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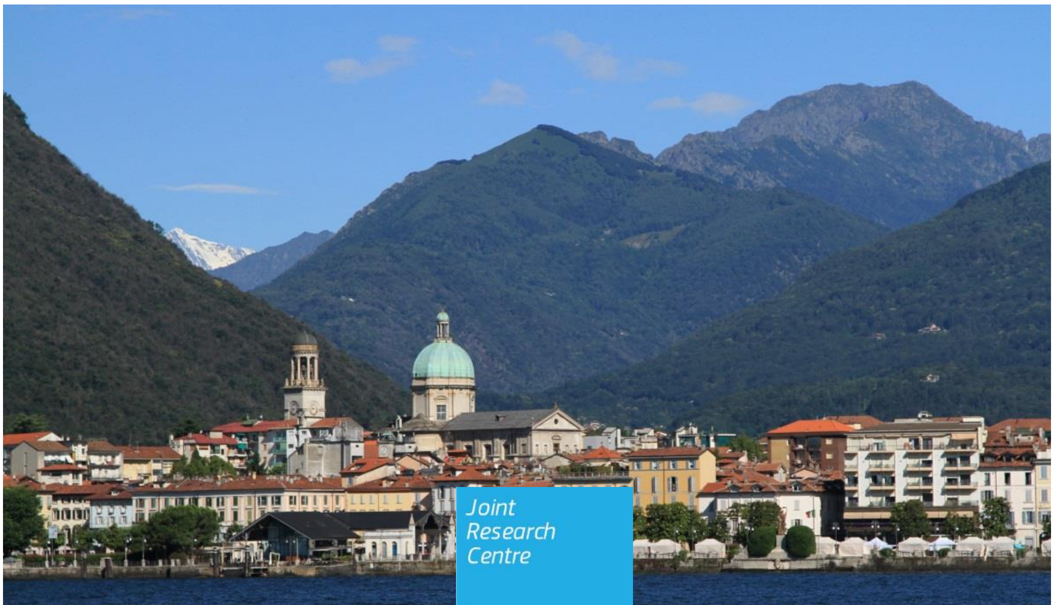

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Title 2nd International Workshop on the European Atlas of Natural Radiation: Book of Abstracts

Abstract:

- Verbania workshop welcomes 100 scientists to discuss progress of European Atlas of Natural Radiation.
- Venue will provide scientific reference frame for EU Member States' authorities to implement their radon action plan under the European Basic Safety Standards Directive.

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Foreword

Dear Participants and Colleagues,

As Director of the Nuclear Safety and Security at the Joint Research Centre, I am delighted to welcome you all to the beautiful small town of Verbania for the **2nd International Workshop on the European Atlas of Natural Radiation** (IWEANR 2017). The main aim of this workshop is to discuss progress of the European Atlas of Natural Radiation.

More than ten years ago, the Joint Research Centre of the European Commission decided to embark upon a European Atlas of Natural Radiation; this is in line with its mission of fulfilling the obligations set up by the Euratom Treaty, namely to collect, validate and report information on radioactivity levels in the environment. Developed and maintained by the Radioactivity Environmental Group (REM) group of the Joint Research Centre, this Atlas has evolved into a collection of maps displaying the levels of natural radioactivity originating from different sources. These maps are now available in digital format and can be viewed through a web portal: https://remon.jrc.ec.europa.eu/About/Atlas-of-Natural-Radiation.

At the first Atlas workshop held in Verbania two years ago, about 60 participants contributed to a lively forum of scientific presentations and round-table discussions. About 20 of these presentations were later elaborated into full-length papers which were published in a Special Issue of the Journal of Environmental Radioactivity, entitled "Geogenic Radiation and its Potential Use for Developing the Geogenic Radon Map."

Since then, I am pleased to see the ever-growing interest in this area with a considerably larger participation to this second workshop. This year in fact, nearly 100 scientists, representing 30 countries (some beyond Europe) and half a dozen international organizations and projects have decided to meet in Verbania.

This workshop will focus on: radon policies; sources of natural radiation and their mapping; relationships between radon-related quantities; radon-priority areas; and indoor radon mapping. In addition, there will be a special session on "Radon and Geology", organised by Italian university colleagues.

In the course of less than four days, we will enjoy more than 60 oral presentations and several round-table discussions. I would like to thank all invited speakers for participating in this workshop and for contributing to the book of abstract. I am also very grateful to the local organizing and scientific committees for the excellent support of setting up this important meeting.

Looking at the programme, with all the interesting presentations that will be given and the round-table discussions organised, I am confident that the workshop will be a great success. From radon experts to young scientists, your exchange of ideas will be stimulating and mutually rewarding.

My colleagues of the local organizing committee will do their best to make your stay a pleasant and fruitful one here at the lakeside.

Once again, I want to wish you a warm welcome to our workshop in Verbania!

Dr. Maria Betti

Director

European Commission

Joint Research Centre – JRC

Directorate G – Nuclear Safety and Security

1 Session 1: Radon policies

1.1 Requirements on indoor radon in Council Directive 2013/59/Euratom – The Basic Safety Standards Directive

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Exposure to indoor radon constitutes an important part of the overall exposure to ionising radiation of the public and of workers in certain geographical areas or specific types of workplaces.

With the publication of the new basic safety standards Directive[1], the European Community modernises and consolidates the European radiation protection legislation based on Articles 2 and 30 of the Euratom Treaty. In line with the 2007 ICRP philosophy, the new BSS Directive applies to any planned, existing or emergency exposure situation which involves a risk from exposure to ionising radiation which cannot be disregarded from a radiation protection point of view. With this, the BSS applies to all relevant radiation sources, including radon, cosmic rays and naturally occurring radioactive material (NORM), with no distinction made between artificial "man-made" radiation and natural radiation.

The new BSS Directive introduces binding requirements on indoor exposure to radon and on radon in workplaces. In particular, the Directive requires the establishment of a national radon action plan addressing long-term risks from radon in buildings and workplaces for any source of radon ingress, whether from soil, building materials or water. The national radon action plan shall include, *inter alia,* the identification of radon-prone areas. Member States need to define national reference levels for indoor radon exposure in dwellings and in workplaces of maximum 300 Bq/m^3.

For radon in dwellings, the provisions aim mainly at the identification of dwellings with radon concentrations above the reference level, the provision of local and national information on radon, and the encouragement of introducing radon concentration reducing measures. In addition, Member States shall ensure that appropriate measures are in place to prevent radon ingress in new buildings. Specific requirements to this end shall be included in national building codes to engage the building industry.

With regard to workplaces, radon measurements are required in workplaces located in radon-prone areas and in specific types of workplaces both identified in the national radon action plan. If, despite all actions to optimise, the radon concentration in a workplace remains above the national reference level, this workplace needs to be notified to the competent authority and the relevant occupational radiation protection requirements may apply.

Transposition and implementation of the new BSS Directive, and in particular its requirements on indoor radon, pose a major challenge for national legislators and regulators in the coming years (the transposition deadline being 6 February 2018).

[1] Council Directive 2013/59/EURATOM of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom.

1.2 Radon related requirements in the IAEA Safety Standards

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In 2009 the International Commission on Radiological Protection (ICRP) released a statement on radon recommending the revision of the upper value for the reference level for radon gas in dwellings from the 2007 Recommendations of the ICRP value of 600 Bq/m^3 to 300 Bq/m^3. In 2014 the IAEA published a new version of General Safety Requirements, formally referred to as the IAEA Safety Standards Series No. GSR Part 3, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards. The document implements the new concept of the radiation protection system recommended by the ICRP in the Publication 103 from 2007 and sets out requirements on governments for control of existing exposure situations. The new IAEA Safety Requirements include also the recommendation of the ICRP from 2009 on exposure due to radon (^{222}Rn) indoors, setting the upper reference level to 300 Bq/m^3.

The governments are responsible for protecting the public against exposure due to radon in dwellings and their responsibilities include arrangement: to collect data on the activity concentrations of radon in dwellings and other buildings with high occupancy by the public; to provide information on exposure of the public due to radon and the associated health risks; and if the levels of radon are of concern for public health, to develop an action plan for controlling public exposure to radon.

Further guidelines were developed and are now available in the IAEA Specific Safety Guide No. SSG-32 Protection of the Public against Exposure Indoors due to Radon and Other Natural Sources of Radiation, published in 2015. This safety guide provides recommendations on how to meet the requirements for justification and for optimization of protection by national authorities in control of natural sources of radiation indoors, such as radon gas and radionuclides in building materials, set in the GSR Part 3. This document also provides guidance on establishing of national radon action plans, radon surveys and radon prone areas mapping, measurement techniques for ^{222}Rn, corrective and preventive actions to reduce ^{222}Rn concentration indoors, and control of exposure indoors due to gamma radiation.

In addition, the World Health Organization (WHO) published its Handbook on Indoor Radon - A Public Health Perspective in September 2009. The Handbook provides information on procedures for the reliable measurement of radon levels, control options for radon in new dwellings and radon reduction in existing dwellings, radon risk communication strategies, and the organization of national radon programmes.

1.3 WHO's public health perspective on radon position

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Over the past 50 years, epidemiological studies have been performed to ascertain an association between lung cancer and exposure to indoor radon at the workplace and, more recently, in residential settings. The International Agency for Research on Cancer (IARC), a WHO specialized agency, has periodically reviewed the scientific evidence which supports the classification of radon as carcinogenic to humans (Group 1) (1988, 2001 and 2012).

The WHO International Radon project was established in 2005, after the publication of several pooled analyzes confirming radon as an established risk factor for lung cancer in the context of residential exposure. It became apparent that national authorities needed methods and tools based on solid scientific evidence and sound public health policies in order to reduce residential radon lung cancer risk. An important output of the project was the 2009 publication of the *WHO Handbook on indoor radon*, which focuses on residential radon exposure from a public health perspective and provides policy options for preventing and mitigating radon exposure. It also assesses costs and benefits of different strategies and covers radon risk communication approaches.

Based on published scientific data on health effects of indoor radon, WHO recommends a reference level of 100 Bq/m^3 as justified from a public health perspective However, if this level cannot be implemented under the prevailing country – specific conditions, the chosen reference level should not exceed 300 Bq/m^3. This value is in line with the *Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards*, which are co-sponsored with 7 other international organizations, and with the European *Council Directive 2013/59/EURATOM*.

The presentation will include a discussion of radon risks in comparison with other radiation and public health risks, including other sources of air pollution.

While the scientific evidence linking increased risk of lung cancer to radon exposure is strong, further research is needed to indicate which interventions to reduce this risk are likely to be most effective over time. Particular interest will be paid to the efficacy of various voluntary measures and regulations. Countries considering new policy changes should therefore consider investing in studies to document the effectiveness and cost of the interventions.

1.4 UNSCEAR's activities on radon

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In 1955, the General Assembly of the United Nations established a Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) to increase knowledge of the levels, effects and risks of ionizing radiation exposure from all sources. The Committee scientific reports to the General Assembly are used by national and international organizations as sources of valuable information for the implementation of radiation protection strategies and programmes.

The Committee considered the issue of sources and effects of exposure to radon and its decay products with regard to workers and the public in several comprehensive UNSCEAR Reports (1993, 2000 and 2006). The Committee concluded in these reports that inhalation of radon and its decay products is mainly carcinogenic for the lungs because of the high lung doses. Doses to other organs and tissues are at least an order of magnitude smaller. The Committee recognized that the annual effective dose per capita from inhalation of radon gas and its decay products represents typically about half of the dose received by members of the public from all natural sources. For certain occupations, radon gas dominates occupational radiation exposure. The release of radon from uranium mine tailings makes a substantial contribution to the effective dose from this practice (UNSCEAR 2016 Report). Coefficients for calculating doses from exposure to radon are needed (1) for radiation protection purposes, which is in the mandate of the International Commission of Radiation Protection (ICRP), and (2) to allow comparison with other sources of radiation exposure, which is the mandate of the Committee.

The Committee evaluated the risk of lung cancer from radon exposure in its UNSCEAR 2006 Report and concluded that extrapolation of radon concentrations in the air in mines to those in homes had provided an indirect basis for assessing the risks of lung cancer from residential exposure to radon. Although there are major uncertainties, the Committee concluded that there was good agreement between the risk factors derived from miners and residential studies.

However, since the publication of the UNSCEAR 2006 Report, there have been several important developments with regard to recommendations on radiation protection including the publication of WHO's Radon Handbook, ICRP's Radon Statement, ICRP's Publications 115 and Publication 126; IAEA's International Basic Safety Standards (GRS-9); and the European Basic Safety Standards (2013/59/EURATOM). Moreover, there have been over 400 scientific publications since the Committee's last evaluation, including those related to lung cancer epidemiology, which could help in better understanding of the risk for smokers and non-smokers or other subgroups and relevant dosimetry reports (e.g. ICRU's Report 88 and ICRP's Publication 137), which have not yet been screened and reviewed by the Committee.

The presentation will focus on the Committee's recent activities with regard to analyzing the recent developments and reviewing the literature on this matter published in the last decade. However, the review will not focus on assessing population exposure levels to radon and its decay products. This is to be conducted under the UNSCEAR Public Exposure Survey over the coming years. The Committee's review also aims to establish a future research agenda.

1.5 The new EURATOM BSS Directive: Current situation of the implementation and ERA's activities

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The Council of the European Union issued the new Directive EURATOM Basic Safety Standards (BSS) in January 2014. This document aims to offer a better protection for people at workplaces and at dwellings. The document introduces radon gas for the first time into the radiological protection system and establishes a reference level of 300 Bq m^{-3}. In addition to this, the occupational exposure arrangements at workplaces has 6 mSv y^{-1} as limit value. Above this limit, the situation should be managed as a planned exposure situation and below the limit the requirement is to keep exposures under review.

The deadline to implement the new Directive is February 2018. Not only reference levels must be introduced in the 28 EU countries, but also national radon action plans have to be developed. Traditionally, the situation of radon policies throughout Europe is very different from country to country. Nordic countries, Ireland and the UK have some of the most advanced radon programmes while southern countries have done much less to tackle the radon issue.

The European Radon Association (ERA) was born officially in December 2013 and it is registered under Belgian law as a non-profit association. It has currently more than 100 individual members and 20 private companies within its membership. Therefore, ERA can provide a clear overview of the situation of the implementation of the new Directive EURATOM BSS in Europe.

This presentation will make an examination of the current situation of the EURATOM BSS implementation in the EU countries. We will show some examples of the transposition of the Directive into national legislations and also the different relevant activities ERA is carrying out at the moment.

1.6 MetroRADON: Metrology for Radon Monitoring project – a European research project

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The European Council Directive 2013/59/EURATOM (EU-BSS) evokes new challenges for the metrology of radon measurements and calibrations in Europe. For the first time, the exposure of the public caused by radon will be part of legal metrology in Europe. Since the EU member states' levels of relevant activity concentration that are laid down in the EU-BSS shall not exceed 300 Bq/m^3, new calibration procedures for existing commercial radon monitors with their limited counting statistics have to be developed. The legal implementation of the new EU-BSS claims a metrological sound basis of radon protection for European citizens. This is one of the main the objectives of the new EU-BSS, which have to be implemented by national legislatives in the coming years.

MetroRADON is funded by the European Metrology Programme for Innovation and Research (EMPIR) as part of Horizon 2020, the EU Framework programme for Research and Innovation as a Joint Research Project (JRP). The JRP runs from June 2017 to May 2020 with 17 European partner organisations involved.

The overall objective of MetroRADON is to enable the SI traceable monitoring of radon (^{222}Rn) at low radon activity concentrations including calibration and radon mapping. These objectives include the investigation of the influence of thoron (^{220}Rn), the harmonisation of indoor and soil exhalation radon measurements and the development of new methodologies for the identification and characterisation of radon priority areas in Europe. The JRP will provide SI traceable metrological resources (calibration and measurement) for the monitoring of radon, which essentially facilitate the harmonised implementation of the new EU-BSS in Europe. In addition, the composition of the partners will contribute to the creation of metrological infrastructure for radon in Europe suitable for the requirements of the radon action plan requested by the new European Directive.

The contribution will provide an overlook of the partners, structure, goals, work packages and impact of the MetroRadon project.

1.7 Radon real time monitoring system and proactive indoor remediation – LIFE-RESPIRE

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According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), radon (Rn) is the most important source of ionizing radiation related to indoor air quality. The most important health effect of Rn exposure is the increased risk of lung cancer, second only to cigarette smoking (World Health Organization). The most recent European directive regarding human exposure to natural radiation (2013/59/EURATOM) deals primarily with indoor Rn, and encourages national action plans to identify buildings (i.e., areas) where annual Rn average is expected to exceed the national reference level (i.e., Radon Prone Areas, RPA) and propose remediation.

As the direct measurements of soil gas Rn, coupled with geological data, are well recognised to define the Geogenic Radon Potential (GRP) of an area (i.e., an estimate of the Rn originating from geological sources), the GRP can then be used to guide indoor surveys; as indoor Rn values are often highly variable. LIFE-RESPIRE demonstration project objectives are:

- To demonstrate in 4 significant areas, with different GRP in Italy and Belgium, a cost-effective and eco-friendly solution for Rn real-time measurement and remediation to keep indoor Rn levels below 100 Bq/m^3 level (as indicated in European Directive 2013/59/EURATOM). RESPIRE project will implement an intelligent, adaptable and versatile hybrid Rn remediation system composed by sensors, an Air Quality Balancer (SNAP) and an external additional fan-system (eolian and/or electric) working on positive pressure method. A control model based on an IoT protocol will be implemented;

- To construct a real time LIFE-RESPIRE geodatabase of collected continuous Rn measurements, coupled with other geological, geochemical and building characteristics data, that could be integrated within the framework of the European Atlas of Natural Radiation (promoted by the Joint Research Centre-JRC of the European Commission);

- To provide local authorities with Rn hazard guidelines and real-time WebGIS radon maps for land use planning and health risk assessment, helping to prepare relevant national action plans (see Articles 54, 74 and 103 in 2013/59/EURATOM).

The LIFE-RESPIRE project will improve the use of geochemical monitoring of Rn for the assessment and the protection of human health from exposure to natural radioactivity. The visibility of the proposal and the availability of collected data are guaranteed by the WebGIS geodatabase that will be accessible to all stakeholders and several derived Web Mapping Applications to be used by the public and the authorities. Furthermore, a series of actions regarding communication and dissemination activities will be addressed to inform stakeholders and to ensure use and development of project results during and beyond the project completion. The demonstration character is shown by the use of an integrated methodology that will include modified and/or innovative rapid remediation system for the measuring of soil gas Rn activity and the monitoring of the indoor Rn for the protection of human health and the environment. This integrated methodology will be implemented on a pilot scale that allows evaluation of technical and economic viability at larger scale by stakeholders (i.e., national, regional and local authorities). By making data available and accessible through the construction of a geodatabase and a Website, LIFE-RESPIRE aims to bridge the gap between research, policy and development results and widespread implementation, and to improve innovative solutions related to land use planning and for further epidemiological research due to Rn exposure.

1.8 The Radon in Big Buildings Project

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The *Basic Safety Standards* of the European Union (EU-BSS 2013/59/EURATOM) are European law since 2014 and have to be implemented into national law by all Member States. The EU-BSS include radon in common workplaces and buildings for the first time in radioprotection regulation. The new reference values concern not only residential indoor Rn concentration, but also work places and public buildings. The radon concentration limits have been reduced to the values valid for the private environment like one-family houses. The consequences of this decision are quite significant, since work places contain a much wider range of building types than private houses. This fact requires a basic understanding of radon dynamics in a wider environment and the development of appropriate testing procedures. In particular the search for proper test objects and a valid definition of building types and building parameters (i.e. closed windows, doors, usage of air-condition or ventilation systems, presence of elevators etc.) turns out to be essential.

To face up these challenges, in February 2016 the *Ribibui* (Radon in Big Buildings, http://www.ribibui.org) project, a consortium of radon specialists from 11 European countries, has been established with the aim to evaluate a standard protocol for measurements in diverse big building types.

During the presentation, the status and first results of the ongoing project will be presented.

2 Session 2: Sources of natural radiation

2.1 European Atlas of Natural Radiation: digital version and future steps

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The European Atlas of Natural Radiation is a collection of maps displaying levels of natural radioactivity caused by different sources. It has been developed and is being maintained by the Radioactivity Environmental Monitoring (REM) group of the Joint Research Centre (JRC). This is in line with its mission, based on the Euratom Treaty: on behalf of the European Commission, to collect, validate and report information on radioactivity levels in the environment of the EU Member States.

The first version of the European Atlas of Natural Radiation is now available in digital format through a web portal (https://remon.jrc.ec.europa.eu/), in which all the maps are collected and displayed with related information. This digital Atlas contains: a map of indoor radon concentration in many European countries; maps of uranium, thorium and potassium concentration in soil and of the same quantities in bedrock; a terrestrial gamma dose rate map; and an annual cosmic-ray dose map.

Through these maps, the public will be able to: familiarize itself with natural environmental radioactivity; be informed about the levels of natural radioactivity caused by different sources; have a more balanced view of the annual dose received by the European population, to which natural radioactivity is the largest contributor; and make direct comparisons between doses from natural sources of ionizing radiation and those from man-made (artificial) ones, hence, better to assess the latter.

Work will continue on the European Geogenic Radon Map, in order to develop a multivariate classification approach to estimate the geogenic radon hazard index and to estimate the annual dose that the public may receive from natural radioactivity, by combining all the information from the different maps.

More maps could be added to the Atlas, such us radon in outdoor air and in water and concentration of radionuclides in water, even if these sources usually contribute less to the total exposure.

Moreover, a consolidated version of the European Atlas of Natural Radiation is planned. In addition to the maps and their description, it should include a detailed and comprehensive introduction to natural radioactivity and will be based on contributions from experts in each field.

2.2 Insights into terrestrial radionuclides mapping by compiling data from scientific literature

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The European Atlas of Natural Radioactivity (EANR) is a collection of maps developed with the purpose of providing an estimation of the annual dose the general public may receive, including the contribution of the uranium, thorium and potassium radioactive families. The methodology developed to map U, Th and K_2O contents in bedrock relies on the compilation of geochemical and radiological data from scientific literature. These maps display the arithmetic mean contents of the radiogenic elements in bedrock over geological units (GU) defined with expert knowledge and may be easily improved if more data are made available.

In this work, we attempt to validate the methodology developed by comparing the data compiled with those from a radiological survey carried out by the Laboratory of Natural Radioactivity (LNR) of the University of Coimbra. Given the heterogeneity of the databases with respect to the various geological units and their subunits sampled, the statistical analysis encompassed weighting the data by the coverage of each GU. The databases were compared individually and by using the GU classification scheme. The influence of the analytical techniques was assessed through a two-way Analysis of Variance using the GU classification scheme and the analytical techniques as categorical variables.

Overall, a reasonable agreement between the geochemical database compiled and the LNR data is observed. Inconsistencies between the databases seem to be contingent upon the reliability of the data which depends, in turn, on sample and analytical representativeness. However, the influence of the analytical techniques appears to be small and less significant than other sources, such as the variability of U, Th and K_2O contents within the geological units. Despite data limitations, the maps of terrestrial radionuclides developed provide useful information to the general public and which may support further research.

2.3 Radon as an indicator of geological structure and as a source of radiation Hazard to the environment: The case of Ukrainian shield

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The source of radon is the rocks containing uranium and radium-226. So, the higher the content of radioactive elements is in an area, the greater the chances of high radon indoor and outdoor levels. In this respect the Ukrainian Shield, where the Central Ukrainian Uranium Province (CUUP) located, is of high priority to been studied. Moreover, according to the total uranium resources and proven reserves Ukraine is among the ten countries in the world and is considered a key uranium producer in Europe.

Since the experts from the Institute of Environmental Geochemistry, IEG (former Department of Metallogeny of the Institute of Geochemistry, Mineralogy and Ore Formation) have long been involved into scientific research on uranium geology, and, correspondently, outdoor (as well as indoor) radon anomalies from the point of view of uranium deposits search criterion, and so accumulated a lot of experience and archival materials (Lysychenko et al., 2010), the authors put as the presented research goal to generalize and process available data on radon as an indicator of geological structure and a source of potential threat to the environment mainly within the Ukrainian Shield (although other areas of radon anomalies concentration in rocks are also available and worth further considering).

Ukraine is located within two tectonic structures: the East European platform and the Alpine geosynclinals region. The plateau part of Ukraine (about 95 % of the country) is rigid, slightly shifting tectonic structure with ancient crystalline rock and covered sediments. The uranium deposits related to Na-metasomatism of the CUUP and so three operating uranium mines are located within the central Ingul Megablock of the Ukrainian Shield and its slopes. These deposits are of hydrothermal and metasomatic types of sodium-uranium formation. They are all genetically connected with the process of ultra-metamorphic solutions penetrated along long-lived fault zones and led to sodium metamorphism and the following on ore formation in albitites. Uranium was transferred in hydrothermal solutions in the form of uranyl-sodium-carbonate or uranyl-potassium-carbonate ions (complexes).

Underground uranium mining has been developing within the CUUP since early 1970s. The environmental impacts of uranium mining and milling activities are severe. These impacts range from the creation of massive stockpiles of radioactive and toxic waste rocks and sand-like tailings to serious contamination of surface and underground waters with radioactive and toxic pollutants, and releases of conventional, toxic and radioactive air pollutants (Dudar et al., 2015). It highly contributes to the huge amount of radon exposure to the surface. Because of underground explosions and movement of underground transport, the host rocks are being additionally cracked creating easy pathways for radon migration to the surface. Newly created cavities are being filled with new gas, which is continuously formed in the decay of uranium and radium. The maximum amount of radon is established in the geodynamically active zones in overlapping rocks associated with new tectonic anomalies of parent rocks. The most hazards are areas where new tectonic activities and faults are met relatively close to the surface (Verkhovtsev et al., 2014). The example is the Inguls'ka mine area (Kirovograd region of CUUP). This is a unique place in the world as it is located under urban residential neighborhoods where uranium ores occur in the form of lenses. After explosion, the worked out cavities here reach of multistoried building sizes and radiation level – more than 1600 mRh/hour. It has been proven that within 3-4 hours after the explosions, the increased release of radioactive gas is observed and average volumetric radon concentration reaches 250 Bq/m^3 (50 Bq/m^3 – norm).

Apart from radioactive elements in rocks, concentration of uranium daughter products in natural waters is also dependent on migration of radioactive isotopes during their transition from rocks into the water and further transportation with water, as occurs mostly in faults or other permeable zone. On average, river water has less total natural radioactivity than underground waters, except for rivers in regions of uranium mining (for example, the Ingul River in the Kirovograd region). This conclusion was also confirmed for the CUUO by the IEG experts.

Generation a map with delineation of radon priority areas (and series of larger scale maps for the cities, uranium mining and tailing areas, etc.) is planned to be considered for further research.

References:

Lysychenko G., Melnik Yu., Lysenko O., Dudar T. and Nikitina N., 2010. Uranium Ores of Ukraine: Geology, Production, and RAW management/ // K: Naukova Dumka, - 221 pp. (in Ukranian).

Verkhovtsev V., Kramar O., Yuskiv Yu., Krasnov Ye., and Tishchenko Yu., 2014. New tectonics of the Belanovskii iron and Kremenchuk uranium deposits. Journal of Geophysics, 2014(4), pp. 136-148 (in Ukrainian).

Dudar T., Zakrytnyi Ye., Bugera M., 2015. Uranium Mining and Associated Environmental Challenges for Ukraine. Science-Based Technologies. Volume 25, No. 1 (2015), pp. 68-73.

2.4 Radiological studies of zeolites application in the environment

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The present work is focused to natural radioactivity levels of zeolites in order to define their limits of usage in the environment considering dose consequences to the public. The environmental applications of zeolites as cultivation soil improvements and building materials (18 samples from Greece and Turkey) as well as dietary supplements (4 samples from Serbia) has been studied. The natural radionuclides have been measured using gamma-ray spectrometry alongside with the radon emanation factor variations due to granulometric effect. Possible correlations between U-238, Ra-226, Pb-210, Ra-228, Th-228 and K-40 concentrations have been examined regarding to conclude any physicochemical mechanisms. In case of building materials the radon indoors concentrations obtained have been also discussed. Moreover, the external radiation received has been estimated in case of soil improvements and building materials as well as the internal radiation in case of dietary supplements and building materials. Various scenarios have been considered regarding to evaluate the dose calculated taken in to account the international dose limits as well as the national reference levels.

2.5 A national survey of outdoor gamma radiation in urban areas

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The exposure rate due to outdoor gamma radiation in Italy has been studied by means of portable gamma detectors, particularly 3"x3" plastic scintillators. This survey was conducted in the framework of an extensive national survey on indoor radon and indoor+outdoor gamma exposure, carried out in collaboration with an Italian telecommunication company. As regards outdoor gamma exposure, measurements points were selected both close to the entrance of workplace buildings of the telecommunication company levels and in streets close to the entrance of the underground inspection rooms for maintenance of the cable network. These measurement points are generally in urban areas, differently from a the 1972 national survey of outdoor gamma radiation performed mainly in sites far from urban areas. Therefore, this survey can give results more representative of the actual population exposure to outdoor gamma radiation in urban areas.

The total number of measurement points is more than 6000 distributed in all the 21 Regions and 110 Provinces, and located in about 1800 of the 8000 Italian towns.

This is the first paper reporting the results of this national survey.

2.6 Image processing techniques revealing the relationship between the field-measured ambient gamma dose equivalent rate (H*(10)) and geogenic factors at a granitic area, Hungary

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In order to estimate the annual dose that the public receive from natural radioactivity, the identification of the potential risk areas is required which, in turn, necessitates understanding the relationship between the spatial distribution of natural radioactivity and the geogenic factors (e.g., rock types, dykes, faults, etc.). A detailed spatial analysis of ambient gamma dose equivalent rate was performed in the western side of Velence Mountains, the largest outcropped granitic area in Hungary. In order to assess the role of local geology in the spatial distribution of ambient gamma dose rates, field measurements were carried out at ground level at 300 sites along a 250 m x 250 m regular grid in a total surface of 14.7 km^2. Digital image processing methods were applied to identify anomalies, heterogeneities and spatial patterns in the measured gamma dose rates, including local maxima and minima determination, digital cross sections, gradient magnitude and gradient direction, second derivative profile curvature, local variability, lineament density, 2D autocorrelation and directional variogram analyses.

Statistical inference showed that different gamma dose rate levels are associated with the rock types (i.e., Carboniferous granite, Pleistocene colluvial, proluvial, deluvial sediments and talus, and Pannonian sand and pebble), with the highest level on the Carboniferous granite including outlying values. Moreover, digital image processing revealed that linear gamma dose rate spatial features are parallel to the SW-NE dyke system and to the NW-SE main fractures. The results of this study underline the importance of understanding the role of geogenic factors influencing the ambient gamma dose rate received by public. The study also demonstrates the power of the image processing techniques for the identification of spatial pattern in field-measured ambient gamma dose equivalent rate.

2.7 Terrestrial gamma radiation in Montenegro

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Two nationwide surveys on terrestrial gamma radiation have been performed in Montenegro, the first one in 1994 and the second in 2008-2009.

The aim of the first survey was to find national average values of the absorbed dose-rate in the air and activity concentrations of radionuclides in soil. To this end, in each 15 km x 20 km cell of a sampling grid which covers the country' territory one location was selected, typical for region within the cell by its geological and petrological characteristics. Beside these basic 42 locations, the other 25 specific sites (14 beaches, 4 outcrops, 3 plantations, 4 tourist resorts) were also included in the survey. *In situ* HPGe gamma-spectrometry was used to measure terrestrial gamma radiation.

Dose-rates in the air at 42 locations, 1 m above the ground, due to the radionuclides in soil (^{137}Cs contamination included) were found to be in a range from (24.4 ± 1.2) nGy/h to (130 ± 9) nGy/h, with AM = 55 nGy/h and MED = 49 nGy/h.

Characteristics of a content of natural radionuclides in soil at these 42 sites are:

- ^{40}K: range from (78 ± 8) Bq/kg to (481 ± 37) Bq/kg, AM = 246 Bq/kg, MED = 223 Bq/kg;
- ^{232}Th: range from (9.3 ± 1.0) Bq/kg to (74 ± 7) Bq/kg, AM = 23.7 Bq/kg, MED = 19.0 Bq/kg;
- ^{238}U: range from (7.0 ± 0.7) Bq/kg to (166 ± 8) Bq/kg, AM = 29.3 Bq/kg, MED = 18.5 Bq/kg.

The second survey was aimed to find locations in Montenegro with elevated terrestrial gamma radiation and to recognize its main sources. For this purpose, 138 locations, on geological formations known to contain rocks with potentially high concentrations of U, Th and K, were selected throughout the country for field investigations. Selection was made within each of the four distinctive geotectonic units in Montenegro: 47 locations in the Durmitor Tectonic Unit, 37 in the High Karst Zone, 30 in the Adriatic-Ionian Zone and 24 in the Budva-Cukali Zone.

Dose-rates in the air (measured with VICTOREEN 190 SI) at these 138 locations were in range from 10 nGy/h to 192 nGy/h, with AM = 56 nGy/h and MED = 50 nGy/h. Elevated doses were found above the bauxite formations, paleozoic clastites and Middle-Triassic vulkanites. The highest two values are at location on dacite to dacite-rhyolite rocks (192 nGyh^{-1}) and at location on dacite rocks (148 nGyh^{-1}), the both caused primarily by high potassium content in soil.

Field measurements discovered 27 locations with terrestrial radiation more than 50% higher of the national average. Soil samples were collected from these locations and ^{40}K, ^{232}Th, ^{235}U, ^{238}U, ^{226}Ra and ^{137}Cs determined in them by HPGe gamma spectrometry. Characteristics of specific activities of the natural radionuclides in soil at these locations are:

- ^{40}K: range from (27.4 ± 1.8) Bq/kg to (3341 ± 106) Bq/kg, AM = 788 Bq/kg, MED = 635 Bq/kg;
- ^{232}Th: range from (17.2 ± 0.7) Bq/kg to (208 ± 7) Bq/kg, AM = 100 Bq/kg, MED = 66.5 Bq/kg;
- ^{238}U: range from (22 ± 15) Bq/kg to (304 ± 14) Bq/kg, AM = 90.4 Bq/kg, MED = 66.0 Bq/kg.

2.8 Natural radiation in Estonian soil

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In this paper, natural radiation in soil is examined as gamma radiation in soil, expressed as the sum of ^{226}Ra, ^{232}Th and ^{40}K in µSv/h and as the activity concentration index ACI (IAEA Safety Standards, 2015). The sum of ^{226}Ra, ^{232}Th and ^{40}K content in soil was measured with a gamma-spectrometer at a depth of about 80 cm in the context of the ^{222}Rn risk mapping of Estonia. More than 1,000 individual sampling points were taken account in the study.

The most important sources of natural radiation are:

- U-rich graptolite argillite (30–300 ppm) with an elevated K content, and also U-rich (10–30 ppm) phosphorite crop out along the North Estonian Klint zone, that runs parallel with the south coast of the Gulf of Finland.
- Some types of Devonian rocks with elevated U, K and Th content
- Phenomena of U mineralisation or any other unknown source in the bedrock

Additional sources can occur in scattered debris and in the fine sediments of the abovementioned rocks that have been eroded by glacier and sea and also in U-, K- and Th-rich materiel originating from crystalline rocks outcropping to the north of Estonia.

The level of gamma radiation in Estonian soil depends both on the ^{226}Ra, ^{232}Th and ^{40}K content as such, as well as on the ratio between them. Usually the level of gamma radiation varies in a range from 4.4 to 12 µR /h, the average content is 7.18 µR/h, but the maximum level can reach 38 µR/h, or even 190 µR/h within graptolite argillite outcrops.

The level of gamma radiation is different in the main lithological soil types: it is lowest in Holocene marine sediments (ranging dominantly from 2.9 to 8.2 µR/h), and highest in the slope deposits of the North Estonian Klint (ranging dominantly from 7.1 to 19 µR/h).

A comparison of the eU, eTh and eK content as measured with the gamma-spectrometer, with reference soil samples taken from the bottom of the same pit and analysed with the ICP method, results in a satisfactory concurrence for the K- and Th-content, but not for the U-content. The U-content is nearly 20% lower than the eU content. It is carried out and concentrated in peat in bogs while at the same time ^{226}Ra has remained in place.

According to the IAEA safety standard, the gamma radiation dose from building materials for isotopes of the abovementioned 3 elements should, during 7000 hours per year, not exceed an ACI index of "one", this is close to a dose of 1 mSv or 1,25 mSv/a. This indicator informs the public about an elevated risk of natural radiation and prohibits the use of the building materials with a high natural radiation for residential and municipal buildings, for children's sandboxes, and for other public facilities.

There are 73 observation points where the ACI index exceeds the above-mentioned benchmark by up to two times, or where annual dose ranges can be obtained between 1.5 and 3 mSv/a. Measurements above 3 mSv/a were observed in 9 locations. The main reason for a high natural radiation in ACI is the high concentration of high Ra (eU) and its progeny plus a high content of eK and eTh in the soil. As eU is a major source of Rn, high natural radiation drops in most areas with a high Rn-content. In these areas the content of eU usually exceeds 20 ppm, thus exceeding the legal limit for U content in soil in industrial areas in Estonia.

2.9 Investigation on radionuclide content in superphosphate fertilizers, dose assessment and radiation protection measures

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Phosphorus is an essential component of all living systems. The production of phosphate fertilizers constitutes the key commercial activity in the phosphate industry. Phosphate deposits contain the naturally occurring radionuclides ^{238}U and ^{232}Th together with their decay progeny. Generally, the activity concentrations in currently exploited phosphate ores are about 0.1–3 Bq/g for radionuclides in the ^{238}U decay series and 0.1–0.4 Bq/g for radionuclides in the ^{232}Th decay series. Depending on the origin of the raw material there is a possibility to have as result phosphate fertilizers with an over limit (1Bq/g) mass activity of ^{238}U and ^{232}Th together with their decay progeny.

In the paper are presented results for investigation of fertilizers produced in Bulgaria. The highest values were obtained for the Triple Superphosphate (^{238}U 1924±171 Bq/kg; ^{235}U 116±10 Bq/kg; ^{226}Ra 943±230 Bq/kg; ^{210}Pb 776±62 Bq/kg; ^{232}Th < 6.6 Bq/kg). The increase of the natural radionuclides content in the fertilizers is linked with change of the provider of the raw material from Syria to Jordan.

Predicted Annual Effective Dose was estimated on the base of modeling for the representative person from the public dealing with the fertilizer with quantity more than one ton. The results show insignificant doses from External irradiation ranged from 0.32 to 24 μSv/y and internal irradiation from 0 to 340 μSv/y. The highest value was calculated for the fertilizer storage and it is mainly due to inhalation. The assessment was done without application of radiation protection measures.

Proposed radiation protection measures include minimizing the internal irradiation with decreasing of the time into the storage, ventilation, use of personal protective equipment and prohibition of smoking and eating in the storage and in and around the fertilizer machine.

The conclusion of the study is that the attention has to be done on the distribution and use of phosphate fertilizer due to optimizing of the public radiation protection.

2.10 Radon in waters in Serbia

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^{222}Rn is a gas and it may release from the origin material to indoor air and accumulate to high enough concentrations to provide a significant dose. Radon is soluble in water, and if it is present in the ground it can be dissolved into groundwater. When this groundwater is used as a water supply without any pretreatment the dissolved gas can be released in the surrounding air in homes or directly ingested and inhaled with drinking water. Most of the exposure from radon in a private drinking water supply comes from breathing in radon decay products when they are released to indoor air because of normal household uses of water, such as showering and bathing. Radon exposure from drinking the water is much smaller. Elevated radon levels can occur in private water supplies that come from groundwater sources such as wells, boreholes or springs. Although elevated indoor radon concentrations are most often caused by radon in soil gas and not radon in household water, many EPA publications recommend testing for radon in water for all homes with private wells that have found elevated radon concentrations in air. According to the proposed regulation in Serbia the limit for radon in water should be 100 Bql^{-1}, but this regulation is not yet approved by the Government.

This paper presents different methods for measuring of the activity concentrations of radon in water with the appropriate detection limits and all the problems which may arise during sampling of water which introduces the main source of error in these measurements. We will also present the results of measurements of radon in drinking waters (public fountains, tap water, water from deep wells) and radon in thermal waters in some spas in Serbia. Special attention is devoted to the radon in water in radon spa Niska Banja which is well known by the elevated indoor radon levels.

2.11 Radionuclides in drinking water in Serbia

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The ingestion of water is one of the pathways of incorporation of radioactive substances into the human body. Access to safe drinking-water is important as a health and development issue at a national, regional and local level (WHO 2004). In accordance with Council Directive 96/29/Euratom (EC 1996), the contribution to the exposure of the general public must be kept as low as reasonably achievable. The Euratom Drinking Water Directive (European Council 2013) provides a framework for controlling radioactivity in drinking water and the radiation dose received from the consumption of different forms of drinking water. For radioactivity three parametric values are established: 'indicative dose' or 'ID' means the committed effective dose for one year of ingestion resulting from all the radionuclides whose presence has been detected in a supply of water intended for human consumption, of natural and artificial origin, but excluding ^{3}H, ^{40}K, ^{222}Rn and short-lived radon decay products; a ^{3}H activity concentration of 100 $Bq\cdot l^{-1}$ and ^{222}Rn activity concentration of 100 $Bq\cdot l^{-1}$. For the screening strategies for gross alpha activity and gross beta activity, recommended screening level for gross alpha activity is 0.1 $Bq\cdot l^{-1}$, and recommended screening level for gross beta activity is 1.0 $Bq\cdot l^{-1}$. If the gross alpha activity exceeds 0.1 $Bq\cdot l^{-1}$ or the gross beta activity exceeds 1.0 $Bq\cdot l^{-1}$, analysis for specific radionuclides shall be required (European Council 2013). Monitoring for radioactive substances in water intended for human consumption should be undertaken in accordance with the monitoring strategies and frequencies set out in (European Council 2013), in order to check whether the values of radioactive substances comply with the parametric values laid down pursuant to (European Council 2013).

In this paper, results of monitoring studies of radioactive isotopes: ^{226}Ra, ^{3}H, ^{90}Sr and gross alpha/beta activity in drinking water samples from Serbia were presented. The annual effective dose due to consummation of these waters was estimated.

References:

WHO (2004), Guidelines for Drinking-water Quality, Volume 1, Third Edition, Geneva.

European Council (1996). Council Directive 96/29/Euratom.

European Council (2013). Council Directive 2013/51/Euratom.

2.12 A new Atmospheric Radon MONitor (ARMON): calibration, correction biases, inter-comparison and research applications.

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Nowadays, high-quality atmospheric measurements of the radioactive noble gas radon (^{222}Rn) are needed with high spatial resolution for different research topics such as the improvement of radon flux inventories, by inverse modelling techniques, and the characterization of radon prone areas with their associated health risks. Thus, worldwide monitoring networks are already performing atmospheric ^{222}Rn measurements with different measurement methods and at different heights from the ground.

In this state of the research, the Institut de Tècniques Energètiques (INTE) of the Universitat Politècnica de Catalunya (UPC) has developed an Atmospheric Radon MONitor (ARMON) based on the electrostatic deposition method. The ARMON is a portable system which allows hourly continuous measurements of both atmospheric ^{222}Rn and thoron (^{220}Rn) concentrations thanks to the collection of their fast progeny ^{218}Po and ^{216}Po, respectively, on a detector surface. The measurements of ^{222}Rn and ^{220}Rn activity concentrations can offer new opportunities for separating remote and local contributions of emitting radon sources.

Several ARMON monitors, built and calibrated at the Laboratori d´Estudis del Radó (LER) of the INTE-UPC, are currently running at different Spanish mountain and coastal stations thanks to the collaboration with different research entities. The performance of the ARMON has been also tested from inter-comparison studies with ^{222}Rn and ^{222}Rn progeny monitors based on different measurement principles at coastal as well as at mountain sites.

Here we present:

i) the methodology applied to calibrate the ARMON and to correct the humidity influence on the ^{218}Po and ^{216}Po collection efficiency within the INTE-UPC radon chamber;

ii) the study of ARMON response variability under different meteorological and aerosol concentration conditions;

iii) the characterization of ground level ^{222}Rn concentration at coastal/mountain Spanish stations;

iv) the application of ^{222}Rn/^{220}Rn ratio as tool for identification of local/remote radon prone areas.

2.13 Design and development of a laboratory facility to assess ^{222}Rn exhalation variability from Phosphogypsum material

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A large phosphoric acid production complex has been running at Huelva city (Southwestern Spain) during 45 years (1965-2010) producing average annual values of around 2.5 Mt of Phosphogypsum (PG) material. This PG was routinely deposited at the saltmarshes of the Tinto River estuary. This activity over the years has generated a large PG repository (extension of about 1000 ha) in this area. PG contains enhanced concentrations of U-series radionuclides, particularly specific activity of ^{226}Ra was found to be averagely of 650 ± 60 Bq kg^{-1} in this material. Thus, these piles could be a high potential source of radioactive radon (^{222}Rn) gas, exhaled from the PG surface after its production by the ^{226}Ra decay. ^{222}Rn exhalation from PG material needs to be assessed.

For this purpose, laboratories studies were carried out with the main goal of developing and comparing different ^{222}Rn exhalation methods (closed and open chambers) and instruments (e.g., Alpha Guard, Rad 7, Radon Scout, etc). Two large plastic boxes were filled with homogenized PG material, extracted from the Huelva piles, in order to study the ^{222}Rn exhalation under constant environmental conditions.

Methods based on closed accumulation chambers show a significant influence of leakages on the saturation of the ^{222}Rn concentration measured within the chamber which could lead to an underestimation of the measured ^{222}Rn exhalation or an increase of its associated uncertainty. Open accumulation chambers, used with a fixed flow, allow making use of controlled leaks to measure ^{222}Rn exhalation.

In conclusion, an experimental setup has been designed and developed to measured ^{222}Rn exhalation from PG under controlled conditions. For closed chambers, linear fitting to the first hours of accumulation gives good results provided small leaks are achieved. Exponential fitting may offer better precision but needs more accumulation time in order to reduce uncertainties to an acceptable level. Open chambers allow skipping the leakages influences and carrying out continuous radon exhalation measurements.

Further ^{222}Rn exhalation campaigns will be carried out directly at PG piles using the methods and/or instruments tested in laboratories studies.

2.14 Swedish experience working with building material

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According to the COUNCIL DIRECTIVE 2013/59/EURATOM Article 75 the Member States are required to establish a reference level applying to indoor external exposure to gamma radiation emitted by building materials not exceeding 1 mSv per year and ensure that building materials placed on the market have determined and specified activity concentrations of the radionuclides and that, information on the results of measurements and the corresponding activity concentration index, as well as other relevant factors, are provided to the competent authority, if requested.

The major problem for the industry involved in production of building and construction products, is long time of measurement (more than 28 days), low reliability of results as a very small sample is used, high cost of laboratory (not possible to afford in-situ measurement), lack of laboratories with capability to satisfy huge European construction industry and enormous delays in product delivery.

A method for activity concentration measurement of K-40, Ra-226 (Uranium 238/235) and Th-232 was developed, verified and accredited by the Swedish Accreditation Agency, Swedac 2017-01-16. The accredited test results, from measuring these radionuclides, is calculated for determining activity index, radium index and gamma radiation for the building material which allows a producer to demonstrate a compliance with the requirements of the EU Directive 2013/59.

The MMK A2 605 method allows:

— obtaining the measurement results in only 20 minutes,

— testing construction product in the state of intended use,

— 2 test cubes are included per test (size according to SS-EN 206) and mass ~16000 gram,

— high level of confidence and low level of uncertainty (less than 10%),

— use the measurement results to calculate Activity Index.

The method is simple to use and allows application for both industries' and supervising authorities' need.

The new method was verified by the Swedish Accreditation Authority (SWEDAC) during 2016. The accreditation according to EU Regulation No 305/2011 was obtained 16 January 2017 No 2052. This method, MMK A2 605, is valid for laboratories in all countries included in EU and associates of the European EA.

Table 1. Percentage of the tested Swedish building materials that is above the Activity Concentration Index 1.

Material	Non-compliant, %
Concrete	14
Gravel	22
Rock aggregates	35
Sand	0

2.15 Effective Radium as indoors radon hazard index for building materials

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Radionuclides in building materials are the sources of both external exposure due to gamma-rays emitted by ^{40}K, ^{226}Ra and ^{232}Th as well as internal exposure caused by alpha-particles deposited on the respiratory tract tissues due to inhalation of radon indoors. Indoors environment is generally described by standard room model. Aiming to protect the public from excessive exposure to radioactivity, various radioactivity indices have been proposed in order to assess the natural radioactivity of building materials. In the present study the indices adopted by the European Commission as well ICRP were discussed. In case of internal alpha radiation exposure, an I_α index has been adopted taken under consideration that a building material with ^{226}Ra concentration lower than 200 $Bq.kg^{-1}$ could not cause indoor radon concentration higher than 200 $Bq.m^{-3}$ which is the recommended action level of indoor radon exposure by EU and ICRP for the dwellings (ICRP 1994, EC 1990, Righi & Bruzzi 2006). In the present work a new approach to this problem is presented taken into account not only ^{226}Ra concentration but radon emanation factor (ε) as well. The proposed index is based on so called "effective radium" considering a 20% contribution of building materials to indoor radon for model building in a temperate climate (UNSCEAR, 1993). A variety of building and decorative materials has been

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3.1 Geological and geochemical control on Radon occurrence in Euganean Hills district (North-Eastern Italy)

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Radon isotopes (^{222}Rn and ^{220}Rn) generated within the upper layers of the Earth's crust by the radioactive decay of the ^{238}U and ^{232}Th can migrate during its brief lifetime to the atmosphere, and can enter and accumulate in indoor environments. However, background radon concentrations in the soil pores are specific of the different lithology depending on its parent nuclide ^{226}Ra. Both background and deep radon components, defined as Geogenic Radon Potential (GRP), may lead to a human health concern: a portion of the inhaled air will contain radon, and solid short-lived radon decay products that, bound to fine aerosol particles, are inhaled, and irradiate lung and bronchial tissues. This suggests that the identification of risk areas cannot be disconnected from the underground geological environment (i.e., GRP).

A survey conducted by *ISPRA Ambiente* (formerly ANPA, National Agency for Environmental Protection) and ARPA (the Regional Agency for Environmental Prevention and Protection) in the Veneto region of north-eastern Italy, showed that indoor radon measured in the Euganean Hills district exceeds the reference values (300 Bq/m^3) recommended by the European Community (Council Directive 2013/59/Euratom 5/12/2013), thus suggesting the need to investigate the possible link between the observed radon concentrations and the geological and geophysical framework of this densely populated area.

Radon and thoron concentrations in soil gas were measured in situ by using the Durridge radon equipment (RAD7, Durridge UK Ltd.) in order to provide a representative coverage of the Euganean Hills. Geo-statistically treated data provide a reliable risk map connecting soil gas radon concentrations with different bedrock types and soil features, ^{238}U decay progeny and geology. Moreover, sets of measurement points along profiles crossing structural discontinuities, such as faults and lithological contact zones, clarify their effects and influences on soil radon emission at surface, yielding a better understanding of the migration mechanisms at the base of deep radon remobilization by channelling and enrichment in the soil.

Preliminary results confirm that the most important geological characteristics affecting radon concentrations in soil gas are both lithology and structural features. The highest radon concentrations occur in areas characterised by silicic volcanic and sub-volcanic rocks, such as rhyolites, trachytes, basalts and latites, and in zones close to the main structural lineaments.

The estimation of the deep radon and its exhalation rate at surface is a key factor in predicting indoor concentrations, and hence two main quantities: the doses to dwellers and the risk level. Moreover, the identification of radon priority areas, as requested in the new Euratom directive, can serve as a useful guide in land use planning and in construction siting.

3.2 Spatio-temporal variations of ^{222}Rn and ^{220}Rn across seismogenic faults at Mount Vettore during the seismic sequence of the 24th August 2016 earthquake

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Radon isotopes (^{222}Rn and ^{220}Rn) background values in the soil pore are typical for a specific lithology and depend on the local content of their parent nuclide ^{238}U, ^{232}Th and ^{226}Ra in the subsurface rock. In the international literature, many investigations have reported Rn isotopes anomalies significantly higher than background levels along active faults. Many evidences suggest that these radon anomalies can be linked to the stress/strain changes related to seismic activity that may force crustal fluid to migrate up, thereby altering the geochemical characteristics of the fault zone at surface before and after earthquakes.

In this work, soil gas profiles of radon isotopes have been carried out across buried and exposed segments of the Mt. Vettore fault system, that originated the strong seismic sequence started on the 24th August 2016, as well as in correspondence of its antithetic fault system. The objective of the survey was to explore the mechanisms of migration and the spatial-temporal behaviour of radon isotopes in correspondence of still-degassing seismogenetic fault systems of the central Apennine.

The soil-radon anomalies appear spatially irregular due to variable permeability of the materials of the core zones and the damage zones. In the case of buried segment, the anomalies are 'double-peak' in profile with a maximum ^{222}Rn and ^{220}Rn anomalies (from 2-5 times the background values) located at the periphery in the lateral blocks and a minimum value at the axial part. The sharp spikes at both side of the buried segment of the Mt. Vettore fault are the result of the opening fractures proximal to the fault core that significant increase gas channelling and surface leaks. In contrast, background values occur in correspondence of the fault core, characterised by less permeable gauge material, where the outgassing rate is decreased by the closure of the fractures caused by the strain changes.

In the case of exposed segments of the fault, ^{222}Rn and ^{220}Rn anomalies mainly occur in the hanging wall, whereas diffuse degassing characterises the more exposed footwall of the fault, affected by the shallow conditions (i.e., potential atmospheric dilution due to weathering and to topographic contrast).

The repetition of the profile across the buried segment of the Mt. Vettore fault in the Castelluccio plain four days after the 6.5 Mw earthquake of 30 October 2017 highlighted an increase of ^{222}Rn values (5-10 kBq/l) in correspondence of the same peaks of the previous profile.

These results encourage the idea that space-and-time variations of soil-radon activity in the fault zones are mainly controlled by geodynamic factors (i.e., distribution, intensity and direction of the stress/strain changes) that control size, architecture and activity of a fault and thus determine both the spatial behaviour (i.e., size, geometry and amplitude) of a soil-radon anomaly, as well as the temporal variations of soil-radon activity during the periods of the activation of a fault segment.

The development of a systematic mapping and/or continuous monitoring of the soil-radon anomalies across active fault systems can reveal relation with the architecture of the fault zones, and can have practical application for identification of faults buried under the sedimentary cover. Furthermore, these maps may constitute potentials of further assessments of radon hazard exposure to people.

3.3 Radon anomalies in the northern Upper Rhine Graben (Germany) as result of recent geodynamic processes

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Geological setting

The Upper Rhine Graben (URG) area is part of a Cenozoic sediment basin, framed by Variscan Mountains and has its origin in the Alpine Orogenesis and related tectonic stresses. As a consequence NNE-trending structures developed, which bound the URG on its flanks. As a depot centre, the northern URG accommodated Tertiary and Quaternary sediments. Aside from the major faults the URG hosts a high number of minor faults of which several structures are considered as recently/sub-recently active. Measurements on the eastern master fault of the URG in the area of Darmstadt reveal movement rates, which are in good accordance with the general understanding of tectonics in the URG and thus support the hypothesis of recent geodynamic processes in the area. To investigate possible links between recent geodynamic processes and radon emanation, respective measurements have been conducted.

Radon measurements

Measurements of radon in the soil air right directly to the eastern master fault revealed concentrations of up to 340,000 Bq/m³. Consequently, ambient air shows very high concentrations as well. Authors interpret measurements as result of favorable migration conditions along the master fault. Further investigations have been made, addressing faults in the URG, which have been located in 380 m below the surface through 3D-seismic information. Altogether 96 soil gas measurements were taken. Soil samples for every single measuring point have been analyzed for the presence of radium, the parent nuclide of radon, in order to differentiate between radon that developed in situ and radon that migrated to the measuring environment. To increase the reliability of detected concentrations, CO_2 also has been measured since it could be carrier gas for radon, accelerating the rise of radon from deeper underground.

In general it can be concluded that the concentration of radon and CO_2 show higher values in the fault zones than in areas apart. Based on the high cover of Quaternary sediments in the area of interest the possible peak in the radon concentration is disposed over the area. A clear peak above faults, as shown in other papers, could only be measured in areas with little cover of sediments over the crystalline basement. Further investigations are on the way.

3.4 Geochemical variations of ^{222}Rn and ^{220}Rn in the Modena province during and after the 2012 Emilia seismic sequence

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Soil gas anomalies are useful to recognize influences of surface features on natural gas migration. The study of the association of different gases with different origin and physical/chemical behavior, the collection of a large number of samples during the dry season (under stable meteorological conditions) and the use of proper data analysis are fundamental in the comprehension of gas migration mechanism. The study of spatial distribution of soil gas anomalies, at the surface, can give information on the origin and processes involving deep and superficial gas species. In particular, the study of the spatial distribution of radon (^{222}Rn), often together with other soil gases, in faulted areas appears to be a suitable tool for identifying active tectonic structures.

Several geochemical surveys (soil gas and shallow water) were carried out in the Modena Province (Massa Finalese, Finale Emilia, Medolla and S. Felice sul Panaro), during the 2006-2015 period. In May-June 2012, a seismic sequence (main shocks of ML 5.9 and 5.8) occurred closely to the investigated area. In this area, 150 soil gas concentrations (^{222}Rn, ^{220}Rn) and 30 shallow waters (dissolved Rn) were sampled in April-May 2006, May-July 2008, and repeated in May and September 2012, June 2013, July 2014 and June 2015.

In this work, we show results of soil gas measurements of radon and thoron isotopes, and helium content, which have been carried out in the area struck of the 2012 seismic sequence.

The samples measured and collected from these zones are characterized by ^{222}Rn activity between 2 and 16 kBq/m^3 (below the Italian mean). Among 24 measurement points, using a method with the double depth probe for flux calculation, it was possible to note that only 4 of them have a significant ^{222}Rn soil flux of between 60 and 80 kBq/(m^{2}s)day. Also the other soil gas fluxes, have extremely low values. The presence of deep fluid leakage is not envisaged, suggesting just a local enrichment of gases in the free phase sampled in the wells.

Low radon and thoron values occur in the studied area, showing background values of ^{222}Rn activity in correspondence of the presence of less permeable material and clay soil cover. However, some sectors revealed anomalously high ^{222}Rn activity values soon after the main shocks with values around 28kBq/m^3. These peaks occur in the same sector characterized by high soil gas concentration values. This correlation is more evident in the 2014 survey, after two years from the earthquakes, where the maximum value of radon activity (44kBq/m^3) was found.

The repetition of the surveys for four years after the 2012 Emilia seismic sequence highlighted an increase of ^{222}Rn values (10-15 kBq/m^3) in correspondence of the same points.

Radon vs thoron ratio (around 0.51) highlights a shallow circulation in the huge part of the studied area, while a ratio of 5.48, linked to a deeper circulation, is present in spotty areas.

Dissolved radon displays a very low activity, likely due to the particular hydrogeological setting of the study area, with values spanning from 1 to 7 Bq/l.

Geochemical surveys highlight the importance to carry out a discrete monitoring that can help to study the stress/strain changes related to seismic activity that may force crustal fluid to migrate up, thereby altering the geochemical characteristics of the fault zone at surface before and after earthquakes.

3.5 Quantification of lead concentration and radon emanation in soils: a study in a region of geological faults

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The emission of radon gas in regions of geological faults, during the radioactive decay of uranium and thorium, results in the formation of lead isotopes ^{210}Pb, ^{208}Pb, ^{207}Pb and ^{206}Pb. As a consequence, lead contamination in the soil poses a hazard to humans through ingestion of food, contaminated water, and even by direct contact with the soil contaminant (Amaral et. al 2012). So far, the relationship between the occurrence of geological faults and soil Pb contamination has not been established. The objective of the present work was to investigate the relationship between total lead soil concentration in regions with geological faults and possible radon emissions. The findings are compared with results obtained in areas outside geological faults. The influence of soil depth and particle size on total lead concentration was assessed. Soils were sampled in Presidente Prudente, located in the far west region of São Paulo State, Brazil. This region presents strong evidence of the existence and direction of geological faults at depths of approximately 200 m. Soil sampling was performed in accordance with the USEPA 3050 method (Chen et. al 1998). Total lead was quantified by anodic stripping voltammetry. The study of radon emanation from soils was conducted using a solid state nuclear track detector, the organic polycarbonate-based CR-39 device (allyl diglycolcarbonate, $C_{12}H_{18}O_7$). Soil samples from the area of fault lines showed Pb concentrations exceeding both reference and prevention values, and above the level at which intervention is required. Pb concentrations outside the faults were far lower than in the faults. Results show that total Pb concentration systematically increases with soil depth. This finding is explained by the fact that the lead originates from radon emissions. The results of the textural analysis showed that most of the soil samples contained high percentages of the sandy fraction; however, lead concentrations were higher in the horizons with larger percentages of clay, in line with the cation exchange capacity of this soil fraction. Pearson correlation analysis further proves the existence of a relationship between the nuclear track density obtained with CR-39 detectors and mean Pb levels within each soil profile. Overall, these findings should improve risk evaluation of Pb contamination derived from radon emission and geological faults. Such findings are relevant for the evaluation of public health risks due to contamination with bioavailable lead derived from radon emissions.

References:

Amaral PGQ, Galembeck TMB, Bonotto DM, Artur AC (2012). Uranium distribution and radon exhalation from Brazilian dimension stones. Appl Radiat Isot 70:808–817. doi:10.1016/j. apradiso.2011.10.010

Chen M, Ma LQ (1998). Comparison of four USEPA digestion methods for trace metal analysis using certified and Florida soils. J Environ Qual 27:1294–1300

3.6 Natural Th, U, and K concentrations in bedrocks of major geological units in Hesse (Germany)

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Natural radiation comprises terrestrial and cosmic radiation. The terrestrial radiation can vary considerably, depending on the geochemical composition of regional geological formations. Decay of radioactive nuclides, in particular of the elements U, Th, and K, contribute the most significant part to the terrestrial radiation as well as radiogenic heat production. Moreover, the radioactive decay of U and Th generates radioactive nuclides of Rn.

In the course of developing a strategy to define specific Rn-prone areas in the federal state of Hesse (Germany), we suggest to focus on the major geological units and characterize them according to their rock types and natural radiation. Hesse consists of geological formations ranging from Paleozoic to Cenozoic times. These include the magmatic basement of the crystalline Odenwald, low-grade metamorphic rock units of sedimentary and volcanic origin in the Rhenohercynian Zone, large areas of Mesozoic strata (e.g. Bunter Sandstone) in Middle- and East-Hesse, Tertiary volcanic rocks from the Vogelsberg, Tertiary sediments of the Mainz and Lower Hessian Basin, and Quaternary sediments of the Upper Rhine Graben.

A vast number of geochemical analyses enable us in a first step to identify the concentration of U, Th, and K in different rock types. Because of their incompatible and lithophile character, these elements accumulate in silica-rich rocks, especially in differentiated igneous rocks such as granites. Accordingly, siliceous igneous rocks tend to have high contents of U, Th, and K (e.g. 4 ppm U, 14 ppm Th, 4 wt.% K), whereas basic rocks show distinctly lower contents (e.g. 1 ppm U, 4 ppm Th, 1 wt.% K). Th and U contents of sedimentary and metamorphic rocks vary at a moderate level (e.g. sandstones 2 ppm U, 8 ppm Th, 0.5 wt.% K). However, due to sedimentation conditions and possible secondary alteration with U-rich fluids, a considerable enrichment of U may occur.

The major geological formations and structural units in Hesse and their content of radioactive nuclides will form the data base to define regions for further radon soil gas measurements.

3.7 Mapping of soil ^{220}Rn flux and dose rates in radon-prone areas. The case of volcanic outcrops in a highly urbanised city

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^{220}Rn (thoron) contribution to indoor radon concentration is generally neglected because thoron is characterised by a very short half-life (about 1 minute) that determines its fast decay. However, its activity concentration is not minor in the basements of edifices built on thorium-enriched geological backgrounds or when thorium-enriched rocks or sediments are employed as building materials. These materials in Italy, but also in other areas of Europe, are generally of igneous origin, with an average Th/U ratio larger than 3. Mapping of soil thoron flux in radon prone areas maybe an additional tool to evaluate natural radioactivity and assess population exposure.

A rapid and reliable method to measure in-situ soil thoron fluxes consists of a small accumulation chamber connected to a continuous radon monitor (RAD7, Durridge Co.) equipped with a flowmeter to correct for thoron decay during soil gas sampling. A second approach to detect thoron fluxes makes use of special acrylic cloth which are left over the soil for a short period of time to collect thoron daughters to be then measured as ^{212}Pb activity by gamma spectrometry.

Soil thoron fluxes may be associated with measurements of total gamma radiation converted into dose rate to better assess human exposition to natural radiation. Natural gamma radiation is mainly due to the occurrence of ^{40}K, uranium and thorium series radionuclides. This can be achieved using a Ludlum digital ratemeter with a built-in scaler that provides timed counts over a specified period and translate it into total dose rate. This device is a NaI (Tl) crystal optically coupled to a photomultiplier tube.

Both measurements have been carried out in Valle della Caffarella, a green area surrounded by highly populated neighbourhoods in Roma (Italy), where volcanic rocks from Colli Albani volcano outcrop. This region is affected by release of endogenous gases and mapping of soil radon and CO_2, along with soil intrinsic permeability, was previously investigated. The comparison of these maps is very useful to better investigate soil radon transport and origin in the subsoil and assess the risk.

Mapping of soil ^{220}Rn flux and dose rates have the advantage of being fast and reliable. Large areas with a good space resolution may be investigated in radon-prone areas where a future urbanisation is planned, in addition to standard soil radon and thoron concentration and soil permeability field surveys.

3.8 Deviations in radon risk mapping using random soil gas sampling

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Fundamental factors affecting results of radon risk mapping are homogeneity of the geological basement and the number of observed field stations, providing the soil gas sampling and radon measurement fulfil the basic requirements.

Three radon reference sites Cetyne (orthogneiss, 32 kBq/m^3), Bohostice (orthogneiss, 52 kBq/m^3) and Buk (granodiorite, 155 kBq/m^3) in the Czech Republic serve for tests and standardization of radon in soil gas data. Each radon reference site has fifteen fixed stations in a grid of 5 m x 5 m. The effect of random choice of soil gas sampling in identical geological conditions was studied by measurement on fifteen basic stations of each radon reference site and measurement in a similar grid of stations shifted 2.5 m aside. Resultant data illustrate the magnitude of expected deviations due to random soil gas sampling and emphasize the importance of a sufficient number of field radon observations. Mean deviation is also a key for the definition of a radon anomaly.

The magnitude of long term variations of radon in soil gas due to meteorological changes were registered on the three radon reference sites in the period 2000 – 2017.

4 Session 4: Radon-priority areas

4.1 The geogenic radon hazard index – another try

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The concept of Geogenic Radon Hazard Index (GRHI) has been developed in the context of the European Atlas of Natural Radiation. One of its targeted maps is one that shows the geogenic cause of the indoor radon risk. Usually, the geogenic radon potential (GRP), estimated using radon soil gas and permeability values, is considered to be the most straightforward measure of this hazard, defined on the basis of radon source terms and transport properties in the ground. However, GRPA data are available only from a few countries or regions of Europe.

On the other hand, predictor and proxy quantities are often available instead (or additionally). Among predictor data are uranium concentration in soil or geological and tectonic features, for proxy quantities we name ambient dose rate. The availability of these quantities, as well as their definition (e.g., sampled according which protocol), often differs between European countries and even regions.

The idea of the GRHI is to construct a new variable by combining available ones, which to an utmost degree quantifies the geogenic radon hazard and which is able to cover as large a fraction of Europe as possible. This is a multivariate approach which exploits statistical relationships (originating from physical ones) between predictor, proxy and target or primary quantities (for the latter, e.g. the GRPA or indoor radon concentration).

The GRHI must be *consistent*; that is, ideally, two locations with identical geogenic conditions shall have the same GRHI value, independent of the quantities from which it has been estimated; this leads to the problem of "gauging" these quantities against each other. It must also be *universal*, which means that the model through which it is defined (or the algorithm, as its numerical representation) must not depend on regional peculiarities. Instead, these enter as possibly regionally variable model parameters, as available. In addition, of course, accuracy and preciseness must comply with external requirements, as optimally as data and models allow.

In this presentation, we critically review two previous attempts to construct a GRHI (based on German data, presented at the Prague radon conference, 2016, and on Cantabrian data, TEERAS, Sofia 2017) and propose improvements. Further, we shall discuss metrics or scores for assessing the performance of a GRHI, and possibilities for validation.

We are aware of the fact that it is no easy task to develop a well-performing GRHI. The challenge consists in finding a solution which largely fulfills the above desiderata, but at the same time is tractable in practice.

Apart from the role of a GRHI map in the European Atlas of Natural Radiation, this index is also a step towards harmonizing attempts among European countries that will have to adopt the requirements of the EURATOM Basic Safety Standards. Motivated by this, the currently ongoing European "MetroRadon" project includes development of a GRHI; thus, work presented here serves two parallel endeavours.

4.2 Detection of radon priority areas by in-situ radon soil-gas measurements: a case-study in the Cooley Peninsula (County Louth, Ireland)

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Radon in Ireland represents 56% of the total radiation dose received by the Irish population, and it is estimated that every year up to 250 lung cancer cases are related to radon exposure. The radon map of Ireland currently defined in legislation is based solely on existing indoor radon measurements. It illustrates the probability of having an indoor radon concentration above a national reference level of 200 Bq m^{-3} by grids of 10 km x 10 km. A High Risk Area is classified as such when the probability of exceeding the national reference level is 10%, or higher. To improve the resolution of the radon map geogenic factors have been incorporated into the data interpretation and are currently being evaluated.

In this work we present a method for detecting radon priority areas using in-situ radon measurements and soil permeability data. The method was tested and validated in the High Risk Area of the Cooley Peninsula (County Louth, Ireland). In total, 60 radon soil-gas measurements from 48 points were carried out in an area of approximately 160 km^2. Results of Radon Potential classification were compared with the Indoor Radon Map of Ireland, the latter constructed using more than 400 indoor radon measurements in the study area.

Soil-gas radon concentrations in the Cooley Peninsula ranged from very low values (less than 10 kBq m^{-3}) to extremely high (up to 112 kBq m^{-3}), and indoor radon concentration from 3 to 863 Bq m^{-3}. The percentage of indoor radon variance explained by soil-gas radon concentration, estimated soil permeability and geology was approximately 30% (12%, 9.3% and 8.6%, respectively). The Cooley Peninsula is subsequently mostly classified as a Moderate-High and High Radon Potential area.

Radon Potential classification detects radon priority areas with a reasonable degree of accuracy, indicating that in-situ soil-gas radon measurements are useful for radon mapping at a local scale. Soil permeability has also a high influence on Radon Potential, and in-situ measurements are recommended to better estimate the radon risk.

Active soil gas radon measurements and modelling can significantly reduce the time and cost required to evaluate an area in relation to expected indoor radon concentrations. This method is also a viable method to produce a Radon Potential Map in rural areas or where few indoor radon measurements are available. In the absence of a national-scale soil gas radon data set, the technique is best suited to local-scale studies.

4.3 Geogenic Radon Potential map of the Celleno municipality (Lazio, central Italy)

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In the international literature new methodological approaches and modelling, based on spatially continuous geological and environmental radon proxy parameters (e.g., lithology, permeability and airborne total gamma radiation), were recently proposed to construct maps of the Geogenic Radon Potential (GRP) in order to identify radon-prone areas.

In this work are presented data collected in the municipality of Celleno (VT) that was selected for a detailed study within the framework of the research project INAIL/CNR-IGAG P19L06 "Studio dei processi di migrazione e accumulo dei gas endogeni e del radon dai suoli verso gli ambienti di vita e di lavoro in funzione delle caratteristiche geologiche presenti al contorno". The aims of the project were:

1) to investigate the main factors affecting the GRP at local scale through the development of a spatial regression model considering soil-gas radon concentrations as the response variable and developing proxy variables as predictors;

2) to construct a map of the GRP, thus providing the local administration of a useful tool for land use planning and strategies aimed at radon health risk reduction;

3) to use a soil-indoor transfer factor to discriminate the amount of the geogenic radon vs the rate due to building and habit characteristics.

The study area is located along the western margin of central Italy characterized by extensional tectonics, high heat flow and widespread CO_2 gas emissions. The municipality of Celleno extends on a surface of about 25 km^2 and is located 80 km NW of Rome, at the eastern border of the Quaternary Vulsini volcanic district, whose activity produced mainly pyroclastic products and minor lava flows with potassic to ultrapotassic affinity. The outcropping volcanic rocks were traditionally used as building materials in the old center of the Celleno village.

Soil-gas surveys and laboratory analyses were carried out to measure the concentrations of radon and other endogenic gases in the shallow environment, as well as the activity concentrations of natural radionuclides (^{238}U, ^{226}Ra, ^{232}Th, ^{40}K) and the radon emanation coefficient of several soil and rock samples, representative of the different lithotypes outcropping in the area. Indoor radon measurements were also carried out in selected private and public dwellings and cellars.

Soil gas ^{222}Rn concentrations range from 6 to 253 kBq/m^3; CO_2 concentrations range between 0.3% and 11%. Samples collected from outcropping volcanic and sedimentary rocks highlight: significant concentrations of ^{238}U, ^{226}Ra and ^{40}K for lavas (183, 181 and 1671 Bq/kg, respectively), lower concentrations for tuffs (110, 92 and 756 Bq/kg, respectively) and very low for sedimentary rocks (42, 47 and 572 Bq/kg, respectively). Indoor radon activity ranges from 162 to 1044 Bq/m^3, the highest value (4256 Bq/m^3) was collected in a cellar directly carved into a tuff deposit. About 50% of the measured dwellings show radon indoor values above 300 Bq/m^3 (threshold value recommended in the 2013/59/Euratom Directive), whereas all investigated sites show radon indoor values above 100 Bq/m^3.

Classical (Ordinary Least Square, OLS) and spatial (Geographically Weighted Regression, GWR) regression models were applied to investigate the relationships between soil-gas radon concentrations and some proxy explanatory variables, and to construct the GRP map. The OLS regression highlights that CO_2 concentrations in soil gas, ^{226}Ra content, radon emanation coefficient and Digital Terrain Model are statistical significant in the model. These variables were used to improve the model performances within GWR. The final map shows areas with high GRP on the western sector of the municipality of Celleno; as this area is sparsely populated, the GPR map may facilitate the future urban planning and should allow the improvement of public health management strategies.

A radon soil-indoor transfer factor was calculated to discriminate the geogenic vs indoor contribution. Preliminary results highlight that ventilation habits and building materials (mainly tuff) appear to be important parameters affecting the radon accumulation. According to these promising results, the Celleno municipality has been selected and further investigated within the new LIFE-Respire project.

4.4 An extensive indoor radon measurement campaign to define radon-priority areas in Austria – methods, influences and challenges

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According to the new EU BSS all member states have to identify areas where the radon concentration in a significant number of buildings is expected to exceed the relevant national reference level. Defining such areas will be fundamental for establishing legislation and future strategies.

The current radon map of Austria is already based on quite a large indoor radon data basis but the uncertainty in the classification of municipalities according to their radon potential is still high. To implement the requirements of the EU-BSS (e.g. obligatory radon measurement at workplaces in "radon areas") an improved, sound radon map is needed. An extensive indoor radon measurement campaign was designed with planned radon measurements in about 35,000 dwellings.

The measurements are carried out in the houses of selected members of the voluntary fire brigades for 6 months. The measurement locations are selected based on a regular 2 km x 2 km grid, taking geology into account. Because of resources and administrative issues, the campaign is carried out over several years and is done province by province. Until now, measurements in 3 provinces are finished, the measurements in 2 provinces were started in June 2017, and the rest will follow in 2018.

In the contribution the developed model for radon mapping and possibilities for the delineation of radon priority areas in Austria will be presented. In addition the challenges conducting such an extensive survey and the processing of the data are discussed - addressing effects as representativeness of the measurements, influences of different building characteristics, impacts on the modeling by differences in the provinces (housing stock, geology etc.) and validation of the model. The discussions will be based on the results and experiences of the surveys in the already measured provinces.

4.5 The influence of geological formations on geogenic radon potential and/or indoor radon in Croatia

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In the last few years, the targeted surveys of indoor radon in homes as well as in public buildings with high occupancy (kindergartens and schools) were performed in several counties in Croatia with different geological formations. In the southern part of Croatia, geological structure mainly consists of a limestone plateau and dolomites formed in the Jurassic and Late Cretaceous while carbonate rocks, especially flysch, during Paleogene period. The northern part consists geologically mainly of sandstones and soft clay formed during the Neogene and Quaternary periods. Sediments are of gravels, loess and silts and are all the products of mostly continental environments and alluvial fans. Differences in geological structures of these two areas inevitable supposed to have, as a consequence, very different geogenic radon potential (GRP).

Indoor radon was measured by track etched detectors which were randomly distributed in homes, schools and kindergartens across the whole geographic areas and the number of detectors depended on population densities of the investigated areas. Radon concentrations in soil gas in Croatia were measured with the AlphaGUARD and RM-2 measuring systems while soil permeability was measured by Radon-JOK permeameter. A detailed GRP map based on in-field soil gas radon and soil gas permeability measurements was carried out using "Neznal's" approach. The relationships between geological formations and GRPs or indoor radon were examined.

According to the obtained results, the criteria for identification of "radon prone area", as part of the future National Action Plan, for radon is proposed and discussed.

4.6 Method of identification of radon-priority areas according to the standard European 10 km x 10 km map system

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The present work focuses on the spatial analysis of the of indoor radon concentration in dwellings and their relation with different geological variables (external gamma radiation rate and geology-lithostratigraphies 1: 200,000) that are *a priori* related in the identification of presence of high concentrations of ^{222}Rn.

Based on the information available in one of the region best studied from the point of view of exposure to radon gas in Spain (2,000 indoor residential radon concentration data are available), a model has been developed for the relationship between the indicated variables. This region (Galicia) has a geology with predominance of granite formations, and is one of the zones with higher levels of residential radon of Spain. In order to test the hypothetical validity of this model in the rest of the Spanish geography, a validation has been made in the Madrid region (with 700 indoor residential radon concentration measurements) that has different geological characteristics, presenting clayey domains in the south of the region.

The working methodology used, respects the parameters established by the JRC (Joint Research Center) EC, for the elaboration of the European Atlas of Natural Radiation. A cell system 10 km x 10 km using the GISCO-LAEA projection has been used. The spatial analysis of the variables was performed using two complementary techniques for assigning numerical values to each cell 10 km x 10 km. On the one hand, to assign values to empty cells, a deterministic inverse distance weighting (IDW) method has been used, which uses a weighting of neighboring values as a function of the inverse square of the distance. This interpolation has been validated by an independent validation of the data from a simple random sampling. On the other hand, the variables of qualitative character have been quantified through logical Boolean operators of presence / absence, each cell being characterized by means of a numerical value between 0 and 1.

The presentation will show how the combination of the studied variables using the aforementioned work methodology allows the identification of potential areas to ^{222}Rn in geographically distinct regions based on the analyzed geological information

4.7 Multi-approach assessment of radon risk in Spanish soils

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According to the Council Directive 2013/59/Euratom of the European Union, Member States shall establish a national action plan addressing long-term risks from radon (^{222}Rn) exposures in dwellings, buildings with public access and workplaces for any ^{222}Rn source ingress (e.g. from soil, building materials or water) (European Council 2014). In this context, the Spanish Nuclear Safety Council (CSN) has funded a research project exploring different methodologies to estimate the ^{222}Rn risk at new build sites (Font et al. 2016). Eight locations, with different soil characteristics and climatology, have been studied for one year. In addition to the characterization of soil ^{222}Rn levels and their typical spatial and temporal variations, other potential indicators for radon risk have been explored, i.e.: soil radium content measured from soil samples in the laboratory or derived from *in-situ* gamma-ray spectrometry; experimental and modeled ^{222}Rn exhalation at each site; radon index (as defined in Neznal et al., 2004), and the use of different types of maps. In this work we present the main conclusions of this project and their implications in the Spanish strategy to minimize radon risk in new buildings.

References:

European Council (2014). Council Directive 2013/59/Euratom, of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom, 2014, *Official Journal of the European Union L 13*, 17.1.2014, p. 73.

Font, Ll. et al. (2016). The Spanish strategy to estimate annual-averaged soil radon levels for the next amendment of Building Regulations. 13th GARRM Workshop, Prague, September 15, 2016.

Neznal M., Neznal M., Matolín M., Barnet I. & Miksova J. (2004). The new method for assessing the radon risk of building sites. Czech Geological Survey Special Papers, CGS Prague.

4.8 Mapping Natural Occurring Radioactive Materials (U, Th and K) in Ireland: implications for radon mapping

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Ireland through the Geological Survey, Ireland, and the Geological Survey of Northern Ireland is undertaking a national mapping programme (i.e. Tellus Project, www.tellus.ie) collecting chemical and geophysical data of the soil which will inform Irish state agencies about the environment and natural resources. Tellus involves airborne geophysical surveys (measurement of the Earth's magnetic field, gamma-ray spectrometry and electrical conductivity) and ground surveys (geochemical analysis of soil, stream water and stream sediment). Of particular relevance to natural radiation protection are the uranium (U), thorium (Th) and potassium (K) measurements, and these data are being used to construct a high-resolution radon risk map of Ireland.

Airborne geophysical surveys employ a low-flying aircraft (flying at 60 m in rural areas and 240 m in urban areas) to collect geophysical information on the properties of soils, rocks and waters below ground. A gamma-ray spectrometer (Exploranium GR820) is used to measure the concentration of eU (ppm), eTh (ppm) and K (%). Airborne surveys have been completed in Northern Ireland (2004–2008), the border region of Ireland (2011–2013), the north midlands region of Ireland (2014–2015), eastern midlands region (2015) and Galway and Waterford areas (2016). It is expected that 50% coverage of the island of Ireland will be complete by end of 2017, and all of the island by 2023.

Geochemical surveying characterises the baseline chemistry of soil, stream water and stream sediment by taking samples of these materials by hand at a density of approximately one per four square kilometres. Surveying has already been completed across Northern Ireland and the border region, collecting 6860 and 3475 soil samples respectively. The concentration of 52 analytes in the topsoil was determined by ICP and XRF (including U, Th and K) together with pH and Loss-on-ignition at 450 ºC (LOI).These data are used to map the distribution of U (ppm), Th (ppm) and K (%) in Irish soil by grids of 1 km^2.

Soil-gas radon concentration is predicted using the results of the airborne radiometrics (i.e. eU) and soil properties (i.e. porosity, density, and radon emanation factor). A Radon Potential is then estimated, taking into account the subsoil permeability with the results compared with indoor radon measurements. Selected test sites are further studied using in-situ soil-gas radon and permeability measurements in order to better understand factors affecting production, transport and accumulation of radon in the natural/build environment.

4.9 Determination of radon priority areas – a classification problem

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The EURATOM Basic Safety Standards require that EU Member States, inter alia, identify areas "where the radon concentration (as an annual average) in a significant number of buildings is expected to exceed the relevant national reference level" (BSS article 103/3). Often these are called Rn priority areas (RPAs) to underline that they serve to identify areas where action to prevent and mitigate Rn hazard should be prioritized. Depending on available data, different methods have been proposed to identify these areas.

More technically, the question is how to estimate the properties of spatial (areal) objects, namely size, extent and boundaries of RPAs. The result will depend on available data from which the areas are estimated, on wanted spatial resolution (map scale) and on estimation support (grid cells, administrative units, geological units). Additionally, models applied in the estimation procedure (e.g. if estimated from predictors or proxies) will affect the result. As outcomes of statistical procedures, the results are affected by uncertainty.

Delineation of RPAs effectively means to divide a spatial domain into priority and non-priority areas, i.e. to classify it into two exclusive sub-domains. The concept can be generalized to multi-class schemes. An essential task is to estimate misclassification error rates, that is, (a) the probabilities that a unit classified as an RPA in reality is a non-RPA, and inversely, and perhaps more importantly, that a unit classified as a non-RPA, in reality is an RPA. The respective errors are called first- and second-kind errors, relating to "false alarms" and "falsely omitted alarms". Apart from an area misclassified as a whole, misclassification also pertains, (b), to *instances* within an area (i.e., individual sub-units, such as municipalities as parts of districts, or even individual houses), which in reality may be classified differently than the areas to which they belong, even if the latter have been classified correctly.

Misclassification errors cannot be excluded, (1) because of the natural variability of the quantity upon whose levels classification is based (e.g., through a reference level of indoor Rn concentration or derived quantities), (2) because the estimate is based on finite and uncertain samples of the quantity (or its predictors or proxies, which adds model "noise"). In practice, one has to optimize classification schemes according to external constraints, which include available data, requested resolution and estimation support, as well as acceptable error tolerance.

In this contribution, conceptual and theoretical background, estimation approaches including modelling steps and effects of external constraints on misclassification errors will be discussed in more detail, and demonstrated through examples.

5 Session 5: Relationships between variables

5.1 A preliminary exercise to derive the map of potential radon release at European scale

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The Geogenic Radon Potential (GRP) defines the availability of radon generated in the ground for surface exhalation or infiltration into buildings. One way to quantify the GRP is through Rn concentration in soil gas and ground permeability. These quantities can be measured, but are available only regionally. Instead there have been attempts to estimate the GRP through proxy quantities, such as U content in the ground, Rn emanation coefficient or ambient dose rate. The difficulty is that relations between these and the GRP have to be established first. Only then, spatial estimation, i.e. mapping can be attempted, for which different techniques have been applied in the past

Since 2008, the Radioactivity Environmental Monitoring (REM) group at the Joint Research Centre (JRC) of the European Commission is working on the development of a Europe wide map of Geogenic Radon Potential (GRP) in the framework of European Atlas of Natural Radiation (EANR) project. The Atlas currently includes maps of indoor Rn concentration, cosmic radiation, and of geochemical quantities (U, Th, K), but the GRP map turned out more complicated.

The factors that control the GRP are source term and transport in the ground. The latter is additionally affected by factors related to tectonics, that is, presence of active faults, seismic and geothermal activity and volcanism.

This work is an attempt to construct a GRP map on a European scale starting from proxy variables (already available in the literature or easily available on the web) affecting the global radon release, without the need for direct measurements of radon concentrations in soil gas. This approach does not suggest that soil Rn and permeability measurements should be bypassed, but it can easily and quickly help establish a preliminary GRP estimate of an area. The exercise presented here has been conducted using the following proxy variables: U, Th, and K radionuclide content in soil (GEMAS (http://gemas.geolba.ac.at/) and FOREGS (http://weppi.gtk.fi/publ/foregsatlas/index.php) data interpolated at 10 km x10km grid cells, https://remon.jrc.ec.europa.eu/About/Atlas-of-Natural-Radiation)), the soil permeability in terms of percentage of topsoil fine fraction (<63 micro m) (estimated using LUCAS database (Ballabio et al., 2014)), the spatial distribution of world active faults (Global Faults layer from ArcAtlas, ESRI) and the location of earthquakes of local magnitude > 4 (USGS, https://earthquake.usgs.gov/earthquakes/browse/), the distribution of the global volcanism (Global Volcanism Program, Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution) and the geothermal areas in terms of heat flow (the heat flow map of Europe has been obtained by the analysis of the Global Heat Flow data maintained by the International Heat Flow Commission (IHFC) of the International Association of seismology and Physics of the Earth's Interior, IASPEI). All this information is transformed in raster layers according to a 10x10 km² grid, reclassified by using the Jenks Natural Break classification method and then summed to obtain a new grid map that represents the potential radon release map at European scale. All data has been integrated and analysed in the GIS environment.

We would like to underline that the resulting map has not yet been validated neither against other existing regional GRP mapping approaches, nor against the European Radon Indoor Map, and that this exercise is only a preliminary proposal for a method that could be improved, both regarding selection of variables and statistical methodology. Furthermore, we would like to thank JRC/REM for making available part of the data used in this work through the EANR.

5.2 The influence of numbers of measurements and location on radon distribution parameters for a single geology

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Public Health England and British Geological Survey have worked together to produce radon probability maps in the UK for many years. As part of this process a mapping methodology is reviewed periodically to improve estimates of areas where high radon levels are more likely. This presentation will provide results of a study to test the effect of numbers of measurements selected and their locality on the predicted radon distributions for a single geology. An area in Southwest England was chosen. At surface, the area has five main outcropping granite batholiths contacting sedimentary deposits.

The hypothesis tested was that the same geology generated the same radon potential independently of the location. Geometric means and geometric standard deviations of the radon distributions for each of the five selected areas were compared. The results showed that individual distributions were close to the expected lognormal distribution but they do not come from a single parent distribution. Thus the same geological unit which is spatially separated yielded different radon distributions.

The same geology was also chosen to study the minimum number of measurements required to characterise a radon distribution. Radon measurements in the granite area were used to generate several radon distributions using Monte Carlo simulations. The simulated data were sampled periodically using a systematic sampling method. Sample sizes vary from 10 to 110. The results confirm that at least 30 measurements are needed to characterise a lognormal distribution.

5.3 Indoor radon in south west England predicted by topsoil and stream sediment geochemistry. Selecting the relevant elements through a CoDA approach.

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Abstract: The present work focuses on the selection of the relevant chemical elements from two environmental geochemistry datasets for predicting indoor radon in South West England and maps the results. This is a follow up of previous work by Ferreira et al., (2016).

Data: Indoor radon data (197,464 measurements) from Public Health England (PHE) and G-BASE / NSI topsoil (TSG) and stream sediment (SSG) geochemistry data (41 elements in 987 and 3382 samples respectively) from British Geological Survey (BGS) have been used. There are 600 topsoil and 1182 stream sediment records co-located with indoor radon data, on which the models are based.

Methodology: A compositional data analysis (CoDA) approach is used. The complete SSG composition (41 elements) is *ILR* (isometric log-ratio) transformed (in *compositions* R statistical package) and used to predict the logarithm of indoor radon (lnRn); the model's adjusted R^2 (*adj* R^2) provides an estimate for the maximum lnRn variation explained (MVE) by the composition, against which, any further model with SSG data is compared. A compositional cluster analysis on the variables is computed for the SSG composition, aiming to detect natural elements' associations while focusing on the relative position in the dendrogram of U, the key source element of radon, and the major elements, the key minerals' components. The methodology is then based on both data-driven and knowledge base steps. *ILR*s for sub-compositions with U, starting from the simplest (2 parts) to the most complex (41 parts), are successively tested; as to keep the parsimony principle, the best model(s) compromise the smallest sub-composition with the greatest adjusted R^2. The same procedure is carried out for TSG data.

Preliminary results for Stream sediment (SSG) models show that Si is the element to pair with U in a SSG 2-part sub-composition, as this *ILR* provides the highest lnRn explained variance (*adj* R^2 =20.3%) among the forty possible combinations of the SSG 2-part sub-compositions. The highest *adj* R^2 among the 3-part SSG sub-compositions is for Si-U-Br (25.1%), corresponding to 77% of the lnRn variance explained by the 'total' 41-part SSG composition (SSG_{MVE} = 32.6%). The *adj* R^2 keep increasing with the number of parts in the model. Among the 7-part SSG sub-compositions, nineteen show the *adj* R^2 varying from 29.4% to a maximum of 29.8%, thus reaching more than 90% of the SSG_{MVE}, and including the combination Al-K-Si-Sr-U-Br-Sn (*adj* R^2 = 29.4%).

Preliminary results for Topsoil (TSG) models show that Y is the element to pair with U in a TSG 2-part sub-composition, as this *ILR* provides the highest *adj* R^2 (22.6%) among the TSG 2-part sub-compositions. The highest *adj* R^2 observed among the 3-part TSG sub-compositions is for Y-U-As (29.7%), corresponding to 77.7% of the lnRn variance explained by the 41-part TSG composition (TSG_{MVE} = 38.2%). The *adj* R^2 keep increasing with the number of parts in the model. Among the 7-part TSG sub-compositions, 103 combinations show an *adj* R^2 varying from 34.4% to a maximum of 35.2%, thus explaining more than 90% of the TSG_{MVE}, and including the combination Al-K-Sr-Y-U-As-Br (35.0%).

The process was stopped at this point (7-part sub-compositions) for both SSG and TSG, as the *adj* R^2 already corresponded to more than 90% of the respective MVE and the increment observed between the highest 6-part and the highest 7-part models is equal or less than 1%, thus very small *adj* R^2 increments are expected for models with 8 or more parts.

Preliminary conclusions: for South West England, 3 elements (U-Si-Br for SSG, and U-Y-As, for TSG), are needed to account with more than 75% of the lnRn variation explained by the complete (41 elements) composition, while a 7-part sub-composition is necessary to account with 90% of the same explained variation. The best models will be shown after interpolation with universal kriging.

5.4 First steps in the multivariate analysis of Belgian radon data

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Data: About 30 years after the first radon actions in Belgium, several datasets are available which allow the study of the correlations between indoor radon data and various related quantities.

*Indoor radon: T*he database covers the Southern part of Belgium (Walloon region) with an average density of about 1 data/km^2, whereas the Northern part (Flemish region), where no affected area is known, only has about 0.1 data/km^2.

Soil radon and permeability: Ardennes, a radon-affected area of ~4000 km^2, was densely explored (> 1 data/km^2, including thoron), but only small campaigns went in the whole country (~30,000 km^2, ~0.003 data/km^2), one being planned in summer 2017.

Airborne survey of K, Th, U: uncalibrated data are available on a 100 m x 100 m grid.

Soil K, Th, U/Ra: 219 data for U, somewhat less for K and Th, used for the calibration of the airborne data.

Terrestrial gamma dose rate: 379 measurements; calculated values are also derived from the airborne data.

Qualitative information: for each measurement, geological, lithological and pedological information is available.

Analyzing the relations between all these factors could allow developing a model that would predict areas affected by ^{222}Rn, even without any measurement in homes. Because of the strong difference between Ardennes and the whole country in the information available on soil Rn and permeability, Ardennes deserves a specific approach. It is unfortunately not possible to include anthropogenic factors influencing indoor radon, because the available information was never encoded in the computerized databases.

Ardennes: Ardennes is globally a strongly radon-affected area. Despite its homogeneity for geology, lithology and soil type, an important variability is observed in the indoor radon risk (local GM from ~45 to ~450 Bq/m^3) as well as in soil Rn (1 to 400 kBq/m^3), soil permeability (<10^{-15} to 6.10^{-11} m^2), and airborne U (0.1 to 5.7 ppm). These variables were transformed in order to obtain roughly normal distributions. As the datasets were not collected at the same sampling points, a step of interpolation / smoothing was necessary for some of them before the analysis. Three methods were tried: (a) data mapped on a kilometric grid, by moving average (indoor Rn, soil Rn, soil permeability) or interpolation (airborne U); (b) data mapped at the soil sampling points by moving average (indoor Rn) or interpolation (airborne U) without processing soil Rn and permeability; (c) mean values determined for the squares of a 5x5 km^2 grid (3x3 and 4x4 were also tried). Pearson's correlation coefficients of the data obtained with these methods show the absence of correlation between indoor Rn, soil Rn, soil permeability or airborne soil U in this Rn-affected area. Without surprise, further study by principal component analysis (PCA) does not give interesting results. This leads us to consider grouping by geological and/or lithological unit rather than mapping on a grid. Considering the weighted correlation coefficients between mean values calculated for 20 possible classes defined as lithology-geology pairs reveals better though still rather weak correlations between indoor Rn and soil Rn or permeability, but also a surprising negative correlation with airborne U.

The construction of preliminary multivariate regression models by using classical OLS and spatial GWR was performed with Ardennes dataset in order to individuate those geological parameters that better define the geogenic radon potential of the region. Regression models were constructed by using dataset for 5 km x 5 km, 4 km x 4 km and 3 km x 3 km grids. Results indicate a general good performance of spatial regression models compared with the classical OLS global regression models. The geographical variability test computed for all the different grids shows a spatial variability in terms of model selection criteria, thus strongly supporting the use of spatial models. The 5 km x 5 km dataset provides the best model.

Whole Belgium: the extension to the whole country allows to take into account in the analysis not only strongly radon-affected areas like Ardennes, but also regions where the indoor radon risk is low, such as the Flemish region. Methods (a) and (c) cannot be applied to the too scarce soil Rn and soil permeability data. Method (c) was applied considering all other quantities available at country level and correlations were determined. Method (b) can be used to evaluate the indoor Rn GM and airborne U at the sampling points of soil Rn / permeability. The correlations observed are still weak, but with the expected pattern: positive correlation between indoor Rn, soil Rn and airborne U, positive also between indoor Rn and soil permeability, but negative correlation between soil permeability and soil Rn or airborne U. Organising data in groups according to geology, lithology or soil class is only possible for simple classifications with few groups, but much better correlations can then be observed. This is a good incentive for deeper studies like PCA and spatial regression models.

5.5 Multivariate analysis of radon concentration relation with building characteristics from first indoor radon survey in Serbia

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The first national indoor radon survey in Serbia was conducted from October 2015 till April 2016. In the cooperation with IAEA, SRPNA and radon working group made the design of the first national indoor radon survey in Serbia. IAEA provided 6000 passive radon detectors, based on nuclear track-etched detectors. The distribution of detectors across the Serbian territory was the responsibility of SRPNA. The questionnaire for participants in radon survey included room in dwelling where detector was placed, and building characteristics such as the year of construction, construction material, type of foundation, existence of thermal and hydro insulation. The statistical analysis of the indoor radon results is presented. Results of correlative and multivariate analysis, using TMVA package, of radon concentration relation with building characteristics is presented. The best multivariate method is identified and the list of variables' significance on multivariate methods are presented and discussed.

5.6 Bayesian variable selection for indoor radon risk mapping: the case of Gran Canaria

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The main contribution of indoor radon comes from soils and thus, to prevent the radon hazard in a determinate region, it is essential to identify those areas that could have the potentially of generating high radon indoor levels. The establishment of risk maps of indoor radon in dwellings for a given area is a very complex task since many variables are involved. Thus, local geology, content of ^{226}Ra in soils, concentration of radon gas in soils, radon exhalation by soils, or the gamma exposure rate may be important variables for the analysis of soil contribution to the levels indoor radon concentration. However, not all of these variables contribute in the same way when explaining the presence of radon in dwelling. Therefore, it is important to make a selection of the most relevant variables when establishing a map of radon risk.

During the last decade, we have developed an extensive study of environmental radioactivity on the island of Gran Canaria, and detailed maps of gamma radiation at one meter from the soil, activity concentration of the main environmental radionuclides (^{226}Ra, ^{232}Th, ^{40}K), radon gas concentration in soils and permeability has been obtained. Recently, an extensive measurement campaign of indoor radon has also been carried out in all the municipalities of the island. Thus a great amount of information is available to test statistical models of variable selection.

This work we present the results of a statistical Bayesian approach to select the most relevant radiological and geogenic variables to explain indoor radon results obtained. Several approaches are tested:

- Bayesian prediction model by multivariable linear regression.
- Bayesian prediction model by multivariable linear regression with complete data.
- Bayesian prediction model by multivariable linear regression with imputation of unavailable data.

As a result, a classification of the variables that influence the concentration of indoor radon in Gran Canaria has been obtained.

Acknowledgments:

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Reference:

M.A. Arnedo, J. G. Rubiano, H. Alonso, A. Tejera, A. G. Guerra, JM Gil, R. Rodríguez, P. Martel, JP Bolivar. (2017). Mapping natural radioactivity of soils in the eastern Canary Islands. Journal of Environmental Radioactivity, 166 (2), pp. 242-258.

5.7 Experimental setup for the measurement of the radon transport from the soil under controlled activation of convection

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Geological media is considered to be the main source of the radon in dwellings. In general, there is common view on the processes of radon transport between geological media and building. However, the reliable quantitative models are made only for some specific conditions, for example, for the case of the diffusion entry. In contrast to diffusion, the convection/advection transport is poorly understood. The pressure difference that causes the advection from the soil appears after the building construction. Usually, the situation "after construction" is not considered in analysis of geogenic radon potential. At the same time, frequently, it is the advection that creates the conditions for elevated indoor radon entry. As a result, the reliability of developed methods of radon potential assessment is insufficient. The aim of our study is to develop experimental method for assessment of radon potential taking to account the main processes of radon migration and evolution of transport conditions after building construction, in particular, the activation of advection transport in the system "geological media-building".

The experimental setup consists of the accumulation chamber (0.2 m^3), radon monitor AlphaGuard, differential manometer, pumps of various capacity and other equipment. Cylindrical tank (accumulation chamber) is set up with open base to the ground. Advection from the soil to the chamber is activated by pump with capacity from 1 to 30 l/min, while the pressure difference between the inside and the outside atmosphere ranges from 0.5 to 50 Pa. To enlarge the volume of soil affected to the depressurization, the surface layer of the turf is removed and narrow one-meter deep well is drilled under the chamber. Radon concentration in the chamber is measured with radon monitor during few hours. Simultaneously, the parameters as follow are measured at the same site: radon surface flux from the soil (diffusion), radon concentration in the soil air, concentration of the Radium-226 in the soil. The series of measurements (accumulation curve) under various pressure differences and in the diffusion mode can be used to estimate the rate of radon entry to the accumulation chamber and to analyze the dependence of entry rate on the generated pressure difference and other parameters.

The dependence of the radon entry rate to the accumulation chamber on the created pressure difference is considered to be important characteristic of the radon potential.

Testing of the experimental setup will be conducted during the summer 2017 in real conditions. The results will be presented as well.

6 Session 6: Indoor radon

6.1 *E pluribus unum*: The European Indoor Radon Map

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More than ten years ago, the Radioactivity Environmental Monitoring (REM) group of the Joint Research Centre (JRC) embarked upon the European Atlas of Natural Radiation project. Developed and maintained by the REM group, this Atlas now features a collection of maps displaying levels of natural radioactivity caused by different sources. This is in line with the mission, based on the Euratom Treaty: on behalf of the European Commission, to collect, validate and report information on radioactivity levels in the environment of the EU Member States.

Since indoor radon is the most important contributor to population dose and thus a number of European countries had already carried out surveys years ago, the JRC started by creating a European Indoor Radon Map, inviting countries to participate on a voluntary basis. These countries send their statistics (mean, median, min, max and number of measurements), based on long-term (ideally annually means) of indoor radon concentration on ground floor of dwellings, to the JRC. These estimates have been calculated on a 10 km x 10 km common grid across Europe, which is defined and maintained by the JRC. As the original measurements remain with the national authorities, data privacy is respected. Since the first data were submitted ten years ago, by now (August 2017) the map has grown to cover a fair part of Europe, including 32 countries, spanning nearly 28,000 non-empty grid cells, which in turn are based on more than 1,150,000 individual measurements.

The current version of the map is available in digital format through the web portal for the European Atlas of Natural Radiation (https://remon.jrc.ec.europa.eu/), in which all the maps are collected and displayed with related information.

Still, there are several countries for which data exist but have not been made available to the public or the JRC, or are stored in a format which does not allow easy integration into the European grid. At the workshop in Verbania two years ago, invited experts from mainly Eastern European countries agreed to participate, or continue to participate, to this mapping effort. This has resulted in extended coverage.

It should be noted that the European Indoor Radon Map will never be complete for a number of reasons. In light of the new European Basic Safety Standards Directive, Art. 103, this motivates developing a European Geogenic Radon Map whose objective is to estimate the geogenic radon hazard. Given the data situation, the most viable method appears to be a multivariate index or classification approach which takes advantage of whatever data are regionally available.

In a further perspective, the objective is to estimate the annual dose that the public may receive from natural radioactivity, by combining all the information from the different maps.

In this talk, we will describe the evolution and current state of the European Indoor Radon Map, review some outstanding issues and cast plans for further development. Work will continue on this map, just like for the other components of the European Atlas of Natural Radiation.

6.2 National indoor radon survey in Bulgaria

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The National survey on average radon concentration in Bulgarian dwellings was carried out from 2015 to 2016, under the National Radon Program. The survey was population based. The sample points were divided into 100 detectors per districts. A two-stage stratified sampling scheme was used. The first stage included stratification of districts to 264 municipalities than which municipalities subdivided into towns and villages. The number of detectors in each strata was determined, proportionally to the population density. The survey was promoted and coordinated by National Centre of Radiobiology and Radiation Protection (NCRRP) and carried out in collaboration with Regional Health Inspectorates. The dwellings were randomly selected by the choice of adopting a door-to-door approach for contacting families and distributing detectors. Survey participants received detectors together with instruction and questionnaires for dwelling characteristics. Measurement period was one year into two phases. The first phase started from April 2015 and finished in December 2015. The second phase continued from January 2016 to March 2016. Detectors were deployed on the ground floor and during the year were changed with detectors of seconds phase to allowed assessing the average indoor radon concentration. The measurements were made under the occupants' normal living conditions. The measurements were performed with passive track detectors (CR-39). Each detector contains two chips for providing the linearity of calibration. The annual radon concentration for each dwelling was calculated as weighted average of the results from two phase's measurements. The measurements were completed in 2776 dwellings. The mean radon concentration is 111 Bq/m^3 with a maximum value of 1314 Bq/m^3. The radon concentrations follow a log-normal distribution, with significant level 0.1 of Kolmogorov-Smirnov test. The geometric average is 81 Bq/m^3 with geometric standard deviation 2.15. The statistical difference between districts was found (Kruskal-Wallis test $p<0.0001$). The National Survey was not designed to find radon-prone areas, however some previously unknown area with high radon concentration have been identified. The National Survey allows presenting a systematized distribution of indoor radon concentrations on the territory of the country, which is representative for the exposure of the Bulgarian population to radon in homes. The results of the National Survey confirm the need to continue the joint efforts of national institutions to reduce the general risk to the population as well as the individual risk for each individual.

6.3 From motivation through the national radon survey to European indoor radon map

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By 2014, radon issues were treated in Serbia through the scientific research projects. Among radon professionals, there was always the desire to create a radon risk map first of all. In 2014, with a certain amount of lucky circumstances, there was a chance that the radon problem would be raised to the national level. In that sense, Serbia has started to work on the national radon action plan (RAP), and in 2014 made its decision to perform the first national indoor radon survey. The responsibility for the establishment RAP and make indoor radon map in Serbia is on national regulatory body in the field of radiation protection: Serbian Radiation Protection and Nuclear Safety Agency (SRPNA). The project was supported by the IAEA through the technical cooperation programme. In this work, the planning and execution of the survey, including sampling design of the first national indoor radon survey are described in detail. Also, the results from national indoor radon survey and indoor radon mapping based on GPS coordinates was transformed to square map by creating a 10 km x 10 km squares where the starting point (0,0) is the center of Belgrade - Slavia Square are presented. To complete our work, we prepare data from the first Serbian indoor radon survey together with the data from indoor radon survey of Vojvodina, north province of Republic of Serbia performed during 2002-2005, and send to European Indoor Radon Map Group in JRC, Ispra, Italy.

6.4 A detailed indoor radon mapping of surrounding of Niška Banja, high radon area in Serbia

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The municipality of Niška Banja consists of the settlement with the same name and 11 more settlements. Niška Banja settlement is a radon spa in Serbia and it is well known for its high radon concentration. It has been thoroughly investigated by various complementary techniques applied to measure indoor radon and thoron concentrations, radon in soil gas and water, radon exhalation rate from soil, as well as radionuclide content in soil and gamma dose rates. Some of very remarkable results were obtained in the "hot zones" of Niška Banja in which are soil-gas radon concentration measured to be more than 2 MBq m^{-3}, radon exhalation rate from the soil of the order of 1.5 mBq m^{-2} s^{-1}, with indoor radon concentration of more than 10,000 Bq m^{-3} in winter season. While indoor radon concentrations in the settlement of Niška Banja were investigated in details, there is no information of radon concentration among the rest of 11 settlements. In order to be able to perform radon risk assessment and estimate the influence of the indoor radon concentration to the incidence of lung cancer from radon in Niška Banja municipality, a measurement of indoor radon concentration in these settlements were performed.

6.5 Nationwide indoor radon survey in Montenegro

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Montenegro has land area of 13,812 km^2, population of 620,029, and 247,000 permanently inhabited dwellings, with approximately 50% of them on ground floor (Census 2011).

Preparation of the first nationwide systematic indoor radon survey commenced in 2000. A combination of geographically based and population-weighted survey was chosen as the most appropriate for the survey goals. The first type of survey is based on a national grid of 5 km × 5 km mesh, with 552 squares in it, and the second type on the national grid and local grids. The local grids cover main towns and have 0.5 km × 0.5 km squares. Using door-to-door approach, in each of the squares from both grids one dwelling on the ground floor or the first floor was selected for radon survey. Radon measurements, with CR-39 nuclear track detectors during two consecutive six-month periods, were performed in 2002–2003 in a half of the Montenegrin territory. Planed measurements in the rest of the country were not possible in that time due to a lack of financial means. Following the same methodology, radon measurements continued in 2014–2015, and radon survey in the whole country, in 953 dwellings selected within national and local grids, has been completed in 2016.

Based on these 953 dwellings, the national average radon activity concentration in indoor air of homes in Montenegro is calculated to be 110 Bq/m^3 and median 52 Bq/m^3. The average indoor radon concentration in rural areas (144 Bq/m^3) is much higher than in urban areas (86 Bq/m^3). Also, the average radon activity concentration in single-family detached houses (119 Bq/m^3) is more than twice higher than in apartment buildings (51 Bq/m^3).

From the experimental results for radon concentrations, a transformed lognormal distribution of the data was created, based on which percentage of dwellings in Montenegro where radon concentration above a given level could be expected is estimated (e.g. 7.4% above 300 Bq/m^3).

In order to increase the number of sampled dwellings in some municipalities and due to some specific research goals, radon was also measured in additional 142 dwellings, so the total number of dwellings with known radon concentration was 1095. Based on these 1095 dwellings, the average indoor radon concentrations in all 23 municipalities in Montenegro are calculated, as well as ones in all 131 squares of the 10 km × 10 km national grid. In the municipalities they range from 40 Bq/m^3 to 201 Bq/m^3, and in the grid squares from 30 Bq/m^3 to 732 Bq/m^3.

Finally, three radon maps of Montenegro have been produced: 1. Map of average radon activity concentrations in the cells of 10 km x 10 km grid, 2. Map of average radon activity concentrations in the municipalities, and 3. Map of the expected percentage of homes, in the municipalities, with average annual radon activity concentrations above 300 Bq/m^3.

6.6 Indoor radon mapping in Bosnia & Herzegovina: Existing situation and future plans

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6.7 Development of the first Luxembourgian Indoor Radon Map

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On 16 June 2017, Luxembourg became the 32nd country to be represented on the European Indoor Radon Map by finishing the Luxembourgian Indoor Radon Map. For making this map, we used data from the Ardennes-Eifel project, studies from 2000 to 2015, the Wahl pilot project and the new campaign for passive dwellings. For each study, two nuclear solid-track detectors were sent to each private dwellings, but we only considered the one on ground floor level for making this map (n=3739). We referred each detector by longitude/latitude coordinates given in decimal degrees and we converted them into GISCO-Lambert format (x,y) in metres. No seasonal correction factors were applied. Once this conversion had been made we used Rstudio to calculate the statistics we needed for the map (AM, SD, aml, sdl, med, min, max, n). After all this processing, we used ArcGIS mapping software to attribute each statistic to the respective 10 km x 10 km grid cell, in cooperation with the JRC. Finally, two maps were created, the first one with arithmetic means over 10 km x 10 km grid cells of long-term radon concentration, and the second one with the number of measurements per grid cell, with an average density of nearly 100 points per 10 km x 10 km grid cell.

For the survey, 3739 nuclear solid-track detectors were considered in dwellings (corresponding to <1% of Luxembourg's population). The indoor Radon concentration was: Min 1 Bq/m^3, Max 2838 Bq/m^3, first quartile 47.0 Bq/m^3, median 77.0 Bq/m^3, arithmetic mean 140.8 Bq/m^3 and third quartile 142 Bq/m^3. Two spatial variations have emerged: the north, which is a radon prone area, and the south, which has lower radon concentration. The rocks from the north's underlying geology came from the Paleozoic era; so the rock is more cracked and allows more exhalation of Radon. The south's rocks are from the Mesozoic, whose rock is younger than the Paleozoic, so it's less cracked and allows less vertical exhalation of radon.

The Joint Research Centre of the European Commission updated the European Indoor Radon Map with our data in August 2017. The results will be presented at the Second International Workshop on the European Atlas of Natural Radiation (IWEANR 2017) in November.

6.8 Current status of the Romanian indoor radon survey linked with SMART_RAD_EN European project

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Radon is one of the most surveyed indoor pollutants, which is causing lung cancer. According to the new BSS standards, the Romanian National Programme coordinated by National Commission for Nuclear Activities Control (CNCAN) was initiated in 2017, in order to complete the indoor radon map and to establish a national radon strategy.

The main purpose of the study is to present the current results of the annual average indoor radon concentration in Romania, based on approximately 7000 radon measurements, as an update to the preliminary Romanian Indoor Radon Map, previously reported by our studies (Cosma et al., 2013; Tollefsen et al., 2014; Cucoş et al., 2017). Indoor radon measurements were performed by using nuclear track detectors CR-39 exposed for 3-6 months on ground floor levels of dwellings, according to the NRPB Measurements Protocol.

The first systematic data for indoor radon measurements in Romania were obtained since 2013, in the frame on an ongoing research project (RAMARO), implemented by Babes-Bolyai University. Comprehensive surveys of radon in homes, soil and water for roughly 43% of the Romanian territory have been begun with the aim to create a radon database. The measurements were completed in 1,000 dwellings within SMART_RAD_EN European Project. At present, an extensive campaign by passive monitoring of indoor radon concentration is being carried out in 1,000 energy efficient houses in order to obtain a detailed picture of indoor air quality in five urban agglomerations in Romania (Bucharest, Cluj-Napoca, Iaşi, Sibiu and Timişoara). Along with the distribution of the radon detectors, a detailed questionnaire that collects qualitative aspects related to the quality of the interior air was completed by the house's occupants. The qualitative evaluation of the indoor air quality, the variability of the measured data between all the surveyed regions, as well as the relationship between radon-related quantities was investigated and presented.

The preliminary results reveal that in about 17% of the investigated houses the radon concentration exceed the recommended level of 300 Bq m^{-3}, suggested by the European Commission under the Council Directive 2013/59/Euratom.

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References:

Cosma C., Cucoş (Dinu) A., Dicu T. (2013). Preliminary results regarding the first map of residential radon in some regions in Romania, Radiation Protection Dosimetry, 155(3), pp. 343-350.

Tollefsen T., Cinelli G., Bossew P., Gruber V., De Cort M. (2014). From the European Indoor Radon Map towards an Atlas of Natural Radiation, Radiation Protection Dosimetry, 162 (1–2), pp. 129–134.

Cucos (Dinu), A., Papp, B., Dicu, T., Moldovan, M., Burghele, B.D., Moraru, I., Tenter, A., Cosma, C. (2017). Residential, soil and water radon surveys in north-western part of Romania, Journal of Environmental Radioactivity, Vol. 166/2, pp. 412-416.

6.9 Comparison of indoor radon levels in public building (schools) with radon distribution in dwellings located in Cluj-Napoca area (Romania)

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The radon requirements in the new Euratom Basic Safety Standards Directive include the establishment of a national reference level for indoor radon concentration in workplaces and public buildings ≤ 300 Bq/m^3. Although research on indoor radon concentrations in dwellings is actively conducted in Romania, systematic surveys in public buildings is still lacking.

This present study aims to determine the distribution of indoor radon in schools and kindergartens from Cluj-Napoca, in comparison with the radon concentration levels in dwellings from the same region, and to analyse the main factors affecting indoor radon levels.

Indoor radon measurements were performed by using CR-39 passive detectors (RSKS type; RadoSys Hungary), in agreement with validated procedures proposed by HPA Radiation Protection Division. Adequate quality and control system, along with good laboratory practices were ensured by performing international intercomparison exercises and periodically applying practical calibration tests. Together with the detectors a detailed standardized questionnaire was completed in each surveyed building in order to collect relevant information about factors relating to measurement site as characterization of house, building materials, occupancy hours, indoor air quality etc.

A comprehensive radon survey has been carried out in 2015 in 62 schools and kindergartens located in Cluj-Napoca area. The results in these high occupancy public buildings were compared with the indoor radon levels obtained for 256 dwellings in the frame of SMART_RAD_EN project.

The percentage of schools as well as houses showing radon activity concentrations exceeding the recommended level of 300 Bq/m^3 was 11%.

The preliminary results clearly show the need to implement mitigation actions in all affected public buildings in the frame of the national radon program. In workplaces where radon concentrations continue to exceed the national reference level all actions must be taken to optimize the exposure.

Acknowledgement: The research is supported by the project ID P_37_229, Contract No. 22/01.09.2016, with the title "Smart Systems for Public Safety through Control and Mitigation of Residential Radon linked with Energy Efficiency Optimization of Buildings in Romanian Major Urban Agglomerations SMART-RAD-EN" of the POC Program.

6.10 Indoor radon and gamma dose rate in Hungarian kindergartens, a pilot survey

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Following the EU-BSS (2013/59/EURATOM directive) national radon action plan has to be established and dose to the population caused by radon inhalation has to be controlled and regulate in each EU member states. Long term and representative radon survey is required to support a comprehensive legislation. Several member states already carried out surveys but in the main part of the states the action plan is in planning phase yet.

In this study kindergartens were chosen as an object of a pilot survey preparing the radon action plan. Three different regions with different geological background were selected and 99 kindergartens were involved by volunteering of them. Indoor radon concentration was measured in every kindergarten in every season for one year by discriminative SSNTD (Solid State Nuclear Track Detector). The detectors were placed on ground floor in three rooms of each kindergarten near to the wall (maximum distance 15 cm). Gamma dose rate was measured by passive TL (thermo-luminesces) detectors for 6-9 months at the same place. Head of the kindergartens were interviewed and questionnaires were filled with relevant information about the building characteristics e.g. usage and ventilation habit, building materials. The results of the questionnaire and gamma measurement help us to get information about the source of the detected radon.

The annual average radon concentration was below 300 Bq/m^3 in each kindergarten correspond to the reference level in Hungary. Clear differences of radon concentrations revealed in case of different building characteristics, e.g. building material. Gamma dose rates were below the World average.

Based on our results, the data management protocol and harmonized measurement system of this pilot study is an excellent base for development of the Hungarian radon action plan.

6.11 Development of indoor radon map in Lithuania

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Radiation Protection Centre (RPC) is responsible at national level for control of general population exposure caused by indoor radon in Lithuania. RPC performs measurements of indoor radon, administrates radon measurements database, creates indoor radon map.

Radon measurement in Lithuania has been started in 1995 year. During 1995-1998 year, indoor radon was measured in 400 randomly selected houses. The arithmetical mean of the indoor radon concentrations in tested houses was 55±5 Bq/m^3. The higher radon concentration was detected in Northern Lithuania, geological karst region. More than 500 detailed measurements were performed in that region. During 1995-2007 year period about 2500 dwellings was measured in Lithuania. In 2007 year all these data were placed on European radon map with a grid of 10 km x 10 km, also it was the first Lithuanian radon map.

In order to fill not measured 10 x 10 grid cells RPC performed additional radon surveys in country. During period of 2008-2017 year around 500 dwellings was measured. All these radon measurement data were placed on 2017 European radon map.

Using ArcView software in 2017, a new radon map of Lithuania was prepared. This new radon map now can be split into the different administration levels. Using this map new radon survey is prepared for the period of 2017 – 2022 year. The purpose of the survey:

1. Finish Lithuanian radon map using 10 m x 10 km grid.

2. Using radon map with smallest administration unit, perform more detailed radon measurements in the territories with higher radon concentrations.

6.12 Indoor radon monitoring in Belarus and creating of specialised database for storage of measurement results and mapping

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One of the directions of radiation monitoring is the observation of the natural radiation background. More than 40% of the territory of Belarus belongs to the radon priority areas. Inhalation of daughter products of radon and radon rich water using may cause additional individual dose load along with doses from Chernobyl radioactive contamination. Radon contribution is accounted for up to 50%.

Considering the extensive negative consequences of the Chernobyl catastrophe, the need for measures to reduce the components of additional radiation is obvious. For the population living on the radioactively contaminated territory, the lowering of doses from other sources of ionizing radiation, including radon, in a number of cases can prove to be much more efficient and economical compared to decreasing doses from technogenic radioactive contamination.

Indoor radon monitoring has been conducted since 2004 by the Laboratory of Nuclear Physics Research and Expert Analysis of Radioactive Materials of the Joint Institute For Power and Nuclear Research – "Sosny" of NAS of Belarus using SSNTD method with nitrocellulose film LR-115 type II as the detector. Indoor radon monitoring before 2010 was conducted on potentially radon-prone areas, determined from analysis of tectonic faults distribution and deposition depth of radon generating granitoid of the crystalic foundation. Since 2010 buildings for the survey were selected randomly.

Research statistics of radon monitoring in Belarus on 2016 is presented. Number of observed premises is 4880 that is 513 observed premises per million people.

The max indoor VA_{Rn} values fixed in premises in different regions of Belarus is 1415 $Bq{\cdot}m^{-3}$, mean value is 85 $Bq{\cdot}m^{-3}$. Doses from radon are estimated using Dose conversion factor taken equal $9{\cdot}10^{-6}$ $mSv/Bq{\cdot}h^{-1}{\cdot}m^{-3}$ or 0.063 $mSv{\cdot}year^{-1}/Bq{\cdot}m^{-3}$, which is also consistent with the recommendations of UNSCEAR.

At present, the Belarus-Serbia joint project "Preparation of radon maps and dose assessment in Belarus and Serbia" is being implemented by the JIPNR-Sosny, Hydromet, Belarus and the Institute of Physics, Serbia.

In the framework of the project, work is being done to measure indoor radon in the settlements of Belarus and to create a cartographic database for subsequent mapping and dose assessment.

In order to ensure the uniform distribution of radon-222 values on the territory of the countries, as well as to increase the representativeness of the data displayed on the map, the option of constructing radon hazard maps using a 10-by-10-kilometer grid as elementary sites was proposed. Evaluation of potential radon risk in the territory of Belarus was estimated using geological information also.

The measurement results are entered in a specially created database. Information content of the database consists of two blocks: Description and Measurements.

Indoor radon data acquisition is continuing. The results of the project will allow expanding and supplementing the European atlas of natural radioactivity developed by the Joint Research Center under the European Commission in order to create a complete picture of the geographical distribution of natural radioactivity in Europe and to inform the public about the risks associated with natural radioactivity.

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