Radon Mapping in the European Atlas of Natural Radiation

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Contents

• REM Activities

• Why a European Atlas of Natural Radiation (EANR)?

• Overview on Radon Mapping

  ✓ INDOOR RADON:
    - European Indoor Radon Map _ Belgium (Walloon)_ UK

  ✓ GEOGENIC RADON POTENTIAL:
    - Multivariate classification approach
      Geochemical maps: U, Th, K in soil
      Geochemical maps: U, Th, K in in bedrock
      Map of terrestrial gamma ray intensity

• Conclusions
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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</table>
| REMdb   | Euratom Art 36 data base:  
On-line database that contains the environmental monitoring data from EU28 and serves as basis to produce the “Monitoring Reports”. |
| EANR    | European Atlas of Natural Radiation:  
Atlas focussed on indoor radon, but will also cover information on the components contributing to the natural background |
| ECURIE  | European Community Urgent Radiological Information Exchange:  
The official early notification system of the Commission. REM develops the software and provides maintenance, training and technical assistance in case of exercise/emergency |
| EURDEP  | EUropean Radiological Data Exchange Platform:  
complementary to ECURIE, it continuously provides results from the automatic early warning networks in Europe (38 countries) |
| CBRN    | Local atmospheric dispersion modelling in the frame of CBRN threats |
| EPR     | Emergency Preparedness and Response:  
First steps to develop an “operational” nuclear emergency response system |
Legal Framework of the REM Activities

- Euratom Treaty

Art. 35 Each Member State shall establish the facilities necessary to carry out continuous monitoring of the level of radioactivity in the air, water and soil and to ensure compliance with the basic standards...

Art. 36 The appropriate authorities shall periodically communicate information on the checks referred to in Article 35 to the Commission so that it is kept informed of the level of radioactivity to which the public is exposed.

Art. 39 The Commission shall set up within the framework of the Joint Nuclear Research Centre, as soon as the latter has been established, a health and safety documentation and study section. This section shall in particular have the task of collecting the documentation and information referred to in Articles 33, 36 and 37 and of assisting the Commission in carrying out the tasks assigned to it by this Chapter.

- Recommendation Euratom/2000/473/Euratom on the application of Article 36 of the Euratom Treaty concerning the monitoring of the levels of radioactivity in the environment for the purpose of assessing the exposure of the population as a whole

- Council Decision 87/600/Euratom on Community arrangements for the early exchange of information in the event of a radiological emergency

- Council Directive 2013/59/Euratom laying down basic safety standards for protection against the dangers arising from exposure to ionizing radiation (BSS)
**Primary objectives:**

- Increase public (and political) awareness of radioactive environment
- Visualize the situation on a European level
- Contribute to methodology and scientific aspects

**Indirect objectives and results:**

- Potential support to EU Member States for the radon action plan (new European Basic Safety Standards Directive, Art. 103):
  
  “Member States shall identify areas where the radon concentration (as annual average) in a significant number of buildings is expected to exceed the relevant national reference level” (cf. “radon priority area”, “high radon area”, "radon affected area”)

- Stimulate research on radon mapping, risk definition and estimation etc.
- Generate and provide methodically harmonized datasets
## European Atlas of Natural Radiation: Contents

<table>
<thead>
<tr>
<th>MAPS</th>
<th>STATUS</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor Radon - EIRM</td>
<td>advanced</td>
<td>30 countries!!</td>
</tr>
<tr>
<td>Geogenic Radon - EGRM</td>
<td>first version</td>
<td>Improvements: Multivariate approach</td>
</tr>
<tr>
<td>Cosmic radiation</td>
<td>advanced</td>
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<tr>
<td>Terrestrial gamma dose rate - TGDR</td>
<td>first version</td>
<td>Estimation from EURDEP data</td>
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<tr>
<td>U, Th and K in soil and bedrock</td>
<td>first version</td>
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<tr>
<td>Outdoor radon</td>
<td>in discussion phase</td>
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<td>Water (ground and surface water)</td>
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<tr>
<td>Total dose by natural radiation</td>
<td>in discussion phase</td>
<td>Extensive modelling &amp; additional spatial demographic data needed</td>
</tr>
</tbody>
</table>
EUR radon survey 2005:

- Many countries had radon “maps”
- Different visualization techniques
- Different input data
- Different mapping methods
- Different purposes

Dubois, G. (2005): An Overview of Radon Surveys in Europe
EUR Report 21892, Office for Official Publications of the European Communities, Luxembourg
Overview on Radon Mapping

Purpose of Radon Maps

- **Display**: Describe the actual situation

- **Predict** probability that a certain building could have high radon exposition

- **Identify** radon priority areas (as in article 103), areas in which more measurements are required or remediation actions should be taken
Two main strategies for delineating radon exposure geographically

- Direct measurements of *indoor radon* concentration:
  - European Indoor Radon Map
  - Belgium (Wallon) Map
  - UK

- Indirect methods (concept of *geogenic radon potential*):
  1. Soil gas radon and permeability _ Neznal
     - European Geogenic Radon Map _Trial map
  2. Gamma dose assessment based on gamma-spectrometry from laboratory, field and aerial surveys
  3. U, Ra concentration in soil and rock
  4. Geological maps
  5. ....
moreover maps differ in terms of....

- Displayed variables and levels
- Interpolation methods
- Spatial resolution
In 2006 during the Prague Radon conference:

- JRC to collect statistics of these data from National Authorities on 10 km x 10 km grid cells

- Annual mean of radon concentration in ground-floor rooms of dwellings

“long term”: to ± cover annual variability; through long-term measurement (better) or seasonal modelling (worse)

“ground floor” – why?
Because the discussions at the time (2005-6) resulted in that ± representative databases are better available for ground floor.
European Indoor Radon Map:

- 10 km x 10 km grid cells
- Living rooms, ground floor
- Long term
- Participants send statistics

Participants:

- 2007: AT, CH, FI, LT, PL, UK
- 2008: BE, CZ, DE, EE, ES, PT
- 2009: AL, DK, FR, HR, IT, NL, SI
- 2010: GR, HU, MK
- 2011: NO, RO
- 2012:
- 2013:
- 2014: IS
- 2015: AZ, BG, IE, MT, SE
- 2016: TR foreseen

European Indoor Radon Map, February 2016

Indoor Rn, ground floor, Number of measurements per 10 km x 10 km grid cell

Number of measurements per cell, MED ± MAD: 4 ± 3
Min/Max number of measurements per cell: 1/23,993

MAD (Median absolute deviation) = \( \text{median}_i \{ | x_i - \text{median}_j (x_j) | \} \)
• 10 km x 10 km grid cells
• Living rooms, ground floor
• Long term
• Participants send statistics

**Status (February 2016):**
• 30 countries participate
• ~25,000 non-empty cells
• ~960,000 original measurements

**EU MS not yet participating:**
• No national survey (LV)
• No national database (SK)
• Not yet replied with data (CY, LU)

Be aware:
AM over cells = estim. spatial mean
≠ mean over exposure
Would require data about building types, distribution of floor levels, demographic data, etc
Some statistics:
- number non-empty cells: 24,779
- original measurements: 962,441
- most populated cell: 23,993 data
- AM(cell AM)= 98.5 Bq/m³
- 95% conf.int. (cell AM): 16.5 ... 272
- Max(cell AM)= 10,117 Bq/m³
- Max(all data)=32,659 Bq/m³
- Variability: CV(cell AM)= 145%

Geographical distribution:
- essentially reflects geology
- probably also tendency reflecting building types and
  living habits, $\propto$ climatic conditions, cultural factors;
  not yet investigated!

European Indoor Radon Map:
Arithmetic means over grid cells

European Indoor Radon Map, February 2016

Indoor Rn, ground floor,
Arithmetic means over 10 km x 10 km grid cells
Retrospect:

- 2005: Mosaic of radon “maps” (indoor conc., radon potential etc.)
- 2006: Prague decision to create a European Indoor Radon Map
- 2007 onwards: Countries send statistics from original measurements
- 2016: 30 countries participate (24 EU-MS + 6 others)
  ~25,000 non-empty 10 km x 10 km grid cells
  ~960,000 original measurements

Prospect:

- JRC to continue to collect statistics, invite more countries (ongoing)
- To succeed we need strong collaboration with countries
- JRC to write summary paper in 2016
Merge the two database!

**Indoor Radon Database**
with different geographical distributions
- long-term track-etch measurements (~7500)
- short-term charcoal measurements (~5000)

**Geological groups**
The data are organized into geological groups, grouping formations of similar ages

**Statistical Analysis**
It showed that a log-normal distribution provides a reasonable description of the data. The t-test results show that the two databases are nearly equivalent from a statistical point of view suggesting that they can be integrated into one.

Mapping

- 1 km X 1 km grid dimension
- Association of geological information to each cell
- Moving average is used to predict the Logarithmic mean in each node using the data belonging to the same geological unit as the node:
  - 30: the maximum number of data to use;
  - 20: the minimum number of data;
  - 20,000 m: the distance (radius) from the grid node that we look up to find data points when calculating the
- Map of the geometrical mean (logarithmic mean)


**PURPOSE:** to estimate the % of dwellings above the Action level

**Mapping**

- Map of percentage above the action level (400 Bq/m$^3$)

\[
\% \text{ above AL} = \left[ \frac{\exp \left( -\frac{(x - \mu)^2}{2 \times \sigma_G^2} \right)}{\sigma_G \times \sqrt{2 \times \pi}} \right] \times \frac{1}{5.99} \times 100
\] % above AL
Mapping

% above AL

Joint Research Centre
• Collaboration between the PHE (Public Health England) and the BGS (British Geological Survey)

• Based on indoor radon measurements and geology

• 2 track detectors per house (bedroom+living room); data corrected occupancy and season factors

• Geology refers Geological combinations derived from the two 1:50000 scale layers available in the UK: Bedrock and Superficial

PURPOSE: maps to show the probability of dwellings exceeding the Rn AL (200 Bq/m3). The variation of radon probability is mapped not only between but also within geological combination.
2 maps are produced in UK:

- **RADON POTENTIAL DATASET**: with detail inside each square km (not freely available, only for commercial use and building regulations)
- **INDICATIVE ATLAS**: showing the maximum radon classes observed at km level

http://www.ukradon.org/information/ukmaps

New European Basic Safety Standards Directive, Art. 103:

“Member States shall identify areas where the radon concentration (as annual average) in a significant number of buildings is expected to exceed the relevant national reference level”

Possible explanations:
- Not inhabited
- Not targeted a priori
- Lack of funding
- Political reasons?
- Radon potential map already exists

=> European Geogenic Radon Map
Geogenic Rn map = independent of anthropogenic factors

defined only in a house

indoor Rn

subject to human activity, temporally variable

variability at different time scales

temporal variability e.g. through upgrading insulation

“what earth delivers”, without influence of human interference, temporally constant over geologic timescale

defined everywhere on solid earth

outdoor Rn

living habits

AT Rn-Potential

meteo

house construction

building materials

geogenic Rn

European Geogenic Radon Map: Background
2. The Radon-Potential

The Radon-Potential shall quantify the Radon risk for an area without taking into account building and living conditions.

Such a measure does not necessarily mirror the actual indoor situation, but it should judge an area for the Radon risk from the ground. While the indoor Rn concentration will change when building structure and living conditions change, the Rn-Potential stays unchanged as a measure for the local situation.

Therefore, the Rn-Potential is the main information concerning the Rn-risk for new houses and housing development areas.

During the ARP a Rn-Potential was defined, derived from indoor measurements: Rn-Potential = Annual mean in a living room at ground level in a standard house. Special procedures were developed to calculate the Rn-Potential from the results of the indoor measurements in combination with relevant characteristics of the house construction and the living style of the inhabitants. Municipalities were classified to 3 Rn-Potential classes (low, medium, high Rn-risk). The Rn-Potential can be seen as the essential result of the ARP.
2008 Radon mapping symposium (Oslo)
- Decision taken to embark upon a European Geogenic Radon Map
- Expert group formed (mainly physicists and geologists)

2009-10 First workshops/expert group meetings (Ispra, Prague)
- Discussions of national approaches and methods how to come to a harmonized European map

2011 Radon workshop (Ispra)
- Follow a classification (multivariate) and continuous approach in parallel
- Use input quantities for classification scheme: standardized indoor radon, soil gas radon, permeability, equivalent Uranium, dose rate, geology class, presence of special geological features
- Prepare first classification maps
2012 Radon Workshop (Prague)

- **Aim:** A geogenic map based on geology
- Each geological unit is assigned to an index value 1 – 4, determined by the position of that unit in Radon Potential scale

\[ \text{RP} = \frac{C}{(-10 \log k - 10)} \]

- The Radon Potential of the units is derived from measured concentrations of radon in soil and permeability (Germany, Belgium and Czech Republic)
- Result: A first, trial (simplified) geogenic map

2013-14 Activities

- A critical analysis of the trial map was performed, and considered introducing new parameters (geochemical data and terrestrial gamma dose)

European Geogenic Radon Map: Multivariate classification approach
European Geogenic Radon Map: Multivariate classification scheme

Grid 10 km x 10 km

Input Variable (i)

SOIL GAS Rn (1)
INDOOR Rn (2)
GEOLOGY (3)
U_{soil} (4)
U_{rock} (5)
SOIL Properties (5)
TGDR (7)

Classification

A B C D

s_1 s_2 s_3 s_4, s_5 s_6 s_7

Weight

\omega_1(n) \omega_2(n) \omega_3 \omega_4(n), \omega_5(n) \omega_6(n) \omega_7(n)

Geogenic Radon Risk Index

n – number of samples per grid cell

Low High
**Input Quantities**

- **SOIL GAS Rn**: Collecting available data from the countries
- **INDOOR Rn**: Existing data from the EIRM
- **GEOLOGY**: Needs knowledge and co-operation of geologist experts – One Geology
- **U_{soil}, U_{rock}**: Existing databases: FOREGS, GEMAS, Geochemical Atlases of Europe and IEDA-EarthChem; Collecting data available from the countries
- **SOIL properties**: Estimate soil permeability using soil properties (grain size) data from LUCAS and European Soil Database, soil erodibility; Collecting data available from the countries
- **TGDR**:
European U, Th and K maps

- **Sources:** $^{238}\text{U}$ series, $^{232}\text{Th}$ series, $^{40}\text{K}$
- **Databases:** GEMAS, FOREGS, national and regional databases
- **Methods:** soil / rock samples, stream sediments, in situ gamma spectrometry, air-borne gamma spectrometry
Geochemical data from 2 databases at European scale:

**FOREGS** (Forum of the European Geological Surveys):
- 900 sample sites
- topsoil and subsoil data
- [http://weppi.gtk.fi/publ/foregsatlas/](http://weppi.gtk.fi/publ/foregsatlas/)

**GEMAS** (geochemical mapping of agricultural and grazing land soil):
- 3000 agricultural soil samples-Ap
- 3000 grazing land soil-Gz
- [http://gemas.geolba.ac.at/](http://gemas.geolba.ac.at/)
FOREGS and GEMAS databases

- European wide;
- Sampling, analysis methods: see respective publications;
- Methods are different between FOREGS and GEMAS harmonization necessary!

For Belgium:

- 5 FOREGS data
- 13 Ap GEMAS
- 13 Gr GEMAS

May be not enough data for develop a reliable map....

Essentially reflects geology! Acidic magmatic rocks (granitoids etc) and certain organic-bearing Palaeozoic sediments have often elevated U concentrations.

Bossew P., 2015. ENVIRA
Radiological data from 4 databases in Belgium:

**SCK-IHE:**
- 35 soil samples (30 cm)
- Laboratory γ-spectrometry

**GENT:**
- 62 measurement sites
- in situ γ-spectrometry

**ISIB:**
- 92 soil samples (50-100 cm)
- Laboratory γ-spectrometry(${}^{226}\text{Ra}$)

**AIRBORNE:**
- Data given at node of a 100m x 100m grid

Correlation with soil classes and with geological units

Existing maps:

Belgian soil maps
- Texture data

European soil maps (1:1000000)
- World soil classes (WRB) and European texture classes (ESB)
  (several parameters available)

European geological maps: OneGeology-Europe
1. Extended set based on indoor radon risk map: 37 units
2. Reduced set: 12 units
2. Schematic set: 4 units

Chronostratigraphic basis
Belgium Example: U maps
• Create homogeneous geological group using lithostratigraphic, petrology and mineralogy knowledge

• Assign U, Th an K concentration value to each geological unit using data from scientific literature

• Preliminary results for Austria

• more than 3000 data analysed!
Targeted quantity: natural terrestrial gamma component of ambient dose equivalent rate, $H^*(10)$

Source: $^{238}$U series, $^{232}$Th series, $^{40}$K in the ground
**Objective A:**

- Better Knowledge and Evaluation of constant contributions

a) inherent background (up to several tens of nSv/h)
b) cosmic dose rate (range EURDEP stations: 40 – 143 nSv/h)
c) artificial gamma dose rate (137Cs after Chernobyl, global fallout)
d) terrestrial gamma dose rate (238U, 235U, 232Th families and 40K)

**Benefits:**

- **EURDEP:** Data Harmonization
- **EANR:** Map the terrestrial gamma dose rate
EURDEP Data

Public interpretation:

NPPs

Expert interpretation:

Different geology

Central Italy

191 nSv/h

86 nSv/h

147 nSv/h

98 nSv/h

136 nSv/h

81 nSv/h

144 nSv/h

144 nSv/h

Apennine Mountains

< DETECTION LIMIT

EURDEP Map 5.4.0
cudep.jrc.ec.europa.eu

Time Interval: 2015-02-26 09:30 - 2015-02-27 09:30
Nuclide: T-GAMMA
Sample Type: EXTERNAL RADIATION

40 Kilometers

Joint Research Centre
**Objective B:**
- Better Knowledge and Evaluation of variable contributions

  a) airborne gamma dose rate
  b) wet deposition gamma dose rate
  c) radiological release

**Benefits:**
- **EURDEP:** Limit the uncertainties and risks in the identification of false-positive peaks
- **EANR:** Map outdoor radon map
To achieve these objectives…..

We have developed a methodology to identify the terrestrial gamma dose rate
Methodology:
Identification of peaks

1. **Smoothing of total ambient equivalent rate (T-Gamma)** to remove the short-term variations in the data whilst preserving the medium-term trend (low pass filtering)

2. **Definition of the 75th percentile (P75)** as the minimum threshold to select peaks with the highest concentrations

3. **Identification of valley values** corresponding to the lowest values before and after the selected peaks
Or it is better to write: An algorithm for estimating the terrestrial gamma dose rate time series
Giorgia Cinelli, 2014-08-29
4. **Estimation of the cosmic dose rate** considering the altitude a.s.l. of each station - the latitude and the longitude have not been taken into account.

5. **Subtraction of constant contribution**: cosmic contribution and the inherent background have been subtracted from the data.

6. **Estimation of the TGDR**: the average of “net” valley values in time series has been considered to represent the estimated TGDR at 1 metre above the ground.

so far calculated for AT, BE, DE this map by ordinary kriging

because in these countries the necessary parameters are ± known.

Still includes anthropogenic component: \(^{137}\text{Cs Chernobyl, global fallout ... very difficult to separate!}\)

- **European Indoor Radon Map** advanced status: Collect more data, contact more countries, work on data harmonization (Metrology, sampling and measurement protocols)

- Develop the **European maps of U, Th and K concentration in soil and bedrock** to be included in the European Atlas of Natural Radiation and study (and use) the U as possible predictor in the EGRM (Harmonization, Missing-incomplete data)

- Develop the **European Terrestrial Gamma Dose Rate map** to be included in the European Atlas of Natural Radiation and study (and use) the TGDR as possible predictor in the EGRM (Harmonization EURDEP data, Missing-incomplete data)
Conclusions 2/2


- Develop the Multivariate classification approach for the European Geogenic Radon Map (Spatial estimation, mapping, Correlations between quantities, Uncertainty budgets)

- Other maps...
  - Rn exhalation rate (flux) from the ground
  - Ra, Rn in well water
  - Thoron
  - Dose due to Rn progeny washout (“Rn peaks”)

- Toward the estimation of the total dose due to natural radiation (Inclusion of demographic data, dosimetric interpretation)
Acknowledgements

European Geogenic Radon Map Expert Group
(about 60 experts!!!)

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Tänan!
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http://rem.jrc.ec.europa.eu
Objective A:

Create geological group homogeneous in U content using **lithographic, petrology and mineralogy knowledge**

Source Data: OneGeology-Europe – 1M:M Harmonized Geological Map

http://geoportal.onegeology-europe.org/geoportal/viewer.jsp
Objective A:

Create geological group homogeneous in U content using **lithographic, petrology and mineralogy knowledge**
Objective B: 
Assign U concentration in bedrock value to each geological unit using data from scientific literature

EarthChem Library
Data repository that archives, publishes and makes accessible data and other digital content from geoscience research (analytical data, data syntheses, models, technical reports, etc.).
**Objective B:**

Assign U concentration in bedrock value to each geological unit using data from scientific literature

**EarthChem Library**

30 data of U concentration (28 of K, Th)
Objective B:
Assign U concentration in bedrock value to each geological unit using data from scientific literature

EarthChem Library

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<td>Miocene</td>
<td>Pliocene</td>
<td>tonalite</td>
<td>granodiorite</td>
</tr>
</tbody>
</table>
Objective B:
Assign U concentration in bedrock value to each geological unit using data from scientific literature

EarthChem advantages:
- Large database (~55,000 samples over Europe)
- Possibly the only input data known so far for characterizing the U content in bedrock

EarthChem disadvantages:
- Huge variability in the number of samples per country (e.g. Austria 30 vs Italy 14,000)
- Biased sampling (often clustered)
**Objective B:**

Assign U concentration in bedrock value to each geological unit using data from scientific literature

**Literature**

Research paper

Geochemistry of fine-grained sediments of the upper Cretaceous to Paleogene Gosau Group (Austria, Slovakia): Implications for paleoenvironmental and provenance studies

Gerald Hofer*, Michael Wagreich, Stephanie Neuhuber

Department of Geodynamics and Sedimentology, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria

C. Vellner · K.H. Wedepohl

Geochemical characterization and origin of granitoids from the South Bohemian Batholith in Lower Austria

Austrian Journal of Earth Sciences | Volume 104/2 | 90 - 107 | Vienna | 2011
**Objective B:**

Assign U concentration in bedrock value to each geological unit using data from scientific literature

**Literature**

More than 3000 data analysed!

<table>
<thead>
<tr>
<th>Geological Unit</th>
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