$ -from APD-
- Committed effective dose: $4.2mSv$ -calculated by MONDAL-
  (Thyroid committed equivalent dose: $27.4mSv$)
- Total dose: $24.2mSv$

Slight $^{90}\text{Sr}-^{90}\text{Y}$ was detected in the urine but the dose contribution could be disregarded.
Emergency measure for thyroid measurement

This technique stayed in use to the infant this time, it’s thought to be useful for screening in the emergency

1. Only one thyroid monitor was left in high contaminated area

2. NaI(Tl) scintillation survey meter was applied as the substitution

3. Conversion coefficient between μSv/h and Bq was decided by neck phantom which included thyroid phantom filled with standard Ba-133

4. The value is 1μSv/h=22kBq
In the early phase, the small number of private fire-fighters who belonged to the subsidiary of TEPCO played the most important role for reactor cooling.

The maximum external exposure of them was 88 mSv evaluated by the same personal dosimeter as TEPCO worker.

The maximum thyroid equivalent dose was estimated as 230 mSv calculated conditions: inhaled iodine for 3 days uniformly examined 8 days later.
Fire-fighters - Tokyo Fire Department -

139 fire-fighters of Tokyo Fire Department were sent from 19\textsuperscript{th} March 2011

The air dose rate where they worked was approx. 400\textmu Sv/h

Their maximum external exposure did not exceed 30mSv

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Activity (Bq)</th>
<th>Ratio to total</th>
</tr>
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<tbody>
<tr>
<td>Cs-134</td>
<td>1.93E+02</td>
<td>9.87%</td>
</tr>
<tr>
<td>Cs-136</td>
<td>1.99E-01</td>
<td>0.01%</td>
</tr>
<tr>
<td>Cs-137</td>
<td>2.61E+02</td>
<td>13.32%</td>
</tr>
<tr>
<td>Ag-110m</td>
<td>3.00E+01</td>
<td>1.53%</td>
</tr>
<tr>
<td>I-131</td>
<td>4.34E+00</td>
<td>0.22%</td>
</tr>
<tr>
<td>Te-129</td>
<td>6.39E+02</td>
<td>32.58%</td>
</tr>
<tr>
<td>Te-129m</td>
<td>8.18E+02</td>
<td>41.73%</td>
</tr>
<tr>
<td>La-140</td>
<td>9.35E-01</td>
<td>0.05%</td>
</tr>
<tr>
<td>Sb-125</td>
<td>1.34E+01</td>
<td>0.68%</td>
</tr>
</tbody>
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Radio nuclides detected from the surface of their personal dosimeter on 3\textsuperscript{rd} June 2011
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<td>1.99E-01</td>
<td>0.01%</td>
</tr>
<tr>
<td>Cs-137</td>
<td>2.62E+2</td>
<td>2.09%</td>
</tr>
<tr>
<td>Ag-110m</td>
<td>3.00E+01</td>
<td>1.53%</td>
</tr>
<tr>
<td>I-131</td>
<td>4.36E+3</td>
<td>34.64%</td>
</tr>
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<td>Te-129</td>
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</table>
Approx. 5000 APDs were unusable because of inundation by the tsunami

Only 320 APDs gathered from buildings in FDNPS were available until 1st April 2011

Panasonic APDs using a silicon semiconductor were used both by Self-Defense Force and TEPCO

The APDs were allocated only to the representative of same working group whose planned exposure was below 10mSv

The dose records were made by handwriting because of the malfunction of access control and dose management system

This might cause some uncertainty to the evaluation of individual dose
TEPCO and contractor’s worker - internal exposure -

In the early phase, *in-vivo* monitoring was carried out by using WBC installed at Kashiwazaki-kariwa NPS, which was calibrated by Co-60.

From the end of March 2011, the JAEA sent mobile WBC in which Canberra FASTSCAN was installed.

During 20 April to 5 August 2011, worker whose preliminary estimated dose become over 20 mSv went to the JAEA Tokai for additional monitoring.

The JAEA reported only the internal activity, and TEPCO evaluated the committed effective dose by MONDAL.
TEPCO and contractor’s worker - internal exposure
additional monitoring at JAEA -

560 subjects were measured during the period between 20 April to 5 August 2011.

The first group, 39 subjects, were carefully measured by means of several monitoring techniques.

For the second group, 521 subjects, some monitoring techniques had to be reduced because of the limitation on the monitoring capability.
The HPGe detector was calibrated with the neck part of a Transfer phantom (Canberra) based on the specifications of ANSI.
Thyroid monitoring ($^{131}I$)

The largest thyroid content of $^{131}I$ was 9760 Bq, which was found in a male subject measured on 23 May. His committed effective dose was calculated as 590 mSv on the assumption of a single intake scenario via inhalation of elemental iodine on 12 March.

Up to the end of Jun (39 subjects)

Straight lines: thyroid $^{131}I$ residual activity corresponding to committed effective doses of 20, 100 and 250 mSv in the case of acute intake of elemental iodine.

- 250 mSv
- 100 mSv
- 20 mSv

The first day of work

MDA value
Whole body measurements ($^{137}$Cs)

Straight line: $^{137}$Cs amount corresponding to committed effective doses of 20 mSv in the case of acute intake of Type F compounds with 5 μm.

Group 1
Whole body measurements ($^{134}\text{Cs}$ vs. $^{137}\text{Cs}$)

(N=39)

Group 1
Conclusion

The personal dosimeter of the waterproofing type is indispensable considering worker’s sweat as well as the inundation

Administration of iodine tablet in advance and fitting of full-face mask with charcoal filter is effective in the environment where the radioiodine exists. As for the charcoal filter it is necessary to examine the filtering efficiency of radioiodine because of its high specific activity.

Evaluated dose is changed depending on scenario of intake. Data on workplace monitoring and interview to workers is important for adequate dose evaluation.

Further studies are still needed for the improvement of internal dose estimations especially for subjects who were suspected to have extremely high internal exposure, considering more realistic intake scenarios and the intake of other short-life radionuclides (e.g., $^{132}\text{I}$, $^{133}\text{I}$, and $^{132}\text{Te}$).
Thank you for your support!
Occupational exposure
Distribution of occupational exposure 
( until September 30, 2011)

Dose limit to emergency worker
:250mSv (Japan)
:500mSv (IAEA)

<table>
<thead>
<tr>
<th>(mSv)</th>
<th>TEPCO</th>
<th>Contractor</th>
<th>Total</th>
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<tbody>
<tr>
<td>250&lt;</td>
<td>6</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>200~250</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>150~200</td>
<td>18</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>100~150</td>
<td>110</td>
<td>23</td>
<td>133</td>
</tr>
<tr>
<td>50~100</td>
<td>297</td>
<td>291</td>
<td>588</td>
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<tr>
<td>20~50</td>
<td>640</td>
<td>1,553</td>
<td>2,193</td>
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<td>10~20</td>
<td>479</td>
<td>2,154</td>
<td>2,633</td>
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<tr>
<td>&lt;10</td>
<td>1,630</td>
<td>9,710</td>
<td>11,340</td>
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</table>
Distribution of external and internal exposure (at the end of September)

### External Exposure of emergency workers

<table>
<thead>
<tr>
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<th>TEPCO</th>
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<th>Total</th>
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<td>150~200</td>
<td>6</td>
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<td>9</td>
</tr>
<tr>
<td>100~150</td>
<td>20</td>
<td>8</td>
<td>28</td>
</tr>
<tr>
<td>50~100</td>
<td>108</td>
<td>57</td>
<td>165</td>
</tr>
<tr>
<td>20~50</td>
<td>283</td>
<td>243</td>
<td>526</td>
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<tr>
<td>10~20</td>
<td>596</td>
<td>908</td>
<td>1,504</td>
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<tr>
<td>&lt; 10</td>
<td>2,168</td>
<td>12,516</td>
<td>14,684</td>
</tr>
</tbody>
</table>

Maximum external exposure was **199 mSv**

### Internal Exposure of emergency workers

<table>
<thead>
<tr>
<th>mSv</th>
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<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
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<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>100~150</td>
<td>5</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>50~100</td>
<td>36</td>
<td>42</td>
<td>78</td>
</tr>
<tr>
<td>20~50</td>
<td>182</td>
<td>79</td>
<td>261</td>
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<tr>
<td>10~20</td>
<td>403</td>
<td>283</td>
<td>686</td>
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<tr>
<td>&lt; 10</td>
<td>2,548</td>
<td>13,158</td>
<td>15,706</td>
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</table>

Maximum internal exposure was **590 mSv**
<table>
<thead>
<tr>
<th>Gender</th>
<th>Job title</th>
<th>Total dose</th>
<th>Working period</th>
<th>Mask condition</th>
<th>Iodine tablet administration</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>Operator</td>
<td>679 mSv (Internal 590 mSv)</td>
<td>3/11–4/14</td>
<td>for dust by unit1 explosion, then charcoal</td>
<td>none</td>
<td>plant operation in main control room</td>
</tr>
<tr>
<td></td>
<td>Operator</td>
<td>646 mSv (Internal 540 mSv)</td>
<td>3/11–3/15</td>
<td>for dust by unit1 explosion, then charcoal</td>
<td>total 10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Operator</td>
<td>352 mSv (Internal 242 mSv)</td>
<td>3/11–3/31</td>
<td>charcoal</td>
<td>total 3</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>Maintenance</td>
<td>477 mSv (Internal 433 mSv)</td>
<td>3/11–6/4</td>
<td>for dust by unit1 explosion, then charcoal</td>
<td>total 2</td>
<td>meter restoration in main control room</td>
</tr>
<tr>
<td></td>
<td>Maintenance</td>
<td>361 mSv (Internal 328 mSv)</td>
<td>3/11–6/7</td>
<td>charcoal</td>
<td>total 15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maintenance</td>
<td>311 mSv (Internal 260 mSv)</td>
<td>3/11–6/15</td>
<td>for dust by unit1 explosion, then charcoal</td>
<td>total 2</td>
<td></td>
</tr>
</tbody>
</table>
Number of annual exposure over 50mSv was 992

Red-letter shows an increase since October, 2011
放医研での線量評価

2人の足の被ばく量は2～3Svと推定したが、足及び内部被ばくとともに治療が必要となるレベルではなかった。その後3名とも、入院して経過を確認し、3月28日に3名全て退院した。両足に局所被ばくのあった2名の皮膚に熱傷の症状や紅斑などは認められていなかった。

■外部被ばく線量評価
  ・実効線量評価
  個人線量計指示値
  染色体分析
  ・皮膚等価線量評価*
    ガンマ線寄与分
    ベータ線寄与分

■内部被ばく線量評価
  ・Ge検出器を用いたWBC計測
    → 各人の摂取シナリオで核種別に預託実効線量評価
  ・Ge検出器を用いた甲状腺モニタ計測
    → 各人の摂取シナリオで甲状腺等価線量評価（I-131寄与分のみ）
  ・バイオアッセイ分析（尿中排泄量） → 線量評価には使用せず

*:汚染水の核種別濃度は東電提供の分析データを使用

10x10x0.2m³の汚染水をγ線源としたモンテカルロ計算で評価

最大飛程範囲内のβ線皮膚吸収線量（70μm厚）から評価

国際放射線科学研究所での線量評価

Cs-137, 0.514MeV
I-131, 0.606MeV
La-140, 1.349MeV

皮膚

人体

β線皮膚吸収線量

Sr-Y90

10m
20cm
10m
5.98mm
1.46mm
1.95mm

汚染水
Contamination measurement of a patient

Measurement of worker who dipped his foot into highly contaminated water leaked from reactor containment vessel
Situation of personal monitoring

Early stage
- 80% of 700 charcoal filters, 1000 full face masks, 6000 Tyvek suits, 94% of 5000 APDs, 100% of WBCs were sunk in the sea water
- Only 320 APDs were available for emergency job
- Using charcoal air filter again by choosing the less surface contamination

Improvement
- The number of APD increased to approx. 5,500 by Nov. 2011
- Glass badges were provided for all TEPCO personnel by Nov. 2011
- 12 WBCs were available by Dec. 2011
Public exposure
Thyroid monitoring for infants

It is an infant to receive the influence of the radioactive iodine strongly. Over 6000 cases of thyroid cancer in infants have been reported after Chernobyl accident.

In early stage of Fukushima accident, the necessity of thyroid measurement for the infants was clear.

Unfortunately, the two thyroid monitors installed in Off-site center were unusable.

Then, the thyroid measurement using the survey meter was executed.

Thyroid monitors left in high contaminated area

Applied Aloka NaI(Tl) scintillation survey meter as substitution
Comparison of gamma spectrum between $^{133}$I and $^{133}$Ba

$E_{\text{ave}} = 375 \text{ keV}$

$E_{\text{ave}} = 276 \text{ keV}$

Decided to use $^{133}$Ba as the alternative of $^{131}$I from this spectrum
The $^{133}$Ba solution with the same mass of the infant thyroid gland was put in the neck phantom. Then the conversion coefficient between gamma dose rate indicated by the survey meter and $^{133}$Ba activity was decided.

Among 272402 children lived in Fukushima, we could measure 1080. This means ±3% accuracy in 95% reliability as a sample size. No infant who exceeded 36mSv as thyroid equivalent dose as a result
Dose distribution of age dependency

0~2 years-old infant is dominant
Internal exposure

Date: June 27 - December 31
Object: resident of Kawamata-cho, Namie-cho, Iitate-mura, where were highly contaminated
Examination: WBC in JAEA and NIRS

Among 11,816, the ratio of resident that exceeded 1 mSv by the committed effective dose was 0.1%
External exposure

Date: September-December, 2011
Object: Baby, junior high school student, and pregnant woman, total 4010
Dosimeter: Glass badge

Among 4010, the ratio of resident that exceeded 1 mSv/year by the effective dose was 14% (0.8% exceeded 2 mSv)
Radiation measurement devices used in Fukushima
Portable environment monitor

Portable environment monitor with NaI(Tl)/CsI(Tl) + Si detector, solar panel and mobile-telecommunication had been developed in haste, according to the request from MEXT.
Anyone can access from MEXT HP

Real time trend

Real time dose rate

Anyone can access from MEXT HP
Portable surface contamination monitor used for mass screening

It was impossible to enter hotels, restaurant, even hospitals if there was no proof that had been screened in early stage of the accident

Necessity of quick mass screening as a labor-saving equipment

- Quick assemble: 20 min
- Quick start: 1 min
- Light weight: 50kg
- Firmness: Si SSD
- No detector for foot (Contamination of the foot was premise)
Real time PC screen by wireless

Map

Spectrum

Trend

coordinate/ nuclide data
Trunk road mapping result of Chiba prefecture

It was confirmed that there is a good correspondence to the simulation.
Conclusion

The personal dosimeter of the waterproofing type is indispensable considering worker’s sweat as well as the inundation

Administration of iodine tablet in advance and fitting of full-face mask with charcoal filter is effective in the environment where the radioiodine exists. As for the charcoal filter it is necessary to examine the filtering efficiency of radioiodine because of its high specific activity.

Evaluated dose is changed depending on scenario of intake. Data on workplace monitoring and interview to workers is important for adequate dose evaluation.

Further studies are still needed for the improvement of internal dose estimations especially for subjects who were suspected to have extremely high internal exposure, considering more realistic intake scenarios and the intake of other short-life radionuclides (e.g., $^{132}$I, $^{133}$I, and $^{132}$Te).
Effective dose integrated for 50 years at the maximum dose point

- $^{137}$Cs (BP: 671°C) /volatile $\rightarrow 2000\text{mSv}$
- $^{134}$Cs (BP: 671°C) /volatile $\rightarrow 710\text{mSv}$
- $^{110m}$Ag (BP: 2164°C) /particle $\rightarrow 3.2\text{mSv}$
- $^{129m}$Te (BP: 988°C) /volatile $\rightarrow 0.6\text{mSv}$
- $^{90}$Sr (BP: 1382°C) /medium volatile $\rightarrow 0.12\text{mSv}$
- $^{89}$Sr (BP: 1382°C) /medium volatile $\rightarrow 0.00061\text{mSv}$
- $^{239+240}$Pu (BP: 3228°C) /non volatile $\rightarrow 0.12\text{mSv}$
- $^{238}$Pu (BP: 3228°C) /non volatile $\rightarrow 0.027\text{mSv}$
- $^{131}$I (BP: 184°C) /volatile $\rightarrow 0.015\text{mSv}$

Based on IAEA TECDOC-955
Emission of radioactivity

$^{137}\text{Cs}$ 10PBq
$^{131}\text{I}$ 500PBq

Total 900PBq (5200PBq in Chernobyl)

Based on TEPCO evaluation reported in May 2012