Remediation actions applied after the accidents in Chernobyl, Fukushima and Goiania: Effectiveness and lessons learned

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Agenda Item 4.1

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Topical Session: Remediation Strategies after an Emergency

2-3 November 2015, Vienna
Chernobyl and the Fukushima: Releases to the terrestrial environment *(IAEA 2015, IAEA 2015)*

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Chernobyl (IAEA 2008)</th>
<th>Fukushima</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-131</td>
<td>1760</td>
<td>100-400</td>
</tr>
<tr>
<td>Cs-134</td>
<td>47</td>
<td>8.3-50</td>
</tr>
<tr>
<td>Cs-137</td>
<td>85</td>
<td>7-20</td>
</tr>
<tr>
<td>Sr-90</td>
<td>10</td>
<td>0.003-0.14</td>
</tr>
</tbody>
</table>
Deposition of Cs-137 in Ukraine, Belarus and the Russian Federation and in Japan

Surface ground deposition of Cs-137 near Chernobyl. (IAEA “STI/PUB/1239”, 2006)

Same scale

Surface ground deposition of Cs-137 near Fukushima-1. (Based on MEXT Data)
Thyroid dose in affected areas (Cs-137-deposition $> 37$ kBq/m$^2$)
Average of Belarus, Russian Federation, Ukraine (UNSCEAR, 2008)

<table>
<thead>
<tr>
<th>Country</th>
<th>Average thyroid dose (mGy)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All groups</td>
</tr>
<tr>
<td>Belarus</td>
<td>450</td>
</tr>
<tr>
<td>Russian Federation (19 regions)</td>
<td>27</td>
</tr>
<tr>
<td>Ukraine</td>
<td>120</td>
</tr>
<tr>
<td>All affected areas</td>
<td>100</td>
</tr>
<tr>
<td>All countries</td>
<td>48</td>
</tr>
</tbody>
</table>

Total collective thyroid dose:
- In affected areas: 6.4 million person-Gy
- In the whole countries: 98 million person-Gy
Estimated thyroid doses to children and adolescents
Importance of pathways:
Average of Belarus, Russian Federation, Ukraine (UNSCEAR, 2008)

<table>
<thead>
<tr>
<th>Cs-137-deposition (kBq/m²)</th>
<th>Total effective dose mid 1986 to 2005 (mSv)</th>
<th>Ingestion (%)</th>
<th>Collective dose in deposition category (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 37</td>
<td>0.7</td>
<td>31</td>
<td>53</td>
</tr>
<tr>
<td>37-185</td>
<td>5.8</td>
<td>33</td>
<td>26</td>
</tr>
<tr>
<td>185-555</td>
<td>21.6</td>
<td>29</td>
<td>11</td>
</tr>
<tr>
<td>555-1480</td>
<td>53</td>
<td>27</td>
<td>8</td>
</tr>
<tr>
<td>&gt;1480</td>
<td>121</td>
<td>23</td>
<td>2</td>
</tr>
<tr>
<td>All categories</td>
<td>1.25</td>
<td>31</td>
<td>100</td>
</tr>
</tbody>
</table>

Total collective dose: 125000 person-Sv
Importance of ingestion

Urban areas

Rural, intensive agriculture
- Mineral soils,
- K-fertilizer

Rural, extensive agriculture
- very acid organic soils,
- no K-fertilizer

Rural, extensive agriculture, close to forests
- very acid organic soils,
- no K-fertilizer
- Intake of mushrooms, berries, game

Increasing contribution of ingestion
Cs-137 in milk from private and collective farms (Rovno oblast, Ukraine) (IAEA, 2006)

Private farms: Grazing on poor, organic acid pasture, no K-fertilizer, => high Cs-137 uptake
Chernobyl: Decline of γ-dose rates on different surfaces (Dose rate on to virgin land = 1 at t=0) (UNSCEAR 2008)
Fukushima: District average dose to a representative person in 2012 (IAEA, 2015)

- External exposure by far dominating
- Internal exposure is very low
  - Strict monitoring of food
  - Low limits in foods
  - Nation-wide food supply
Fukushima: Decline of effective dose from external exposure to the representative person (IAEA, 2015)
Criteria for remediation

Chernobyl: In 1986, the USSR Ministry of Health introduced
- \(100\, mSv\) as a temporary limit for the average equivalent whole body dose for the period 26 April 1986 until 26 April 1987,
- \(30\, mSv\) for the 2\(^{nd}\) year
- \(25\, mSv\) for the 3\(^{rd}\) and the 4\(^{th}\) year (1988 and 1989)

From 1991: Belarus, Russian Federation, Ukraine:
- Intervention level of \(1\, mSv/a\) for post-emergency situations
- Exceeding this level triggered the implementation of remediation measures

Fukushima: Government of Japan (2011)
- Reference level for remediation of \(1mSv/a\) as a long-term goal
Remediation activities
Aims of remediation

Reduce external exposure
- Focus on public buildings, kindergartens, schools
- Chernobyl and Fukushima

Reduce internal exposures
- Modification of agricultural practices (fertilizer, ploughing)
- Food restrictions
- Recommendations on the intake of specific foods

Regain and maintain market shares for food
- Fukushima
Techniques for decontamination and remediation

Source: HPA - EURANOS Handbook
## Chernobyl: Achievable decontamination factors (Roed et al., 1995)

<table>
<thead>
<tr>
<th>Surface</th>
<th>Technique</th>
<th>DRRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window</td>
<td>Washing</td>
<td>10</td>
</tr>
<tr>
<td>Walls</td>
<td>Sandblasting</td>
<td>10-100</td>
</tr>
<tr>
<td>Roofs</td>
<td>Hosing and/or sandblasting</td>
<td>1-100</td>
</tr>
<tr>
<td>Gardens</td>
<td>Digging</td>
<td>6</td>
</tr>
<tr>
<td>Gardens</td>
<td>Removal of surface</td>
<td>4-10</td>
</tr>
<tr>
<td>Tree and shrubs</td>
<td>Cutting back or removal</td>
<td>~ 10</td>
</tr>
<tr>
<td>Streets</td>
<td>Sweeping and vacuum cleaning</td>
<td>1-50</td>
</tr>
<tr>
<td>Streets (asphalt)</td>
<td>Lining</td>
<td>&gt; 100</td>
</tr>
</tbody>
</table>
## Fukushima: Commonly implemented remediation measures (IAEA, 2015)

<table>
<thead>
<tr>
<th>Target</th>
<th>Remediation measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Houses, buildings</td>
<td>Removal of deposits from the roof, gutters and any decking</td>
</tr>
<tr>
<td></td>
<td>Wiping roofs and walls</td>
</tr>
<tr>
<td></td>
<td>Vacuum sanding</td>
</tr>
<tr>
<td></td>
<td>High pressure washing</td>
</tr>
<tr>
<td>Schoolyards, gardens and parks</td>
<td>Topsoil removal</td>
</tr>
<tr>
<td></td>
<td>Weed/grass/pasture removal</td>
</tr>
<tr>
<td>Roads</td>
<td>Removal of deposits in ditches</td>
</tr>
<tr>
<td></td>
<td>High pressure washing</td>
</tr>
<tr>
<td>Gardens and trees</td>
<td>Mowing</td>
</tr>
<tr>
<td></td>
<td>Removal of fallen leaves</td>
</tr>
<tr>
<td></td>
<td>Removal of topsoil</td>
</tr>
<tr>
<td></td>
<td>High pressure washing</td>
</tr>
<tr>
<td></td>
<td>Paring of fruit trees</td>
</tr>
<tr>
<td>Farmlands</td>
<td>Tillage reversal</td>
</tr>
<tr>
<td></td>
<td>Topsoil removal</td>
</tr>
<tr>
<td></td>
<td>Soil treatment (e.g. enhanced application of fertilizer)</td>
</tr>
<tr>
<td></td>
<td>Soil hardening and removal</td>
</tr>
<tr>
<td></td>
<td>Weed/grass/pasture removal</td>
</tr>
<tr>
<td>Animal production</td>
<td>Control of radiocaesium levels in animal feed</td>
</tr>
<tr>
<td>Forests and woodland</td>
<td>Removal of fallen leaves and lower twigs</td>
</tr>
<tr>
<td></td>
<td>Pruning</td>
</tr>
</tbody>
</table>
Reduction of surface decontamination factor in residential areas
(Data mostly from 2011, MoE, Japan, 2013)

<table>
<thead>
<tr>
<th>Surface (Observations)</th>
<th>Method</th>
<th>Reduction of activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eaves, roofs, gutters (343)</td>
<td>Removal of deposits, Subsequent high pressure washing</td>
<td>3.5 (2-5)</td>
</tr>
<tr>
<td>Storm watch bassins (85)</td>
<td>Subsequent high pressure washing</td>
<td>3.8 (2-5)</td>
</tr>
<tr>
<td>Street gutters (132)</td>
<td>Wiping off; washing with brushes; high pressure washing, often with brushing or wiping off</td>
<td>4 (2.5-10)</td>
</tr>
<tr>
<td>Roofs (464)</td>
<td>Wiping off; washing with brushes; high pressure washing, often with brushing or wiping off</td>
<td>2.0 (1.3-10)</td>
</tr>
<tr>
<td>Outer walls (64)</td>
<td>Mowing; topsoil stripping (3–5 cm or more); soil replacement; lawn stripping; replacement with quarried stone following removal</td>
<td>2.4 (1.1-10)</td>
</tr>
<tr>
<td>Garden, other ground (446)</td>
<td>Topsoil stripping</td>
<td>2.4 (1-10)</td>
</tr>
<tr>
<td>Sport grounds, unpaved (271)</td>
<td>Topsoil stripping</td>
<td>8.3 (5-10)</td>
</tr>
<tr>
<td>Roads, paved surfaces (506)</td>
<td>Some sweeping; (high pressure) washing, Removal of sand/soil or brushing; grinding (shot blasting)</td>
<td>1.4 (1-3)</td>
</tr>
<tr>
<td>Parking lots, other paved areas (601)</td>
<td>Washing, (some sweeping); high pressure washing, often with brushing; grinding (shot blasting, vacuum blasting, dust collection sanders and grinders)</td>
<td>2.4 (1.4-10)</td>
</tr>
</tbody>
</table>
Reduction factors for the Cs-transfer to agricultural products derived after the Chernobyl and Fukushima accidents

<table>
<thead>
<tr>
<th>Remedial option</th>
<th>Chernobyl accident</th>
<th>Fukushima Daiichi accident</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top soil removal</td>
<td>Not applied to farmland</td>
<td>4-5</td>
</tr>
<tr>
<td>Normal ploughing</td>
<td>2.5-3</td>
<td>1.5-2.5</td>
</tr>
<tr>
<td>Deep ploughing (Dose rate reduction at 1 m)</td>
<td>3-8</td>
<td>2-3</td>
</tr>
<tr>
<td>Replace 0-5 cm-layer with soil from 50 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reverse tilling soil</td>
<td>10-16</td>
<td>-</td>
</tr>
<tr>
<td>Potassium application</td>
<td>1.5-3</td>
<td>1.5-3</td>
</tr>
<tr>
<td>Application of organic fertilizer</td>
<td>1.5-3</td>
<td>1.3-2.5</td>
</tr>
<tr>
<td>Application of sorbents</td>
<td>1.3-2</td>
<td>1.5-1.8</td>
</tr>
<tr>
<td>Radical renovation</td>
<td>2-9</td>
<td>8</td>
</tr>
<tr>
<td>Simple renovation</td>
<td>2-3</td>
<td>4</td>
</tr>
</tbody>
</table>

Renovation: Combination of ploughing, re-seeding, fertilization and drainage
Remediation success
Short – and long-term countermeasures after the Chernobyl accident to reduce internal exposure

- **Restrictions on grazing and fresh fodder to reduce thyroid doses**
  - Very effective, if applied immediately
  - Delayed implementation of early countermeasures in the former Soviet Union
  - Immediate information was not given, particularly for private farmers

- **Agricultural countermeasures to reduce the long-term exposures from radiocaesium**
  - Food restriction: especially in milk and meat
  - Treatment of pasture: ploughing, re-seeding, K-fertilizer, lime
  - Clean fodder and caesium binders (Prussian Blue)

- **Aquatic pathways**
  - Early restrictions on drinking water
  - Early restrictions on the consumption of freshwater fish
  - Other countermeasures generally ineffective
Countermeasures after the Chernobyl accident to reduce external exposure (IAEA, 2006)

Activities

- Washing of buildings with water or special solutions
- Cleaning of residential areas
- Cleaning and washing of roads
- Removal of contaminated soil
- Decontamination of open water supplies

Emphasis

- Schools and kindergartens
- Hospitals
- Frequently visited buildings

1000 settlements with tens of thousands of residences and public buildings

IAEA
Chernobyl: Effectiveness of remedial actions
Chernobyl Forum Report (IAEA, 2006)

• Decontamination of settlements reduced external dose during the first years
  • Proper remediation assessment is necessary for ensure success
  • Reduction of dose rates over treated plots by a factor of 1.5-15
  • Generation of large amounts of low-level waste
  • High costs, not all areas were treated

• Average reductions of annual external exposures
  • Confirmed by individual measurements
    • General population: 10-20 %
    • Children in kindergarten: 30 %
    • Outdoor workers: 10 %
Reductions in ambient dose rate in Tamura City in Special Decontamination Area 1

A) Residential areas (n = 4,130)
Before > After — 36% reduced
Before > Post monitoring — 45% reduced

B) Farmland (n = 3,774)
Before > After — 25% reduced
Before > Post monitoring — 37% reduced

C) Forests close to residential areas (n = 3,359)
Before > After — 21% reduced
Before > Post monitoring — 27% reduced

D) Roads (n = 2,250)
Before > After — 25% reduced
Before > Post monitoring — 39% reduced

*Conducted between Sep – Oct 2013
Decontamination factors ($DF_a$) for different targets: MOE decontamination model evaluation project in six SDA 3 sites
Remediation after the radiological accident in the city of Goiania (Brazil)
Place and time of the accident

**Goiania (Brazil), September 1987**

- Population: 1 million
- 1350 km to Rio de Janeiro, 900 km to Sao Paolo
- Accident in the poorer part of the city
Background

- A private radiotherapy institute moved to new premises
  - A radiation therapy unit with a Cs-137 source was left in place

- No safety and security measures taken
  - A notification to the regulator was not given
  - The premises were not secured, access wasn’t restricted
  - The premises were partly demolished
Characteristics of the source

- Activity (Sept. 1987): 50.9 TBq (1375 Ci)
- Mass: 93 gram
- Volume: 31 cm³
- Chemical form: Cesium-chloride
  - Characteristics: Water soluble, readily dispersible
- Dose rate at 1 m: 4.6 Gy/h (460 rad/h)
Monitoring points and contamination pattern
Locations of the main contamination
Radiation Protection Criteria

In 1987 accident, the relevant ICRP recommendations were published in Publication 26

Dose criteria applied for the accident
- 5 mSv in the first year
- 1 mSv/a lifetime average (70 years)

Operational criteria
- Control of access: 10 μSv/h
- Evacuation 2.5 10 μSv/h initially, later 10 μSv/h
  150 μSv/h for unoccupied areas
First actions taken

**Screening measurements**
- Elevated dose rates in an area of about 1 km²
- Very heterogeneous contamination pattern

**Measures taken**
- Restricting access to the area
- Evacuation of the area
- Monitoring and treatment of the most exposed people
- Decontamination including soil removal
- If necessary demolition of houses
- Reconstruction of areas
Radiological impact to the local population

- **Area with enhanced radiation levels:** 1 km²
  - Locations with main contamination: 7
  - Additional locations: 42

- **Monitored persons:** 120,000
  - Contaminated persons: 249 (internal/external)

- **Radiation injuries:** 28
  - Hospitalized persons: 20
  - Serious overexposures: 14
  - Fatalities due to acute radiation: 4
Decontamination work

Demolition
- Houses and removal of debris
- Metallic structures

Removal of material
- Bundles of paper, plastic waste
- Felled trees
- House furniture
- Soil according to soil profile measurements

Covering areas
- Padding
- Concrete
Contamination of houses and evacuation

- **Houses**
  - Monitored: 159
  - Contaminated: 101
  - Evacuated: 41
  - Decontaminated: 42
  - Demolished: 6
  - Reconstructed: 53

- **Evacuated people** 200
Demolishing houses
Monitoring during demolishing work
Demolishing houses
Soil removal procedure

- **Dose rate measurements**
  - Identify the area to be remediated

- **Taking soil profiles**
  - Determine the soil layer to be removed
  - Avoiding removal of too much clean soil

- **Step by step removal of soil**
  - Using a mop
  - Removal of the first layer reduced the gamma-dose rate by 50%
Soil removal
Covering contaminated areas

Covering contaminated areas with concrete

Covering contaminated areas with clean soil

Felling contaminated trees
Waste generated during the accident

Mass and volume

- 6000 tons, 3500 m³

Waste storage

- 1343 metallic boxes (1.7 m³)
- 4223 drums (0.2 m³)
- 10 shipping containers (32 m³)
- 8 concrete cylinders

Recovered activity

- 44 TBq in the waste out of 51 TBq
Frequency distribution of projected committed doses without decontamination therapies of persons contaminated number of individuals versus 70 year (Gray)
Frequency distribution of **cytogenetic** dose estimates (Gy)
Remediation success

- Difficult to quantify in terms of averted doses
- Recovered activity in the waste
  - 44 TBq in the waste out of 51 TBq
Conclusions

- **Effective measure available**
  - To reduce surface contaminations
  - To reduce the intake of activity
    - Food restrictions
    - Modification of agricultural practice

- **Reduction of doses to people**
  - Requires rigorous application of those measures
  - Continuous efforts

- **Overall dose reduction**
  - External: 10-50 % (Chernobyl, Fukushima)
  - Internal Chernobyl:
    30 % of the collective ingestion dose (Fesenko, 2009)
  - Internal Fukushima:
    Ingestion doses largely avoided due to strict monitoring and food bans