ABSTRACT
There is almost unanimous agreement that indoor radon (Rn) represents a hazard to human health. Large-scale epidemiological studies gave evidence that Rn is the second-most important cause of lung cancer after smoking and that also relatively low Rn concentrations can be detrimental. This has increasingly led to attempts to limit Rn exposure through regulation, mainly building codes. The proposed Euratom Basic Safety Standards (BSS) require Member States to establish Rn action plans aimed at reducing Rn risk, and to set reference values for limiting indoor Rn concentration.

In 2006 the JRC started a project on mapping Rn at the European level, in addition and complementary to (but not as a substitute for) national efforts. These maps are part of the European Atlas of Natural Radiation project, which is planned eventually to comprise geographical assessments of all sources of exposure to natural radiation. Started first, a map of indoor Rn is now in an advanced phase, but still incomplete as national Rn surveys are ongoing in a number of European countries. A European map of geogenic Rn, conceptually and technically more complicated, was started in 2008.

The main difficulty encountered is heterogeneity of survey designs, measurement and evaluation methods and database semantics and structures. An important part of the work on the Atlas is therefore to harmonize data and methods.

We present the current state of the Rn maps and discuss some of the methodological challenges.

1. THE EUROPEAN ATLAS OF NATURAL RADIATION: RATIONALE OF THE PROJECT

The European radon maps are part of the European Atlas of Natural Radiation (EANR) project which was started some years ago by the Radioactivity Environmental Monitoring (REM) group of the Joint Research Centre (JRC) of the European Commission according to its mission (based on Euratom Treaty, Art. 39 [1]) to collect and provide information about the levels of radioactivity in the environment.

The objective of the Atlas is to familiarise the public with the radioactive environment and give a more balanced view of the annual dose from natural radioactivity, as well as provide reference material and generate harmonised data for the scientific community. The Atlas should display the geographic distribution of certain physical quantities which are related to sources of natural radiation at different stages in the chain of physical causality, from its very generation up to derived phenomena, which are themselves sources of risk or hazard. This should result in a collection of maps covering radon-related quantities; but also maps of other
sources of exposure to natural radiation are planned, such as cosmic and terrestrial gamma radiation. A more detailed presentation of the project can be found in [2] (after [3]).

As the Atlas aims at a European scale, its main focus is synopsis on that geographical level. This implies that it is not supposed to, nor does it substitute, national approaches to radiation surveillance in general, and of Rn action plans including maps, in particular.

2. THE EUROPEAN INDOOR RADON MAP

The Atlas project started with a map of indoor Rn, given its dominant radiological significance. In most cases, at least in Europe, exposure to indoor Rn (its progenies, to be more accurate), provides the largest contribution to the budget of exposure to ionizing radiation. Epidemiological studies have shown that already relatively low exposure (corresponding indoor Rn concentration of 100 Bq/m³) yields significantly enhanced risk of lung cancer, and that likely a linear – no-threshold relationship between dose and risk applies. For an overview of studies and epidemiological results, see the WHO’s handbook on indoor radon [4].

A study performed by the JRC in 2005 [5] showed that while most European countries had Rn survey programs and produced Rn maps, practically no two countries had applied the same methodology, in terms of design of the survey, the mapped quantity, mapping methods and radiometry. The resulting maps were therefore not compatible across borders, and results difficult to interpret on a synoptic, European level.

2.1. Methodology

This finding motivated the creation of a European indoor Rn map as first priority. The matter was proposed and discussed at the 8th Rn workshop, Prague 2006 [6], and a decision taken. The mapped quantity was chosen to be the long-term mean Rn-concentration in ground-floor living rooms; compilation, evaluation and mapping is done by the JRC; and the mapping units are 10 km x 10 km cells aligned to a common coordinate system. In order to guarantee privacy, no individual measurement data are transmitted to the JRC, but statistics over grid cells, namely the arithmetical mean (AM) and the standard deviation (SD), AM and SD of ln-transformed data, number of measurements per cell, and minimum, median and maximum Rn concentrations. To a large degree, this choice was made for pragmatic reasons in view of data availability and technical feasibility. The JRC performs plausibility checks and calculates further derived statistics.

As said, methods of data acquisition, viz. design of survey and measurement, are quite different between participating countries. To understand better the differences and their possible impact on the result, and as an additional QA tool, a questionnaire has been sent to all participants addressing possibly relevant methodological questions.

Although conceptualized as an indoor Rn map and though the mapped quantity is the indoor Rn concentration, the map is in fact a compromise between an indoor Rn and a radon potential (RP) map. The reason is that statistics over the chosen quantity do not represent the ones of exposure, but rather spatial means within grid cells, irrespective of population density.
and house characteristics. In reality most people do not live in ground-floor rooms (in particular in cities with high population density) but on higher floors where Rn exposure is in general lower than on ground floor. For the purpose of mapping exposure, either data must result from a carefully designed survey which reflects demographic and sociological reality (samples representative for population density and house and dwelling characteristics), or model-based correction to account for demographic representativeness must be performed. Since few national radon surveys are designed that way, and on the other hand the demographic data are not yet available to us, neither the “design-based” nor the “model-based” approach could be chosen for generating a European radon exposure map; it must therefore be left to future efforts [7].

Further details about procedures and preliminary results can be found in [8] and [9].

### 2.2. Current state of the map

The latest status (by end-2012) is shown in a JRC report [7]. The current state of the map is shown in figure 1. So far 25 European countries participate, and we have more than 18,000 non-empty cells filled with data, based on more than 800,000 individual measurements in total. Descriptive statistics are summarized in table 1. Again we stress that the mean over cell means, 100.2 Bq/m³, is not the mean exposure proxy, but an estimate of the spatial mean. (Neither is it the mean of the individual data (136 Bq/m³) nor the mean over country means (106).) The thresholds 100 and 300 Bq/m³ are motivated by proposals given by the WHO [4] and in the draft European Basic Safety Standards (BSS; still under discussion: the final version can be expected to be somewhat different from the quoted one) [10].

Evidently coverage of Europe is still far from complete. Reasons are (apart from uninhabited areas, which are however very few) missing data, either because Rn surveys are still ongoing or because the national Rn strategy does not rely on indoor data, or incompatibility of data with the European project. It can be expected that the map will fill up slowly in the future but will probably never be perfectly complete. For countries whose survey preferentially covered regions known for high radon potential, the estimated spatial country mean is clearly biased.

<table>
<thead>
<tr>
<th>Number of non-empty cells</th>
<th>18,734</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of measurements</td>
<td>818,704</td>
</tr>
<tr>
<td>Measurements per cell, MED ± MAD</td>
<td>4 ± 3</td>
</tr>
<tr>
<td>Min/Max number of measurements per cell</td>
<td>1 / 23,993</td>
</tr>
<tr>
<td>Cell mean, AM ± CV %</td>
<td>100.2 Bq/m³ ± 152 %</td>
</tr>
<tr>
<td>Cell median, MED ± MAD</td>
<td>64.9 ± 33.1 Bq/m³</td>
</tr>
<tr>
<td>Percentage cell AM &gt; 300 Bq/m³</td>
<td>4.51 %</td>
</tr>
<tr>
<td>Percentage cell AM &gt; 100 Bq/m³</td>
<td>31.0 %</td>
</tr>
<tr>
<td>CV within cells, MED ± MAD</td>
<td>(55.4 ± 27.6) %</td>
</tr>
<tr>
<td>GSD within cells, MED ± MAD</td>
<td>1.87 ± 0.40</td>
</tr>
</tbody>
</table>

CV – coefficient of variation, CV = SD/AM. MAD (median absolute deviation) := MED(|x-MED(x)|).
3. THE EUROPEAN MAP OF GEOGENIC RADON

3.1. The concept of Radon Potential

The idea of the RP is to capture the property of the ground (rock and soil) to make Rn available for exhalation into the atmosphere or for infiltration into houses or, briefly, “what earth delivers in terms of radon”. Different quantities have been proposed to measure this property.

Shortly recall the physical pathway, or rather network, “from rock to risk”, shown as simplified scheme in figure 2. In the geogenic compartment of this pathway Rn is generated and made available. Some therefore term the RP as quantifying the hazard associated to Rn.
Only anthropogenic factors turn the geogenic hazard into a risk: constructional properties of houses and factors related to living habits actually control to which degree available Rn is allowed to infiltrate a building and to accumulate in a room. The idea of the geogenic map is thus to visualize the purely natural Rn hazard, i.e. independently of anthropogenic factors which are subject to secular changes, as building styles and living habits change with time and vary also regionally, while the geogenic RP is constant over geological eras.

**Figure 2: Network of radon-related quantities, “From rock to risk”; simplified!**

A physical quantity RP should therefore quantify the concept of the RP such as to account for the “transfer” from geogenic hazard to indoor Rn risk. Candidates mostly include Rn concentration in soil air, permeability, radium (226Ra) concentration and emanation power as numerical, or geological classes and lithology as categorial controls. One simple definition which has physical plausibility is the so-called Neznal RP, based on a suggestion by M. Neznal et al. [11],

\[ RP := C_\infty / (\lg(k) - 10), \]

where \( C_\infty \) denotes the equilibrium Rn concentration in soil air (kBq/m³), k the air permeability (m²) and \( \lg \) the decadic logarithm. In most real soils or rocks \( C_\infty \) is an ill-defined quantity which for practical purposes is replaced by an operational definition of the Rn concentration, namely the outcome of an observation protocol. It can be shown that the “Neznal RP” equals \( C(\text{soil}) \times k \) up to leading factors for medium permeability (k on the order
of $10^{12}$ m²) and higher terms in the expansion of the logarithm, but is numerically more convenient. (For more extreme permeabilities the RP definition smooths against $C \times k$.) From the full transport equation of Rn in soil one can see that this is the advective component of radon flux across a pressure threshold, normalized to the pressure gradient; this is chosen so as to account for real occurring Rn infiltration from the ground into buildings which is essentially controlled by advective flux, driven by pressure differences generated by buildings. Diffusive transport contributes little in general, and is therefore ignored for the purpose of the RP definition.

An important issue is to establish valid and verifiable (for the given purpose) observation protocols, but this will not be discussed further here; see e.g. [12] and [3].

In a different approach, one cross-tabulates physical, mostly categorical factors which control the concept of the RP. The entries of the (possibly multi-dimensional) table are classified into RP classes. These factors are typically base and surface geology, lithology, granulometry (as a proxy of permeability), hydrological properties, tectonics, and occurrence of “special features” such as caves, mines or other anthropogenically modified conditions which may enhance or reduce the natural RP. Yet another, so-to-say top-down approach starts with observed indoor Rn. Applying models the value is transformed to a standard situation (ground-floor room, presence of basement etc.), this way essentially eliminating the influence of anthropogenic control factors. The resulting value, although given as indoor Rn concentration, essentially represents the geogenic control only. One elaborate example of this approach has been by presented by H. Friedmann [13].

For a more extensive discussion of concepts and methods the reader is referred to [3].

3.2. Methodology

At a workshop under the aegis of the 8th International Geological Congress, Oslo, August 2008, the generation of a European geogenic Rn map was decided as the next step after the indoor map, without at the time specifying the technical details. These were subjects of a series of subsequent meetings organized by the JRC.

However, generating a harmonized European geogenic map turned out far more complicated than the indoor map. While data of indoor Rn concentration are available in many countries, of which a reasonably harmonized map can be generated relatively easily, this is not the case for the RP, however it is defined. Although a number of observable physical quantities can be taken as proxies of the RP, more or less satisfactorily, such as geochemical quantities, external dose rate or a “top-down” RP, “transfer” models from each of these to the RP must be established.

At the 11th International Radon Workshop in Prague, September 2012 [14], a “zero-th” version of the European geogenic Rn map was shown (presentation 03, Gruber et al., ibid.), which uses only geological units as mapping units. Four RP classes were proposed, representing low to high RP index. The geological units were classified according to numerical RP data available in Germany, Belgium and the Czech Republic. The underlying geological legend, which defines the units, follows the scheme proposed by the OneGeology project [15]. This was seen as a way to circumvent the heterogeneity, by legends, of geologic
maps between European countries. At the same time it was maintained that in a more advanced state the European geogenic Rn map should display the numerical “Neznal” RP.

Among the problems of the “geology-only” approach are: (1) not all European countries participate in OneGeology, so that no compatible geological legend is available for these countries; (2) the OneGeology scheme is not very well adapted to classifying the RP; (3) it turns out that the OneGeology scheme is indeed not entirely consistent across national (or even regional) borders; (4) natural variability of the RP within geological units is high so that the ranges of the RP assigned to a class largely overlap; (5) often the RP is dominated by regional or even local peculiarities which are not accounted for in geological maps.

3.3. Current state of the map

The current “zero-th” version of the European geogenic map is shown in Figure 3 (from Gruber et al. in [14]). Large portions of Europe are evidently missing. This is due to a lack of data, so that the geological units occurring in these parts could not yet be assigned RP indices. First discussions have shown that also existing parts may in some cases have been mis-estimated. An improved version is currently under construction.

![Figure 3: Preliminary “zero-th” version of a geology-based geogenic radon map of (parts of) Europe.](image)

As an alternative, a “pixel”-based RP map is shown in figure 4, for Germany only. Here numerical values are assigned to 10 km x 10 km cells. (Technically, the values are expectations of the RP at centres of the cells estimated as AMs over realizations of a
sequential simulation scheme [16].) Without delineating the geological units which appear as polygons in figure 3, the geology is still clearly reproduced.

Zones with enhanced RP are acidic magmatites (in Central Europe and on the Iberian Peninsula mostly Variscan granites, granites of the Alpine and the Caledonian orogeny and certain old plutonites of the Fennoscandian shield; also certain vulcanite such as rhyolite), certain Palaeozoic sedimentite including black shale, pre-Alpine molasse units, and certain glacial structures. Regions with typically low RP are calcareous rocks (except karst, generally high RP), most greywackes and tertiary and quaternary alluvial plains. Contact zones with plutonite and surrounding rock as well as sometimes tectonically active faults also often have elevated RP.

4. CONCLUSIONS AND FURTHER WORK

While creation of the indoor map was quite straightforward, progress with the geogenic map is comparatively slow and cumbersome. However, although a satisfactory geogenic map still appears a way ahead, discussions in its course have led to a greatly improved understanding of the relations between Rn and geology, on the physical, and capabilities to deal with them, on the technical side, including mathematical and statistical procedures.
The main methodical problems are related to semantic and data heterogeneity. The former concerns geological classification, while the latter deals with the variety of quantities which are being measured, and for the same nominal quantities, the diversity of protocols. Since it would be unrealistic to achieve harmonization by forcing identical rules everywhere — after all, large amounts of data already exist, if yet partly incompatible — “transfer” rules between them must be established. Some success has already been achieved in this respect.

![Figure 5: External dose rate (interpolated).](image)

Clearly the European Atlas of Natural Radiation will not be finished very soon. Apart from the ongoing indoor and geogenic maps, there are ideas to map other Rn-related quantities, such as outdoor Rn concentration, exhalation rates, and derived radiologically relevant ones such as exposure or dose. Surely all these will turn out to have their own technical problems. A rough map of external dose rate is shown in figure 5 as an example (data: EURDEP [17] raw data, AM June 2006; cosmic contribution, internal background and Rn peaks included; ordinary block kriging, 10 km x 10 km cells).

Apart from Rn, candidates for mapping are cosmic radiation, geochemical concentrations or terrestrial dose rate. A target, certainly still affording years of work, would be a map showing spatially resolved budgets of the contributions of the various sources to total dose.

The Atlas will not only consist of maps. These will be accompanied by articles about the physical and radiological background, as well as about sampling and measurement methods,
discussions of mapping, and more generally statistical techniques and their problems, and about the technical experiences gained in course of the project. An essential part is conclusions drawn from the synopsis which could not be derived from its constituents alone. Altogether, one must not forget that one element of the rationale of the work is generation and distribution of knowledge.

In a nearer perspective, the indoor map will be continued to be filled. In parallel development of the geogenic map continues. At the same time surveying and mapping of Rn mapping are ongoing tasks in almost all European countries, some having started surveys only recently, others studying the impact of Rn remediation and of energy saving on Rn exposure. National projects, diverse as they are, prove fruitful for the synoptic endeavour while the joint project has turned out to have its impact on directions as well as on methodologies of regional projects.

REFERENCES