Radiological environmental protection at CERN

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Introduction

• CERN accelerators
• The source of the problem – beam loss
• Radiation and radioactive substances
• Monitoring
• Impact assessment
• Example (2003)
• Outlook
CERN accelerators (1)

- Linacs
- PSB
- PS
- SPS
- (LHC)
- Experimental Areas
  - ISOLDE
  - AD, LEAR, n-TOF
  - East Hall, West Hall
  - Prévessin site
  - CNGS
CERN accelerators (2)
The source of the problem – beam loss

- High-energy particle beams must interact with matter to generate radiation and to produce radioactive substances:
  - Beam cleaning elements (collimators)
  - Beam extraction elements (kickers…)
  - Targets
  - Detectors
  - Beam dumps
The source - basic difference

- **Hadron machines (p, HI)**
  - Nuclear cascades (p, n, n-bar, p-bar, $\pi^{0,\pm}$, K, $\gamma$, e$^\pm$, $\mu^\pm$)
  - Activation of materials
  - Synchrotron radiation negligible
- **Example: SPS, LHC**

- **Lepton machines (e$^+e^-$)**
  - Only electromagnetic cascades ($\gamma$, e$^\pm$, $\mu^\pm$)
  - Synchrotron radiation
  - Activation negligible

- **Example: LEP – the clean machine**
Stray radiation (1)

• To get into the environment the radiation must pass thick material layers:
  – Shielding structures
  – Earth (for underground installations)

• It must be **penetrating**
  – Photons (electrons and positrons)
  – Muons
  – Neutrons

• Can be calculated by Monte-Carlo (FLUKA)
Stray radiation (2)

 Courtesy of S. Roesler and G.R. Stevenson (CERN)
Stray radiation - photons

- Propagated EM cascade
- Mixture of $\gamma$ and $e^\pm$
- Lower energies replenished by Compton-scattered $\gamma$ of higher energies
- Up to 10 MeV (neutron shoulder)
Stray radiation - muons

- Progeny of $\pi^\pm$
- All energies
- Usually MIP’s (~GeV/c)
- Difficult to absorb
- Remain well focused
Stray radiation - neutrons

- From thermal to several MeV
- Scattered
- Activating (e.g. (n,γ) events)
Stray radiation - time structure

- An important constraint for monitoring: Pulsed radiation fields
- Two extreme cases:
  - PS super-cycle: ~0.1 μs each 12 s
  - Collider: train of bunches / several μs between two bunches – quasi-continuous
- Photons and muons practically follow the beam time structure
- Neutrons can be de-synchronized through moderation
Stray radiation – minimization strategy

- Avoid beam losses (accelerator technology, reliability of operation)
- Shielding structures (earth, concrete, iron, marble…)
- Chicanes
- Underground (LHC down to -150 m)
Radioactive substances

- Spallation reactions (neutron-deficit radionuclides, $\beta^+$, EC)
- Neutron capture (neutron-rich radionuclides, $\beta^-$)
- $\beta/\gamma$ emitters, no $\alpha$ (except ISOLDE)
- Beam / target – the higher $Z$, the more species
- Wide range of half-lives
- The shorter the half-live, the higher the activity: $A = \lambda N$
- But too short-lived radionuclides do not reach the environment or have a negligible radiological effect
Radioactive substances

• Carried to the environment by fluids:
  – Air
    • Ventilation of beam areas (cooling by air often needed)
  – Water
    • Water-cooling circuits (usually closed, primary circuits have ion exchangers that trap radioactive ions e.g. \(^{7}\text{Be}\))
    • Water leaks (cannot be 100% excluded)
    • Infiltration water (cannot be 100% avoided)
  – Particles from earth and concrete (transported with fluids)
Radioactive substances – air (1)

- **Direct activation:**
  - Targets: O$_2$, N$_2$, Ar, CO$_2$

- **Aerosol:**
  - As from earth & concrete
  - Will be discussed later

- **Dominating short-lived:**
  - $^{11}$C, $^{13}$N, $^{14,15}$O ($\beta^+$)
  - $^{41}$Ar ($\beta^-$, (n, $\gamma$) on $^{40}$Ar)

- **Dominating longer-lived:**
  - $^7$Be (EC)
  - $^3$H (HT), $^{32}$P, $^{33}$P, $^{35}$S, $^{22}$Na

- **Others:**
  - $^{10}$Be, $^{14}$C, $^{19}$O, $^{18}$F, $^{23,24}$Ne, $^{24}$Na, $^{25}$Na, $^{27,28}$Mg, $^{26,28,29}$Al, $^{31,32}$Si, $^{30,35}$P, $^{37,38}$S, $^{34m,36,38,39,40}$Cl, $^{37,39}$Ar, $^{38,40}$K
Radioactive substances – air (2)
Air: effective dose breakdown – urban population

[Graph showing the effective dose breakdown for various elements in the urban population, with percentages on the y-axis and elements on the x-axis.]
Air: effective dose breakdown – rural population

Rural population
(ingestion by infants)
Radioactive substances - water

- **Direct activation:**
  - Target: $H_2O$

- **Particles:**
  - As from earth & concrete
  - Will be discussed later

- **Leached:**
  - $^3H$, $^{24}Na$, $^{22}Na$ (soluble)

- **Dominating short-lived:**
  - $^{11}C$, $^{13}N$, $^{14,15}O$ ($\beta^+$)

- **Dominating longer-lived:**
  - $^3H$ (HTO)
  - $^7Be$ (EC)
Radioactive substances - particles

- Targets with high Z available
- Interplay between mobility and half-life
- Selection
- Sometimes species one would not expect

- $^3$H, $^7$Be,
- $^{22}$Na, $^{24}$Na
- $^{46}$Sc, $^{48}$V, $^{54}$Mn,
- $^{56}$Co, $^{57}$Co, $^{58}$Co, $^{60}$Co
- $^{65}$Zn
- $^{134}$Cs
- $^{152}$Eu

Except for $^3$H, activity densities are 2-3 orders of magnitude below that of $^7$Be but still to be considered.
Radioactive substances - ISOLDE

• Uranium & Thorium carbide targets
  – High-Z targets ⇒ produce anything you can imagine
• Emanating alpha activity ($^{220}$Rn ⇒ $^{212}$Pb)
• Emanating iodine ($^{124}$I, $^{125}$I, $^{126}$I, $^{131}$I)
• Noble gases captured from vacuum pumps ($^{42}$Ar, $^{85}$Kr, $^{127}$Xe, $^{129m}$X, $^{131m}$Xe, $^{133}$Xe)
Air – minimization strategy

- Avoid beam losses
- Avoid development of nuclear cascades in air
  - Solid matter shielding (iron, marble…)
  - Helium balloons (low-Z target)
- Semi-closed cooling circuits
  - Decay of short-lived
  - Pre-cleaning of aerosol
- HEPA filters at the end of the ducts
Water – minimization strategy

- Closed cooling circuits equipped with ion exchangers close to hot areas (only HTO remains)
- Construction in geological layers impermeable to water (molasse)
- Concrete with layers impermeable to water
- Avoid draining over concrete (metallic pipes)
- Cover the facility against rain
- Hydro-geological study before the project starts
Monitoring – main components

• Monitoring of releases of radioactive substances (air, water)
• Monitoring of stray radiation
• Measurement of activity densities in environmental matrices
• Assessment of the ecological and radiological impacts
Monitoring - 9 ventilation stations (1)

- Differential ionization chamber
  - Short-lived radioactive gases
  - $^{11}$C, $^{13}$N, $^{14}$O, $^{15}$O, $^{41}$Ar
  - Online readout

- Aerosol sampler
  - Analyzed offline
  - $^{7}$Be, $^{22}$Na, $^{46}$Sc, $^{48}$V, $^{54}$Mn, $^{60}$Co...

- Ventilation flow-rate sensor
  - Online readout

- Monthly balance sheets of released activity
Monitoring - 9 ventilation stations (2)

- Tritium: Conservative estimates based on
  - Maximum $^3\text{H}$ activity densities measured (HTO, HT)
  - Air amounts released
- ISOLDE:
  - Exchange of UC and ThC targets – short-term operations with alpha emanation
  - Emptying of reservoirs with pump gases
  - Screening of total alpha on aerosol
  - Lucas cell and decay curve analysis
Monitoring - 5 water monitoring stations

- At the end of drainage networks
- Water monitor
  - NaI(Tl) probe in a water tank
  - For short-lived (\(^{11}\text{C}, \^{13}\text{N}, \^{24}\text{Na}\))
  - Online readout
- Automatic water sampler
  - Analyzed offline
  - \(^{3}\text{H}, \^{7}\text{Be}, \^{22}\text{Na}, \text{total beta}\)
- Water flow-rate sensors
- Monthly activity density sheets
- Annual releases
Monitoring - stray radiation

- Two kinds:
  - Gamma and penetrating charged particles (µ)
  - Neutrons
- Two instruments
  - Pressurized ionization chamber
  - Rem-counter
- Calibrated for $H^*(10)$
- Online readout
- Quarterly integration
- 40 stations completed with
  - about 200 $^{6}\text{LiF}/^{7}\text{LiF}$ TLD
Monitoring - environmental samples

- **9 aerosol sampling stations**
  - Filters exchanged twice a month
- **4 grass/soil sampling places**
  - Annual collection (late summer)
- **2 precipitation collectors**
  - Monthly collection (precipitation rate online)
- **6 sampling points in rivers**
  - Annual (late summer)
  - Water
  - Sediment
  - Bryophytes
- **5 groundwater wells**
  - Annual (autumn)
- **Agricultural products**
  - According to availability: colza, asparagus, wheat, sunflower, wine

High volume aerosol sampler
600 m³/h
Filter exchanged once a week
Monitoring – environmental laboratory

- Optimized for $\beta/\gamma$ analyses (+ $\alpha$ screening for ISOLDE)
- Gamma spectrometry
  - 4 HPGe detectors (up to 52% SLL)
  - Genie 2000
- Total $\alpha/\beta$ counting
  - Proportional counter with automatic sample changer (Eberline FHT770GR)
- Liquid scintillation counter ($^3\text{H}$)
  - Packard TRICARB 3700 TR
  - MDA: 1.6 Bq/l, customized DE software
- Auxiliary equipment
  - 4 water evaporators, flame photometer for $[\text{K}+]$, 2 drying ovens, distillation apparatus…
Detection limits

• Release monitors:
  - Short-lived gases in ventilation: ~10 kBq/m³
  - Water (Bq/l):
    • $^{11}$C, $^{13}$N: 1.6
    • $^{24}$Na: 3.0

• Laboratory:
  - Aerosol ($\mu$Bq/m³):
    • Total $\beta$: 25
    • $^{7}$Be: 60
    • $^{22}$Na, $^{60}$Co, $^{137}$Cs: <4
  - Aerosol HVS ($\mu$Bq/m³):
    • $^{7}$Be: 7
    • $^{22}$Na, $^{60}$Co, $^{137}$Cs: <0.5
  - Water (Bq/l):
    • Total $\beta$: 0.014
    • $^{3}$H: 1.6
    • $^{7}$Be: 2
    • $^{22}$Na, $^{60}$Co, $^{137}$Cs: <0.2
Monitoring - spatial extent

Geneva and Pays de Gex

Meyrin site

Prévessin site
Impact assessment – ecological

• Environmental samples:
  • Comparison with Swiss immission limits for air and water (ORaP)
  • Comparison with Swiss exemption limits for other matrices (grass, soil, sediment, bryophytes..., ORaP)

• Agricultural products:
  • Comparison with Swiss food limits (OSEC)
Impact assessment – radiological (1)

- Expressed in terms of effective dose to members of the public
- CERN Radiation Safety Manual:
  - Guideline value related to source: 0.3 mSv/a
- Critical groups of the population:
  - Meyrin Site: Border guards
  - Prévessin Site and SPS: Waste dump workers
  - Water releases: People making use of water from the rivers Nant d’Avril (CH) and Le Lion (F).
Impact assessment – radiological (2)

- **Stray radiation:**
  - Directly from the readings of the stray radiation monitors assuming suitable occupancy factors

- **Releases of radioactive substances:**
  - Methodology based on:
    - HSK-R-41 (mainly air)
    - IAEA Safety Report No. 19 (additional exposure pathways added to those assumed in HSK-R-41)
    - ICRP 72
  - Computer code available
  - Weather statistics from the airport Geneva Cointrin (72 wind direction sectors, 20 wind speed bins, 6 stability classes)
Impact assessment – radiological (3)

- Air releases
  - Scenarios
    - Short-term actual release
    - Short-term hypothetical release for release limit calculation
    - Short-term accident
    - Long-term chronic release
  - Exposure pathways
    - External from radioactive plume and ground deposition
    - Inhalation
    - Ingestion (fruits and vegetables, meat, dairy products)
Impact assessment – radiological (4)

- Water
  - Scenarios
    - Release into a river + field irrigation
    - Release into a sewage treatment plant
  - Exposure pathways
    - External from immersion in the river water and from sediment or sludge
    - Drinking of water and ingestion of fish from the river
    - Ingestion of food (watered animals, irrigated fields, as for air)
    - External on irrigated fields, inhalation on irrigated fields
    - Inhalation of re-suspended sludge
    - Fertilization of fields with sludge (F), burning of sludge (CH)
Impact assessment – radiological (5)

- External exposure from radioactive plume dominates → special attention in the model
- Space integral of the dose kernel from Gaussian plume including conversion from the dose absorbed in air to the effective dose

\[
D_\gamma = Q \frac{\varepsilon}{\rho_{\text{air}}} \frac{1}{4\pi} \sum_i e_{\text{kerma}}(E_i)\mu_{a,i}E_iY_i \int \frac{B(E_i, \mu_ir)\exp(-\mu_ir)\chi(r)}{r^2} d^3r
\]
Impact assessment – radiological (6)

\[
\int e^{-\mu r} f(r) \frac{d^3r}{r^2} \quad \rightarrow \quad \frac{dP}{dr} = \mu e^{-\mu r} \quad \rightarrow \quad \frac{2\pi}{\mu} \frac{1}{N_0} \sum_{i=1}^{N_0} f(r_i)
\]

- Monte Carlo integration with biased sampling of distance to volume elements \(d^3r\)
- Random sampling of weather situations (for long-term releases) according to the weather statistics
- Resembles an analog Monte Carlo simulation
Example – net doses in 2003

![Graph showing ambient dose equivalent in 2003 for different sites and particle types.](image-url)
Example – $^7$Be in aerosol in 2003 (1)

Meyrin site and its vicinity 2003

$^7$Be activity density (mBq/m$^3$)
Example – $^7$Be in aerosol in 2003 (2)

Prévessin site and distant sites
2003

$^7$Be activity density (mBq/m$^3$) vs. Month in 2003
Example – river bryophytes in 2003

Bq/kg dry weight

<table>
<thead>
<tr>
<th>Sample</th>
<th>LL1</th>
<th>LL2</th>
<th>LL3</th>
<th>LL4</th>
<th>NA</th>
<th>VE</th>
<th>Reference river</th>
</tr>
</thead>
<tbody>
<tr>
<td>River</td>
<td>Le Lion (F)</td>
<td>Nant d'Avril (CH)</td>
<td>Versoix (CH)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^7\text{Be}$</td>
<td>1470 ± 70</td>
<td>300 ± 20</td>
<td>340 ± 20</td>
<td>180 ± 30</td>
<td>280 ± 20</td>
<td>380 ± 30</td>
<td></td>
</tr>
<tr>
<td>$^{54}\text{Mn}$</td>
<td>12 ± 2</td>
<td>97 ± 3</td>
<td>&lt; 0.5</td>
<td>&lt; 3</td>
<td>&lt; 2</td>
<td>&lt; 2</td>
<td></td>
</tr>
<tr>
<td>$^{60}\text{Co}$</td>
<td>&lt; 1</td>
<td>2.1 ± 0.6</td>
<td>&lt; 0.6</td>
<td>&lt; 4</td>
<td>&lt; 1</td>
<td>&lt; 2</td>
<td></td>
</tr>
<tr>
<td>$^{137}\text{Cs}$</td>
<td>16.7 ± 0.8</td>
<td>11 ± 2</td>
<td>7.1 ± 0.7</td>
<td>7 ± 4</td>
<td>14 ± 2</td>
<td>6 ± 2</td>
<td></td>
</tr>
</tbody>
</table>
## Releases and effective doses in 2003

<table>
<thead>
<tr>
<th>Radionuclide category</th>
<th>$R$ (GBq)</th>
<th>$D$ (Sv/Bq)</th>
<th>$E$ (µSv)</th>
<th>$R$ (GBq)</th>
<th>$D$ (Sv/Bq)</th>
<th>$E$ (µSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air releases</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tritium (water vapour)</td>
<td>170</td>
<td>5.7E-20</td>
<td>0.0097</td>
<td>17.0</td>
<td>3.8E-19</td>
<td>0.0065</td>
</tr>
<tr>
<td>$^7$Be (aerosol)</td>
<td>0.30</td>
<td>1.9E-17</td>
<td>0.0056</td>
<td>0.017</td>
<td>1.6E-16</td>
<td>0.0028</td>
</tr>
<tr>
<td>Short-lived gases ($^{11}$C)</td>
<td>9600</td>
<td>3.4E-19</td>
<td>3.3</td>
<td>1380</td>
<td>5.5E-19</td>
<td>0.76</td>
</tr>
<tr>
<td>Other beta/gamma ($^{60}$Co)</td>
<td>0.0100</td>
<td>1.5E-14</td>
<td>0.15</td>
<td>0.00073</td>
<td>1.2E-13</td>
<td>0.088</td>
</tr>
<tr>
<td>Radioactive iodine ($^{126}$I)</td>
<td>0.0103</td>
<td>5.6E-16</td>
<td>0.0058</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Alpha emitters ($^{212}$Pb)</td>
<td>0.0076</td>
<td>4.3E-16</td>
<td>0.0032</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total from emissions</strong></td>
<td></td>
<td></td>
<td></td>
<td>3.4</td>
<td></td>
<td>0.86</td>
</tr>
<tr>
<td><strong>Water releases</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Tritium (HTO)</td>
<td>6.3</td>
<td>9.5E-20</td>
<td>0.00060</td>
<td>38</td>
<td>9.5E-20</td>
<td>0.0036</td>
</tr>
<tr>
<td>Other beta/gamma ($^{22}$Na)</td>
<td>0.041</td>
<td>7.1E-16</td>
<td>0.029</td>
<td>0.053</td>
<td>7.1E-16</td>
<td>0.037</td>
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<tr>
<td><strong>Total from water releases</strong></td>
<td></td>
<td></td>
<td>0.030</td>
<td></td>
<td></td>
<td>0.041</td>
</tr>
<tr>
<td><strong>Stray radiation</strong></td>
<td></td>
<td></td>
<td>21</td>
<td></td>
<td></td>
<td>14</td>
</tr>
<tr>
<td><strong>Total from all sources (rounded)</strong></td>
<td>25</td>
<td></td>
<td>15</td>
<td></td>
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</tbody>
</table>
Effective dose breakdown

- Stray radiation: 86%
- Short-lived gases: 13%
- Others: 0.88%
Outlook - on the way

• LHC: unprecedented beam intensity and energy
  – 2 beams with 7 TeV protons
  – 350 MJ of stored energy per beam

• RAMSES project
  – PIPS chambers for short-lived radioactive gases (DL of ~ 1 kBq/m³)
  – Water monitors with spectroscopic analysis
  – Ultrasonic anemometers
  – State-of-the-art data acquisition

• LHC & CNGS: Number of stations and samples will be doubled.
Outlook – future accelerators

• CLIC – Compact Linear Collider (clean like LEP)
• Future challenges:
  – Neutrino factories: hadron beams of MW power
  – Muon colliders
    • Exposure from neutrinos (!!)
    • Critical groups of the population at long distances from the source
    • Neutrino dosimetry (!!)