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Radionuclides and heavy metals bioavailability in a Norwegian area rich in naturally occurring radioactive materials

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Abstract

Recent study on environmental samples from thorium rich Norwegian area showed high gamma dose rate and significant transport of radionuclides into environmental compartments giving multiple stressors action in natural conditions.

The main objective of this work was to investigate distribution and uptake of ^{232}Th, ^{238}U and heavy metals such as Cd, Cu, Zn and Pb from soil and rocks into biota samples in natural conditions.

Soil samples, plant samples of the most abundant species in area and earthworms were sampled on high gamma dose rate location in Fen (Norway). Radionuclides and heavy metals were analyzed by ICP-MS.

Soil analysis showed high level of radionuclides, 4040 and 111 Bq/kg, for ^{232}Th and ^{238}U, respectively. Pb and Zn were in moderate high levels, but comparable with other Norwegian soils, Cd and Cu were in range of non contaminated natural soil. Among the plants collected, the highest uptake of both ^{232}Th and ^{238}U was found in moss. Distribution of these radionuclides was positively correlated with levels found in soil taken below. Different earthworms species showed high levels of ^{232}Th, ^{238}U, Cd and Pb what could suggest bioconcentration from soil – worms' habitat and food. It was shown that these Fen invertebrates had significantly higher levels of several contaminants in comparison to those from chosen reference site in the vicinity.

These preliminary obtained results will form the basis for future work in aspect of:

- determination of sensitive plant, fish, earthworm and mice species,
- determination of transfer factors and possible bioconcentration,
- investigation of different plant parts ability to concentrate naturally occurring radionuclides and study on dependence between uptake and change of natural conditions,
- investigation of target organs for radionuclides and metals deposition and possible biological effects,

which will be presented in the conference.

Introduction

Data on the activity concentration of naturally occurring radionuclides in the environmental media (i.e., soil, water, sediment) and organisms of interests are of high importance when assessing radiation impact on non-human organisms. Parameters obtained in investigation of terrestrial and aquatic biota uptake of radionuclides in natural conditions are highly relevant when it comes to estimate consequences of nuclear pollution or accidents problems. However, the knowledge gap and lack of data considering many organisms must be considered (Jones et al., 2003; Beresford et al., 2008). Additionally, biota is rarely exposed to only radiation, but also very often to some heavy metals. Thus, it is significant to predict the most probable exposure scenario and to investigate both levels of radionuclides and heavy metals in living organisms, as well as to investigate possible diverse i.e., additive, synergistic or antagonistic biological effects (Salbu et al., 2005).

Fen central Complex in southern Norway is geologically specific area of magmatic, carbonatite rocks rich in naturally occurring radioactive materials (NORM), in first place thorium (Th) and uranium (U), but also in iron (Fe) and rare earth elements (REE). This part of the country is well known with its high exposure radiation doses to humans, mainly due to high levels of radon (Sundal and Strand, 2004). Several mining sites were exploited in this area for Fe, niobium (Nb) and scandium (Sc) during the past centuries. All mining activities were finished in 1960s, but technologically enhanced naturally occurring radioactive materials (TENORM) sites are still important sources of environmental pollution. Beside NORM sites, the TENORM sites also contribute to the high exposure dose to the Fen human population (Sundal and Strand, 2004; Mrdakovic Popic et al., 2010, in preparation).

The main objective of this study was to investigate the correlation of high soil concentrations of naturally occurring radionuclides ^{232}Th and ^{238}U and some heavy metals such as Pb, Cd, Zn and Cu and their uptake in the living organism in the NORM rich area. According to that, transfer factors were calculated using organisms concentration and soil concentration. Assessment of environmental impact considering radionuclides is done on the basis of obtained activity concentrations of radionuclides using the ERICA assessment tool (Brown et al., 2008). Further activities will be to investigate possible biological effects on organisms that were shown to be the most sensitive and under risk.

Material and methods

Fen Central Complex is a specific geological area positioned 120 km southeast of Oslo. It is an area rich in volcanic carbonatite rocks: Søvite, Rødberg, Rauhaugit and Fenite (Fig.1). Some of these rocks were first described by Brøgger (1921) and named worldwide after these geographical names. This part of Norway is known with its high thorium ore deposits (USGS, 2007, Thorium report, 2008) and high radon levels and consequently high annual radiation exposure doses (Stranden E., 1986; Solli et al., 1986; Sundal and Strand, 2004; Smerthust et al., 2006).

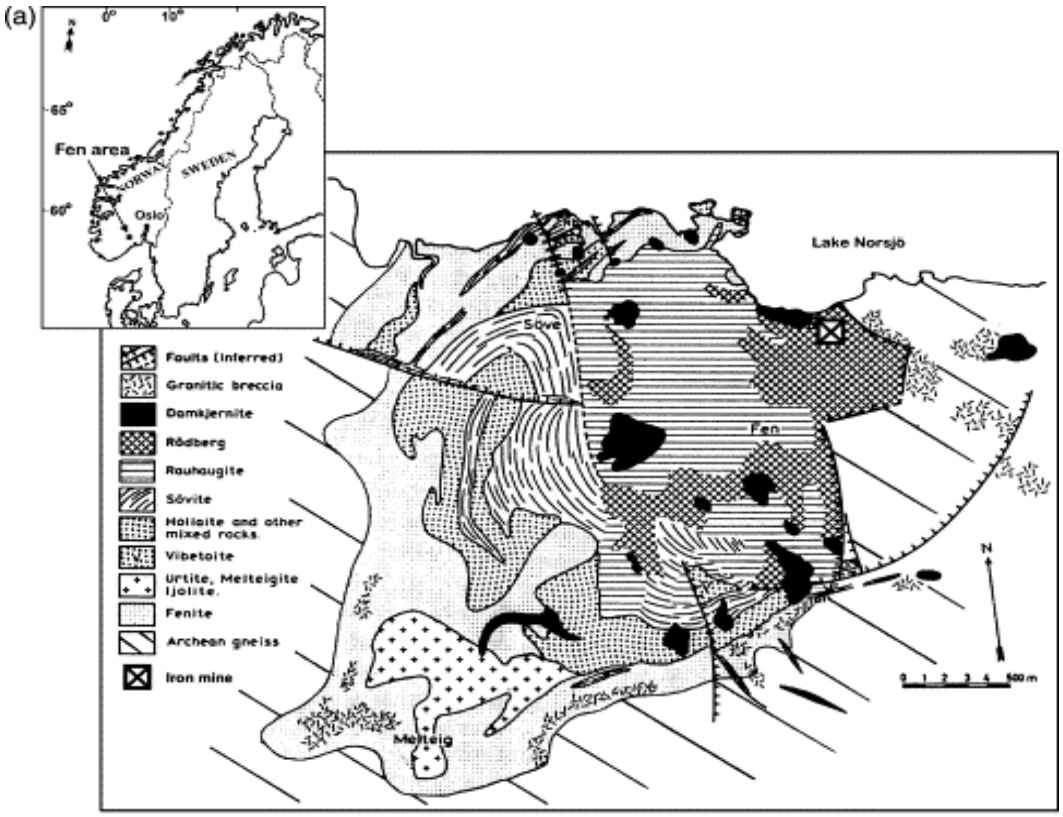

Fig. 1. Bedrock geology of Fen Central Complex (Ramberg and Barth, 1966).

Collection of soil, plants and earthworms were done during the fieldwork at spring 2008, in Fen, Telemark, Norway. Sampling location was chosen according to increased terrestrial gamma exposure dose rate, measured by hand detector type Automess AD4LF, type 6150. Soil samples were collected from depth 0-20 cm as bulk samples. Earthworms (40 adult organisms) were collected from several points at chosen location by hand sorting, and after identifying in the laboratory they were washed and starved for 2 days until their gut contents were completely egested. Earthworms were then frozen in liquid nitrogen, freeze dried and ground to a fine powder. Plants, that were found to be the most abundant in the area i.e., lichen, moss, birch, pine and spruce were collected in paper bags, at least 10 different plants from each species. All plants were, further in the laboratory, cleaned from visible soil, washed several times with distilled water and dry for several weeks at temperature 40°C. They were homogenized by milling. Soil samples were air dried for several weeks, crushed to a fine powder and finally homogenized by sieving through 2 mm sieve. Aliquots of soil were dried at 80°C to constant mass and analyzed for pH, water and organic matter content prior to decomposition for analysis.

Concentrations of radionuclides ^{232}Th, ^{238}U and heavy metals in all samples were measured with ICP-MS after extracting with microwave decomposition (Milestone Inc., Ultraclave High performance reactor, Shelton, CT), employing high-grade purity HNO_3 acid for soil and HNO_3/H_2O_2 for plant and earthworms samples. ICP-MS analysis was done using a Perkin ElmerSciex Elan 6000 (Norwalk CT, USA). Quality control

assurance was performed by substantial use of internal standard, method and instrument blanks and by using proper certified reference materials.

Results and discussion

Results of soil analysis (Table 1) showed high concentrations of ^{232}Th and considerably lower concentrations of ^{238}U, 4040 and 111 Bq/kg, respectively. These values clearly exceed the world average values for soil 30 Bq/kg for ^{232}Th and 35 Bq/kg for ^{238}U given by UNSCEAR (2000). Average value for Pb was approximately 2-3 times higher than non-polluted soil values given by Norwegian Pollution Control Agency, SFT (2009), and values given by Arctic Monitoring and Assessment Programme, AMAP (1998). Local contamination of terrain by physical and chemical weathering of bedrock and rock-forming minerals is the most probable cause of obtained high concentrations. Concentrations of Cd and Cu found in Fen soil samples were in range for non-polluted soil and similar to results obtained for soil from other Norwegain parts (Salbu and Steinnes, 1995; Steinnes and Ruhling, 2002). Zn in our study was present in soil at 2.5 times higher concentrations that given by SFT (2009). These high levels in Fen area are, probably as in the case of Pb, results of local loading of Zn due to weathering of bedrocks and leaching upon different environmental conditions.

Table 1. Thorium and uranium concentrations in soil samples from Fen.

Sample	^{232}Th (mg/kg)	^{238}U (mg/kg)	^{232}Th (Bq/kg)	^{238}U (Bq/kg)
Fen site	995±284	9±3	4040±1153	111±37
UNSCEAR (2000)	-	-	30	35

Table 2. Heavy metals concentrations in soil samples from Fen.

Sample	Pb (mg/kg)	Cd (mg/kg)	Cu (mg/kg)	Zn (mg/kg)
Fen site	126±78	0.5±0.1	8.5±10.5	508±151
SFT (2009)	60	1.5	100	200

To obtain a kind of initial screening and an overall picture about radionuclides and heavy metals bioavailability for living organisms uptake, the typical and the most abundant species in the area were chosen for analysis. In addition to the five plant species we analyzed two different species of earthworms that have habitat in the inner layers of soil. Results obtained in Fen plants and earthworms analysis are given in Tables 3 and 4.

Among the plants, the highest uptake of radionuclides was noticed in moss, 90 and 6.4 Bq/kg for ^{232}Th and ^{238}U, respectively. Obtained values for ^{232}Th and ^{238}U in plant samples were higher than reference values for leafy plants given by UNSCEAR (2000), 0.016 Bq/kg and 0.062 Bq/kg for ^{232}Th and ^{238}U respectively,. Lower but comparable results for moss and grass samples were obtained in similar investigations of Ramli et al. (2005) and Vandenhove at al. (2006). Metals Pb and Cd were also in the

highest concentrations in moss. Essential metals like Cu and Zn were in the highest concentration in birch leaves.

Radionulides concentrations of two different endogeic species of earthworms were significantly high, 316 ad 178 Bq/kg, for *Aporectodea caliginosa* and *Dendrodrilus rubidus*, respectively. These two species, living in the soil, were chosen with expectance that both the internal and external exposure to a cocktail of radionuclides and heavy metals could affect them.

Table 3. Radionuclides and heavy metals concentrations in plant samples from Fen.

Sample	^{232}Th (Bq/kg)	^{238}U (Bq/kg)	Pb (mg/kg)	Cd (mg/kg)	Cu (mg/kg)	Zn (mg/kg)
Pine	0.8	0.2	0.32	0.06	4.4	70
Spruce	0.2	0.04	0.06	0.05	6.1	67
Birch	2.2	0.2	0.27	0.15	8.3	95
Moss	90	6.4	10.2	0.21	4.1	63
Lichen	20	2.6	3.5	0.08	2.2	29

Table 4. Radionuclides and heavy metals concentrations in earthworms from Fen.

Earthworms	^{232}Th (Bq/kg)	^{238}U (Bq/kg)	Pb (mg/kg)	Cd (mg/kg)	Cu (mg/kg)	Zn (mg/kg)
A.caliginosa	316	15	19	4	7	-
D.rubidus	178	5	9	6	6	-

In order to obtain the information on uptake in biota, radionuclide transfer factors (TF) were calculated. TF were calculated as a ratio between radionuclide concentration in organism and radionuclide concentration in soil (Table 5).

Table 5. Transfer factors for ^{232}Th and ^{238}U in Fen plant and earthworms samples.

Sample	TF ^{232}Th	TF ^{238}U
Pine	2E-04	2E-03
Spruce	5E-05	4E-04
Birch	5E-04	2E-03
Moss	3E-02	6E-02
Lichen	5E-03	2E-02
Earthworms	6E-02	9E-02

Average values for plants transfer factors in this study are one order of magnitude lower or comparable with values in ranges published by IUR (1994) and ERICA (2008), for ^{232}Th: 0.001-0.11 and for ^{238}U: 0.002-0.23. The highest transfer factors for

^{232}Th and ^{238}U were obtained for moss and earthworms. Uptake of ^{238}U in the earthworms was higher than the average values given by ERICA data base (2008).

The total exposure rates and risk presented in Fig.2 were obtained by ERICA assessment tool (Brown et al., 2008) on the basis of media concentrations of selected radionuclides. It is also confirmed that bryophytes and earthworms are the most sensitive and potentially vulnerable organisms in this area.

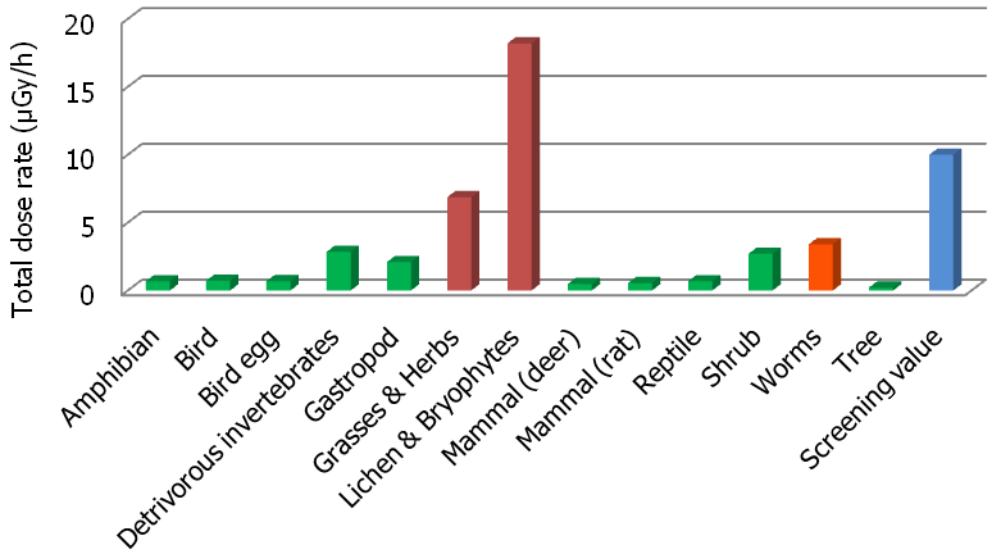

Fig. 2. Total exposure dose per terrestrial organism groups, calculated on the basis of internal exposure.

Conclusions

The main objective of this study was to investigate the correlation of high soil concentrations of naturally occurring radionuclides ^{232}Th and ^{238}U and some heavy metals such as Pb, Cd, Zn and Cu and their uptake in living organism in the area. Data on the activity concentration of naturally occurring radioactive materials in the environmental media (i.e., soil, water, sediment) and organisms of interests are of high importance when assessing radiation impact on non-human biota. Results from this study show some organisms groups that are under high risk and provide information on groups that should be more investigated in terms of early biological responses.

Analysis of Fen soil samples showed high concentrations of both ^{232}Th and ^{238}U, significantly higher than reference values given by UNSCEAR (2000). The found radionuclides concentrations in the soil suggested very inhomogeneous distribution and various influence on living organisms.

When it comes to assessing the radiation risk for terrestrial non-human species the knowledge gap and lack of data must be considered (Jones et al., 2003; Beresford et al., 2008). In our study the selected plant and earthworm species, representative samples from the Fen area, were analyzed for radionuclides and transfer factors were calculated. Levels of both ^{232}Th and ^{238}U in moss and lichen samples were higher than those found in similar plant species (Ramli et al.,2005; Vandenhove at al.,2006). However, no much

data for comparison purposes is available on the species grown in natural conditions and on especially species that are not important when it comes to human consumption. Still, despite the fact that high levels of radionuclides were found in some plants, obtained transfer factors were approximately one order of magnitude lower that those published by IUR (1994) and ERICA (2008). Opposite, the concentrations and transfer factors obtained for earthworms are higher than those published by ERICA (2008) and suggest active biological uptake of these organisms. Considering only radionuclides, the organism groups that are under the highest risk in this area, are bryophytes and earthworms.

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Radionuclides and heavy metals levels in environmental samples from thorium rich Fen area in Norway

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Abstract

Fen area in southern Norway is documented to be among the highest natural world reservoirs of thorium ore. It is geologically well investigated area with ^{232}Th rich carbonatite rocks. Dose risk assessment and radon investigations, done in the past, showed total indoor effective dose up to 14 mSv/year. However, there are still huge knowledge gaps when considering environmental impact from the natural occurring radioactive material. This paper is a result of the first investigation phase on a multiple stressors study which comprises identification of contaminants, distribution in natural compartments, biota uptake and total environmental impact assessment.

Gamma dose rate measurements gave an average dose rate of 4.2 μGy/h, much higher than world's average dose rate of 0.059 μGy/h. Rock levels of radionuclides were consistent with previous findings and positively correlated with recorded gamma dose rates in the area. Total soil analysis showed concentrations in the range 69-6098 Bq/kg for ^{232}Th and 49-128 Bq/kg for ^{238}U. Concentrations of Cd in soil were higher than world average, but in range of Norwegian soil values. However, concentrations for Pb ranged from 47 to 287 ppm and for As from 4 to 20 ppm, probably due to mobilization and weathering from rocks. Despite high soil levels, total and size fractionated water samples showed neither radionuclides nor heavy metals contamination. Size fractionation showed that^{238}U was more soluble and in the low molecular mass fraction, while ^{232}Th was in colloidal and particulate phase, confirming typical behavior in nature.

Considering both radionuclides and heavy metals found in rock and soil from this area, future work will focus on investigation of mobilization conditions, transfer to biota, biological effects and possible synergistic action of different radionuclides and heavy metals.

Introduction

Increasing world's energy demands and limited sources, as well as pollution problems, put the nuclear energy production recently in focus in many different countries worldwide. Considering thorium resources, the Fen area (county of Telemark, southern Norway) is assumed to be among the world's largest with estimated total of 170 000 tones (USGS, 2007).

Related to these high levels of naturally occurring radioactive material (NORM) and technologically enhanced naturally occurring radioactive material (TENORM), the Fen area is well known as area with high mean value of the annual total effective radiation dose to the population. Doses up till 4 times higher than the estimated average effective radiation dose to the Norwegian people are found (Stranden E., 1986; Stranden and Strand, 1986; Sundal and Strand 2004).

Previously, investigations in Fen complex showed unique geology formation with enhanced content of ^{232}Th, ^{238}U and rare earth elements (Brøgger 1921; Landreth 1979; Dahlgren S., 1983, Stranden E, 1982.) and increased gamma radiation dose rates (Sundal and Strand, 2004; Smerthust et al., 2006). Since the main contributor to the total effective radiation dose from naturally occurring radionuclides is exposure to radon, many studies have investigated the indoor radon concentrations in Fen area dwellings, relationship of indoor and outdoor radiation doses and their dependence on geology formation of terrain (Stranden E., 1982; Solli et al., 1986, Sundal and Strand, 2004; Smerthurst et al., 2006).

Typical Fen complex rock types, first described by Brøggger 1921., occupying the largest fraction of the surface, are carbonatite rocks of magmatic origin. Intensive mining activities in the area for iron and niobium production were performed from 17th to 20th century. The radiological and epidemiological impact of these former mining activities, evaluated by Stranden E., 1982, showed that workers received an annual dose equivalent of 150 mSv, obviously much higher than occupational dose limits of 20 mSv/y for radiation workers.

Similar investigations of radioactivity in high background natural radiation areas have been conducted worldwide (Malanca et al., 1993; Quindos et al., 1994; Vera Tome et al., 2002; Ramli et al., 2005; Vandenhove et al., 2006; Prasad et al., 2008). Some studies showed various pathways of radionuclides and heavy metals leaching from rocks and soil and their transportation and concentration into the water, plants and animals in different degrees (Bernhard et al., 1996; Apps et al., 1998; Vandenhove et al., 2006).

The main objective of this work was to determine the concentration of the radionuclides ^{232}Th and ^{238}U and heavy metals such as As, Pb, Cd and Cr in different Fen samples in order to obtain an overall picture on dispersion to different environmental compartments. Relation between radionuclides levels and outdoor radiation doses, together with preliminary estimation of total contamination degree due to former mining activities, were also performed.

Material and methods

The Fen Central Complex is located in Nome municipality, Telemark County in Norway. This complex has carbonatite rocks of volcanic origin, with the most abundant rock types: Søvite (calcite carbonatite), Rauhaugite (dolomite carbonatite), Rødberg (hematite-calcite-carbonatite) and Fenite (alkali-metasomatised granitic gneiss) (Barth and Ramberg, 1966). As mentioned above, intensive mining activities in these locations ended during the 1960s. After that, several recordings of elevated natural gamma radiation doses in this complex were seen, either in portable hand detectors measurements (Dahlgren, 1983; Stranden, 1982) or in helicopter measurements (NGU, 2007).

Field work was conducted in May, 2008 (Fig.1). Terrestrial gamma radiation dose rates were measured by gamma detector (Automess AD4LF type 6150), at approximately 1 m distance above the ground. External gamma dose rates for different locations were calculated as the mean values from separate measurements done at each location. Eleven sampling sites were chosen in NORM and TENORM areas and outside these areas but within Fen. Geographical coordinates of sampling locations were read and recorded with portable GPS (Germin, USA).

Soil samples were collected at seven separate locations, with different gamma radiation levels. At each sampling site, soil was collected as bulk samples from minimum five points, at depth 0-20 cm, and then mixed to combine composite samples for every location. Rock samples of different sizes (3-15 cm) were taken randomly and later identified as rock type Søvite and Rødberg, typical for Fen geology complex. At least ten separate rocks were taken at every sampling location. After identification, rocks were laboratory milled to fine powder, homogenized and further decomposed for ICP-MS analysis of ^{232}Th, ^{238}U and heavy metal contents. Water samples were taken at five different locations. Water of Nordsjø Lake was sampled at four sites within the Fen public area and with different distance to area with high background radiation and at one site in Fengruve area rich in thorium bearing rocks. Physical and chemical parameters were measured *in situ* with portable pH-meter (WTW Multi 340i), previously calibrated with acid and neutral standard solutions. To study size distribution of radionuclides and heavy metals, i*n situ* size filtration with 0.45 µm membrane filter and ultrafiltration with 10 kDa hollow-fiber (Milipore) filter were conducted on Nordsjø lake samples from area with high background radiation. This was done to study behavior, mobility and possible impact on environmental compartments (Salbu et al., 2000). Water on other sampling sites was taken as total samples. All samples were conserved by acidifying with concentrated HNO_3 to obtain pH approximately below 2.

Soil samples were air dried in the laboratory, at ambient temperature for several weeks. Then, they were crushed and homogenized by sieving through 2 mm sieve. Aliquots of each were oven dried (105ºC) to constant mass prior to HNO_3 acid and microwave decomposition (Milestone Inc., Ultraclave High performance reactor, Shelton, CT) and analysis of heavy metals and radionuclides.

Concentrations of radionuclides ^{232}Th, ^{238}U and heavy metals As, Pb, Cd and Cr were measured with ICP-MS analysis using a Perkin ElmerSciex Elan 6000 (Norwalk CT, USA). In order to ensure analysis accuracy and precision, internal standards were added systematically to each sample before decomposition and appropriate standard reference materials were analyzed alongside the samples. All rock and soil samples

were 1 % acid solutions. Each sample was ICP-MS determined by 3 injections. Detection limits were calculated as three times of standard deviation of measured blank samples.

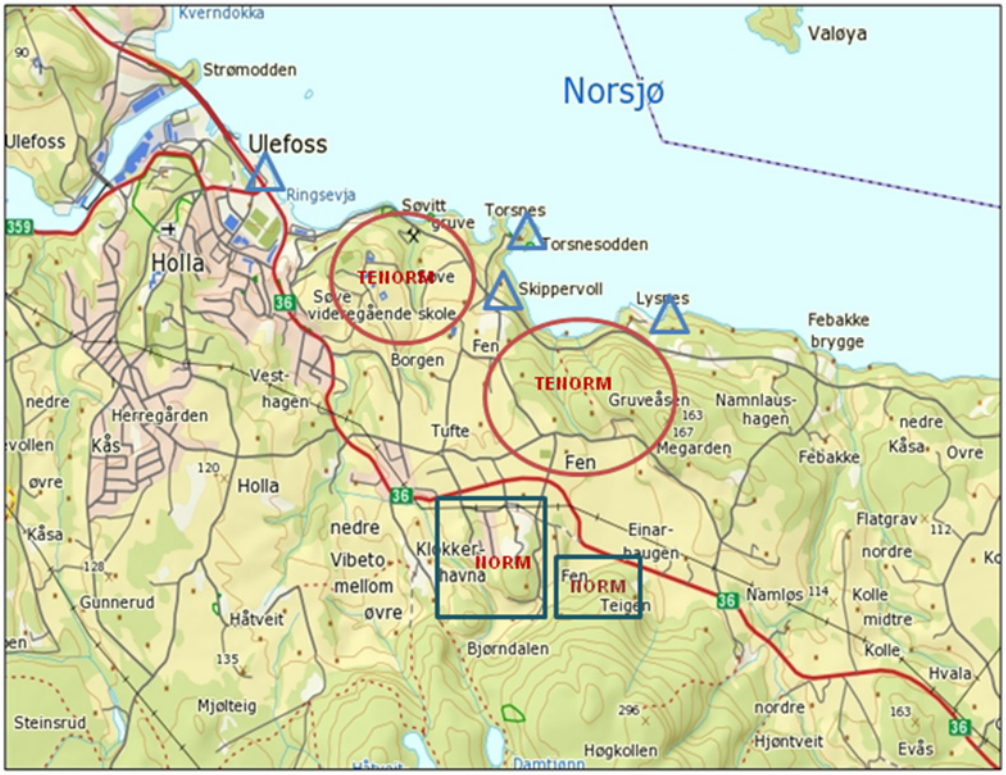

Fig.1. Study area with marked sampling locations in Fen Norway (Norwegian Mapping Authority, 2010), (⬭ TENORM sites, ▭ NORM sites, △ background sites).

Results and discussion

Measurements of gamma ray radiation dose rates (Table 1) showed values ranging from 0.15 to 9.20 μGy/h for different Fen locations. These values are significantly higher than world average terrestrial dose rate of 0.059 μGy/h (UNSCEAR, 2000) and higher than gamma radiation dose rates found in similar investigations of other high NORM areas (Morales et al., 1996; Ramli et al., 2005; Prasad et al., 2008). Maximum gamma dose rate was measured at site G13, in area called Gruveåsen. These readings are related to the significant concentrations of ^{232}Th and ^{238}U found in rødberg rocks and soil samples from the same locations. High readings were also obtained at sampling locations in Fengruve area (F2, F3, F4 and F5) and in Søve area (S1). Locations Gruveåsen, Fengruve and Søvegruve (Fig.1) are previous mining sites and high values for radiation dose rates are directly consequence of TENORM. However, similar values (up till 3.24 μGy/h) were obtained for the measurements done at NORM site Rullekol, away from past mining sites and in the vicinity of houses. Other locations in Fen had lower gamma radiation dose rates measured, i.e. 0.11-0.25 μGy/h. Still, these values are approximately 2-4 times higher than world average level of 0.059 μGy/h published by

UNSCEAR (2000). Values obtained in this study are part consistent with previous measurements done in this Norwegian area (Stranden, E., 1982; Dahlgren, S., 1983; NGU 2007).

Table 1. Terrestrial gamma radiation dose rates at Fen sites.

Sampling sites	Terrestrial gamma dose rates (μGy/h), range
S1	2.09 - 8.50
F2	1.90 - 4.40
F3	3.30 - 3.70
F4	0.80 - 3.80
T1	0.15 - 0.35
F5	2.30 - 4.45
L1	0.11 - 0.34
R1	1.09 - 3.24
G11	4.11 - 5.08
G13	7.20 - 9.20
G14	3.80 - 4.50

The average concentration of ^{232}Th for rødberg rocks collected at Gruveåsen and Fengruve locations (Table 2) was 1552 mg/kg. The average concentration for ^{232}Th for søvite rock samples was found to be considerably lower, 64 mg/kg.

Table 2. Concentrations of ^{232}Th and ^{238}U in rocks from Fen area.

Rock type	^{232}Th (mg/kg)	^{238}U (mg/kg)	^{232}Th/^{238}U ratio
Rødberg	1552	6	342
Søvite	64	6	11

Results of previously reported rock samples analysis (Dahlgren 1983; Sundal and Strand 2004; NGU 2007), showed comparable concentration ranges for ^{232}Th in these rocks. Values for rødberg are much higher than typical values of 0.1-87.5 mg/kg for Norwegian bedrock (Nordic, 2000), giving the highest ^{232}Th level in Norwegian bedrock (Sundal and Strand, 2004). Uranium in rocks was present in much lower concentrations, 6.47 mg/kg and 5.53 mg/kg, for rocks rødberg and søvite, respectively. As presented in Table 2. value for ^{232}Th/^{238}U ratio for søvite rock type was 11.11 and for rødberg rock type was 342. These clearly distinguished values are reflecting the high difference in ^{232}Th concentrations and similar ^{238}U concentrations in the two different rock types.

Results of soil analysis (Table 3) showed wide ranges in radionuclides activity concentrations, 69-6098 Bq/kg and 49-128 Bq/kg, for ^{232}Th and ^{238}U, respectively. These values are obviously higher than the world average values for soil 30 Bq/kg for ^{232}Th and 35 Bq/kg for ^{238}U, given by UNSCEAR (2000).

Table 3. Activity concentrations of radionuclides and concentrations of heavy metals in soil from Fen area.

Sampling sites	^{232}Th (Bq/kg)	^{238}U (Bq/kg)	As (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	Cr (mg/kg)
S1	69 ± 8	49 ± 12	4±4	47 ± 5	0.26±0.01	26±23
F3	4007 ± 1108	111 ± 37	20±5	134 ± 95	0.60 ± 0.14	33±19
F4	4563 ±93	111 ±37	17±1	121 ± 23	0.73 ±0.07	40±8
T1	1059 ±28	128 ± 4	7.1±0.6	287± 10	0.48±0.02	30.0±0.3
G11	6098 ± 1429	74 ± 62	20±6	55±7	1.88±0.59	54±14
G13	5781 ± 848	68 ± 6	20.3±0.9	65± 10	0.68 ± 0.07	66±4
G14	4843 ± 126	85 ± 5	16.7±0.2	59 ± 2	0.54 ± 0.07	89±3

The highest ^{232}Th value was found in soil in the area Gruveåsen (G11), and the lowest in the area Søvegruve (S1). The pattern of ^{232}Th distribution in soil is correlated with the abundance of rock type rødberg (with high ^{232}Th level) in Gruveåsen and Fengruve areas and with the abundance of rock type søvite (considerable lower ^{232}Th level) in area of Søvegruve. In general, soil concentration results suggest that erosion and weathering of rocks containing minerals rich in radionuclide during the time led to formation of soil layers significantly enriched in radionuclides.

To check the possibility for a multiple radiological and metal contamination in this area, soil samples were also analyzed for metals such as As, Cr, Cd and Pb. Obtained concentrations are given in Table 3. Arsenic concentrations in soil samples were higher than norm value of 8 mg/kg for non-polluted Norwegian soil (SFT, 2009). The range of Cd concentrations in soil was from 0.26 mg/kg up till 1.88 mg/kg. These values are higher than the average natural abundance of Cd in the earth's crusts, but are in ranges for soil in the vicinity of sedimentary or Fe rich rocks, 0.1-5.0 mg/kg (Cook and Marrow, 1995; Salbu and Steinnes, 1995). The average Pb concentration in samples of soil taken in Fen area was 110 mg/kg. Non-disturbed Norwegian soil has the average Pb concentration of 15 mg/kg, and range 10-19 mg/kg (Berg et al., 2003), but some places in southern part of country are more exposed to Pb pollution due to long range transport of pollutants and have 10 times higher concentrations than in central part of the country (Steinnes and Ruhling, 2002). A map of Pb distribution in Norway, given by Arctic Monitoring Assessment Program (AMAP, 1998), gave an approximately level of 40-60 mg/kg for Pb in Fen, Telemark area. Cr concentrations exceeded SFT (2009) norm values in samples taken at sites G11, G13 and G14, in wooden area of Gruveåsen.

Radionuclide concentrations in water taken in the Fen area ranged from 0.038-0.187 µg/L and 0.136-4.414 µg/L for ^{232}Th and ^{238}U, respectively. These numbers

exceed values given by UNSCEAR (2000) for world average concentration in water that contribute to exposure from natural sources (0.012 and 0.083 µg/L for ^{232}Th and ^{238}U, respectively). However, values for both radionuclides are still far below the significant contamination levels in the guideline for drinking water (WHO, 2003). Previously, Stranden (1982) also reported no radiation dose contribution for Fen people, regarding Nordsjø lake water. Comparison of ^{232}Th and ^{238}U levels showed several times lower levels of dissolved thorium species in all water samples. This is in agreement with theory and generally low solubility of thorium due to high affinity for sedimentation and particle formation. Results obtained for heavy metals As, Pb, Cd and Cr were below the limit levels for non-polluted water (SFT, 2009).

Size fractionation of ^{232}Th in Nordsjølake samples gave results (Fig.3) as follows: 43.75% were present in particulate fraction, 48.44% as colloids and 7.81% as low molecular mass species. Regarding typical chemical behavior of ^{232}Th, we expected considerable higher percentage in particulate phase. However, more than 50% of ^{232}Th was present in form of mobilizable colloidal and low molecular mass species. Thus, colloidal transportation is expected and might induce further distribution and bioaccumulation in living species of this water system.

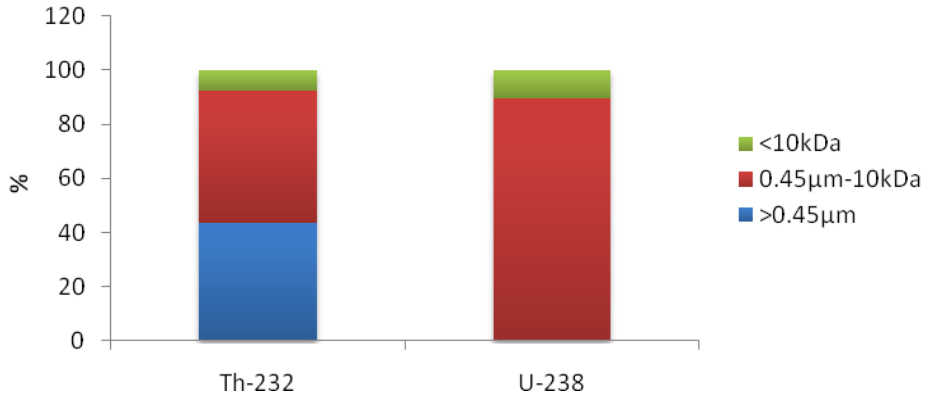

Fig. 2. Size fractionation of ^{232}Th and ^{238}U radionuclides in water samples from lake Nordsjø.

Analysis of uranium showed that ^{238}U was present mainly as colloids (90%) (Fig.2). On the basis of these results, ^{238}U is expected to be mobile, more soluble and could be subject of active uptake by aquatic biota in this water. Values for all measured metals were far below the levels that are expected to pose detectable effects on water living biota (SFT, 2009).

Conclusions

Measurements of gamma radiation dose rates due to NORM and TENORM and investigation of soil, rocks and water concentrations of radionuclides and metals were done in Fen area, Ulefoss, Norway. These activities were conducted as the first stage of environmental impact assessment of this specific area.

Obtained values for exposure dose rates ranged from 0.15 to 9.20 µGy/h. These values clearly exceed world average terrestrial dose rate of 0.059 µGy/h (UNSCEAR, 2000) and highly reflect the presence of radionuclides bearing minerals in volcanic rocks of this terrain. Two typical rock types rødberg and søvite analysis showed

different levels of ^{232}Th and ^{238}U, but the results were consistent with previously reported studies (Dahlgren 1983., Sundal and Strand, 2004; NGU, 2007). The high concentrations of ^{232}Th in rødberg place this rock as the highest in ^{232}Th of Norwegian bedrocks.

Soil ^{232}Th and ^{238}U concentrations were found to be much higher than the Norwegian average soil values and obviously highly correlated with the presence of thorium and uranium rich rock types. Inhomogeneous distribution of radiation was found in the whole area. Radionuclides and heavy metals were particularly high in the vicinity of former iron mining sites. Analyzed water samples showed no contamination, neither with radionuclides nor with heavy metals, despite the high levels in surrounding media. It implicates that there are minor leaching or other transportation from these sites. Still, despite the low total levels, results of size fractionation, i.e., presence of all metals and high percentage of both radionuclides in the biologically most important - low molecular mass fraction, could be reasonable basis for investigation of possible accumulation in fish living in the lake.

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Thoron and its airborne progeny in Irish dwellings

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Abstract

During the period 2007-2009 long term indoor concentrations of thoron gas and airborne thoron progeny were measured using passive detectors in 205 dwellings in Ireland. Passive alpha track detectors of different types were used to make these measurements in the indoor air over a typical exposure period of at least three months. Thoron concentrations were measured using Raduet detectors supplied by Radosys, Budapest while thoron progeny concentrations were measured using passive detectors designed by the National Institute of Radiological Sciences (NIRS), Chiba, Japan. Radon concentrations were also measured in these dwellings using the standard alpha track detectors employed by the Radiological Protection Institute of Ireland (RPII). The main results obtained are given below. It should be noted that these results are based on the actual measurements made and are not seasonally adjusted. The estimated annual doses for thoron progeny (ThP) and radon (Rn) were calculated using dose conversion factors (DCF). The DCF_{ThP} used was based on the dosimetry models of Kendall and Phipps (2007) and of Ishikawa et al (2007). Exposure to indoor air containing thoron decay products at a concentration of 1 Bq/m^3 EETC (Equilibrium Equivalent Thoron Concentration) was estimated to result in an annual effective dose of 0.75 mSv. For radon a DCF_{Rn} of 1 mSv/year for indoor exposure under standard conditions to 40 Bq/m^3 was used.

Thoron gas activity concentrations ranged from < 1 to 174 Bq/m^3 with an arithmetic mean of 22 Bq/m^3. Radon gas concentrations ranged from 4 to 767 Bq/m^3 with an arithmetic mean of 75 Bq/m^3. The corresponding estimated annual doses are 0.1 (min), 19.2 (max) and 1.9 (arith.mean) mSv/year .Thoron progeny ranged from < 0.05 to 3.8 Bq/m^3 (EETC) with an arithmetic mean of 0.47 Bq/m^3 (EETC). The corresponding estimated annual doses are 2.9 (max) and 0.35 (mean) mSv/year.

It is of interest to note that in 14 of the 205 dwellings investigated the estimated annual dose from thoron progeny exceeded that from radon.

Introduction

There are over 30 known isotopic forms of radon. Most of these have very short half-lives in comparison to radon-222. Due to their very short half-lives they cannot migrate far from their origins and consequently are of no radiological health significance. One of them, however, is radon-220 (usually called thoron) and despite its short half-life (55.6 sec) may be present in indoor air at a sufficiently high concentration to be of some radiological significance. Thoron is a member of the thorium-232 decay series. A simplified version of the thoron decay scheme is shown in Figure 1. Henceforth in this paper, for convenience and in keeping with common practice, radon-222 will be referred to as "radon" and radon-220 will be referred to as "thoron". Unlike radon,which can enter a dwelling from the ground underneath it, indoor thoron due to its short half-life almost exclusively comes from the materials of the internal surfaces of rooms in dwellings.On a global basis ,in comparison with radon, information on the concentrations of thoron gas and in particular of its airborne progeny in dwellings is not very extensive (UNSCEAR 2000). Many of the values quoted in the literature are as a result of short-term or grab sampling and therefore are not suitable for estimating long term exposures in dwellings. For this and other reasons in most countries it has been difficult to estimate the long–term radiation dose and risk from indoor thoron and its progeny. In this paper exposure to indoor air containing thoron progeny at a concentration of 1 Bq/m^3 EETC (Equilibrium Equivalent Thoron Concentration) is estimated to result in an annual effective dose of 0.75 mSv. This dose conversion factor (DCF_{ThP}) is based on the dosimetry models of Kendall and Phipps (2007) and of Ishikawa et al (2007). For radon a DCF_{Rn} of 1 mSv/year for indoor exposure under standard conditions to 40 Bq/m^3 was used in this work. It should be noted that this DCF_{Rn} is presently under review and it is anticipated that a dose conversion factor of 1 mSv/year resulting from residential exposure to 30 Bq/m^3 will become the norm in many EU countries. This dose conversion factor is already being used by the World Health Organisation (WHO 2009).

Study outline

A pilot study of 40 Irish dwellings was carried out by University College Dublin in 2005 using passive CR-39 based detectors which give long term measurements of thoron and its progeny. This study found,for these dwellings, that the mean value of indoor thoron gas was 30 Bq/m^3 and the mean value of airborne thoron decay products was approx.1 Bq/m^3 (EETC) (Ní Choncubhair *et al*. 2008.) On the basis of the dosimetric modelling of Kendall and Phipps (2007) and Ishikawa et al (2007) the mean annual dose from thoron progeny in these dwellings is estimated to be 0.75 mSv/year. This is about 38 % of the estimated 2 mSv/year radiation dose that would be expected to be received by occupants of a typical Irish dwelling due to exposure to radon. Even though this pilot study cannot in any way be considered as representative of the national housing stock nevertheless it indicated that doses from thoron decay products are not always negligible and should not be ignored. It was therefore decided to carry out a larger survey of the concentrations of indoor thoron gas and its airborne decay products in Irish dwellings. This survey was carried out during the period 2007-2009 and was a collaboration between the Radiological Protection Institute of Ireland (RPII) and the National Institute of Radiological Sciences (NIRS), Chiba, Japan.

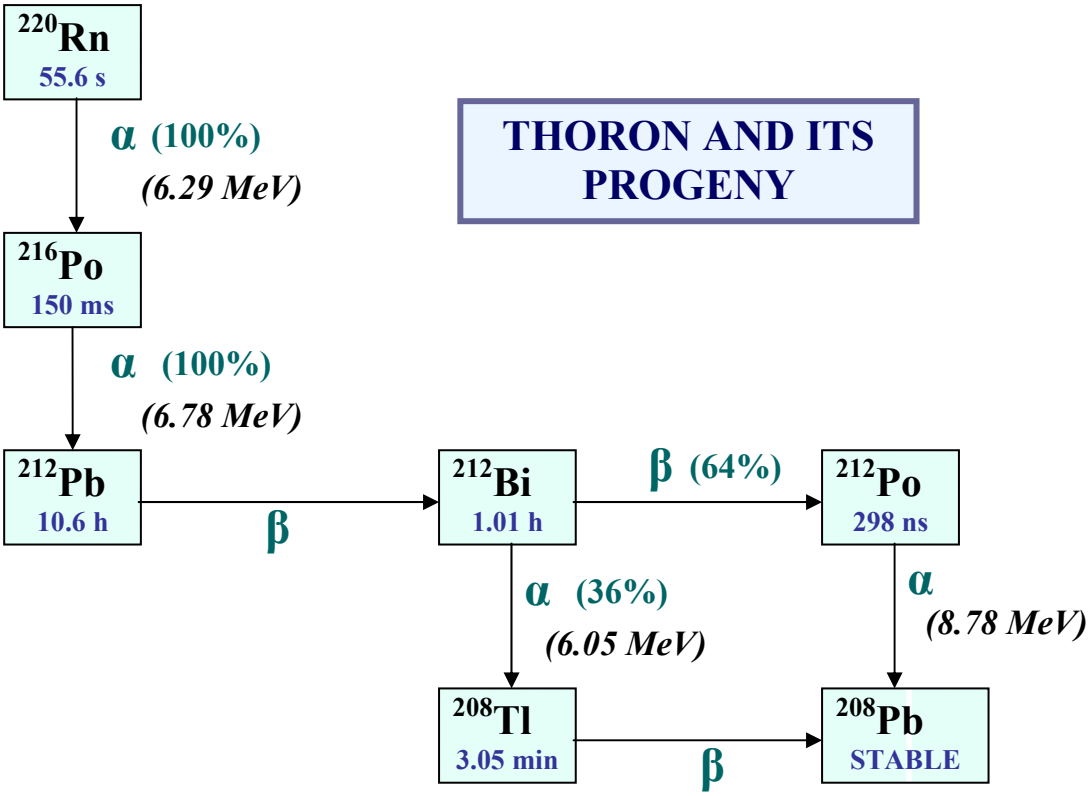

Figure 1. Thoron decay scheme.

The survey was conducted in two phases. Phase 1 comprised households which had participated in the past in the RPII national radon survey in the period 1992-1997 (Fennell et al.,2002) and which were in or around the major population centers of Dublin, Cork and Limerick. Phase 2 households were selected to increase the proportion of new houses in the survey and were comprised mainly of the houses of RPII staff and their families. Phase 2 participants were not part of the national radon survey but did have a previous radon measurement carried out in their home. As explained below the packages of detectors sent to the participating households gave a measurement of radon as well as of thoron and its progeny. Therefore, in addition to thoron/thoron decay product measurements the opportunity was also taken to make comparisons between the present radon concentrations in these dwellings and those in the past. Invitations to participate in the project were sent by post. In phase 1 a total of 365 invitations were issued of which 200 agreed to participate. Detectors for these households were issued in December 2007. During phase 2 detectors were issued to 40 households in June 2008. Of the 240 dwellings surveyed 82 were in or around Dublin, 82 in or around Cork and 69 in or around Limerick. Pre-paid post envelopes for return of detectors were supplied to participating households. A questionnaire dealing with house and household characteristics accompanied the detectors. Detectors were exposed in the dwellings for a minimum of three months in order to obtain long-term average measurements of thoron, thoron progeny and radon.

Satisfactory measurements of thoron and its progeny as well as of radon were completed in a total of 205 dwellings in Ireland. Due to the manner in which they were chosen the 205 dwellings investigated cannot be taken to be an unbiased or fully

representative sample of the national housing stock. Nevertheless this number of dwellings,while small in absolute terms, should be seen in the context of the population of the Republic of Ireland which is approximately 4.5 million.

In this survey the long term measurements of thoron and its progeny and also of radon were made using three types of passive CR-39 alpha track detectors. Thoron gas concentrations were measured using Raduet detectors supplied and processed by Radosys (Budapest). The Raduet thoron detector,derived from an original design of NIRS, consists of two small diffusion chambers one of which is designed to admit both thoron gas and radon gas while the other admits only radon gas (Tokonami et al (2005)). The difference in the CR-39 alpha track density between the two diffusion chambers yields the mean thoron gas concentration over the exposure period at the measurement point in a dwelling. Airborne concentrations of the thoron decay product lead-212 were determined using a passive detector designed and developed by NIRS (Zhou and Iida,2000). In this detector CR-39 is covered with a Mylar film equivalent to an air thickness of about 7 cm so that only the 8.78 MeV alpha particles from polonium-212 can penetrate the Mylar film and are recorded by the CR-39. All other alpha particles from both the thoron and radon decay series , up to and including the 7.68 MeV alpha from polonium-214, have insufficient energy to penetrate the Mylar and are thus not recorded by the CR-39. Thus this detector type is sensitive only to polonium-212 even in the presence of radon and its progeny in the air. On the basis of laboratory calibrations at NIRS the concentration in the air of polonium-212 is determined .This in turn yields the concentration of lead-212 from which the airborne thoron progeny concentration can be expressed as Bq/m^3 EETC (Zhou and Iida (2000)). Radon gas concentration measurements were obtained by using the black SSI type diffusion detectors normally used by the RPII in its various radon surveys.In addition independent measurements of radon were obtained from the Raduet detectors.

As shown in Figure 2 detectors were mounted on a specially designed bar-coded plastic frame which could be easily hung on walls. For each dwelling two such detector frames were supplied. Householders were instructed to mount one of these in the livingroom and the other in the principal bedroom on a wall or other suitable surface. In Figure 2 the thoron/radon Raduet detectors are the two black detectors mounted at the bottom of the frame The NIRS thoron decay product detector is the square metal object mounted in the centre of the frame. The black detector at the top of the frame is the RPII detector.

Figure 2. Typical deployment of detectors in a dwelling.

Results and discussion

In this project thoron,thoron decay products and radon were measured in a total of 205 Irish dwellings. The results obtained are summarized in Table 1 and Table 2.

Table 1.

Thoron Concentration. Bq/m^3		Thoron Decay Products Concentration. Bq/m^3 (EETC)		Estimated Annual Effective Doses from Thoron Decay Products (mSv/year)	
Arith Mean	Maximum	Arith Mean	Maximum	Arith Mean	Maximum
22	174	0.47	3.8	0.35	2.9

Table 2.

Radon Concentration. Bq/m^3		Estimated Annual Effective Doses from Radon Decay Products (mSv/year)	
Arith Mean	Maximum	Arith Mean	Maximum
75	767	1.9	19.2

There are a number of observations that can be made regarding the estimated doses from thoron and radon progeny in the 205 investigated dwellings.

Tables1 and 2 clearly show that ,as not unexpected, in absolute terms the doses from radon and its progeny are much greater than those from thoron and its progeny. It is interesting to note,however, that in 14 or 7% of the dwellings the estimated doses from thoron progeny were greater than those from radon and its progeny.

The total per caput radiation dose in Ireland has most recently been estimated to be 3.95 mSv/year (Colgan *et al 2008)*. This includes an estimated contribution of 0.28 mSv/year from thoron decay products based on the 2005 pilot study of 40 dwellings (Ní Choncubhair *et al*. 2008.) If the measured data from the present study of 205 dwellings given in Table 1 were nationally representative the estimated mean dose of 0.35 mSv /year from thoron decay products would bring the total per caput annual dose to 4.02 mSv. The contribution from thoron progeny would then be about 9% of this total. It should be emphasized that this is a preliminary estimation and is subject to further review but does indicate that thoron derived doses are not always negligible.

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Radiation from geological samples in museums and showrooms

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Abstract

In the last two decades a considerable attention of the radiation safety community is paid to exposures due to natural radioactive materials based on fact that doses when handling such materials can be considerable. In general, the doses are mainly a result of inhalation of radon decay products. In order to identify all practices related to radiation sources, the Slovenian Nuclear Safety Administration (SNSA) as a regulatory authority preformed an extensive campaign of inspections in museums, research institutions, educational institutions and companies handling geological samples. Many radioactive items, mainly radioactive minerals and ores were identified. In some cases the dose rates at the contact of a specimen were few orders of magnitude higher than a natural background and elevated radon concentration was measured in rooms where specimens were collected. In general, users were not aware of risks associated with handling and storing such specimens. As a result of SNSA campaign radiation safety measures were implemented.

Countries use very different approaches regarding radioactive specimens in collections e.g. uranium and thorium minerals, radioactive fossils, petrified wood. No harmonisation on the international level exists regarding handling radioactive specimens in state and private collections resulting in difficulties in posing effective radiation protection control over such specimens.

Introduction

In the nature approximately about 340 nuclides can be found and among them around 70 are radioactive (Eisenbud 1997). Usually they are classified regarding their origin, i.e. primordial radioisotopes (e.g. ^{40}K, ^{87}Rb, ^{238}U, ^{232}Th), secondary radioisotopes and cosmogenic radioisotopes. Primordial radioisotopes have half-lives sufficiently long that they survived since their creation, i.e. comparable to the age of the universe. The secondary radioisotopes are the result of the decay of primordial radioisotopes while the cosmogenic radioisotopes are the result of the continuous bombardment of stable nuclei by cosmic rays (Holmes-Siedler 2006). In addition, the military activities and operation of nuclear installations affected the concentrations of some isotopes in the Earth (UNSCEAR 2000).

In the last two decades the international radiation safety communities e.g. IAEA, EC (IAEA 2003, EC 1999, EC 2002) paid a considerable attention to naturally occurring radioactive materials (NORM) as defined for example in ICRP publications (ICRP 2007) or to technologically processed materials and existence of technologically enhanced naturally occurring radioactive materials (TENORM). Exposures of workers handling such materials can be very high, in some cases even substantially higher than occupational exposures of workers dealing with the licensed radiation sources. Being aware of that, the radiation safety community has published first safety standards related to NORM e.g. given in (IAEA 2004). The natural radioactive materials are mainly used in industry with the highest radioactivity levels in uranium mining and lower levels in phosphate processing, oil and gas industry etc. The working conditions in industry are a subject to a control not only due to the exposure to the radiation but in many cases the good general safety practice to handle materials is enough also in order to provide sufficient radiation protection. For example, a use of a mask when handling dust materials can provide at specific circumstances a sufficient protection against internal exposure.

Natural radioactive materials are also quite frequently present in research laboratories and educational institutions. For example, the geological faculties usually have a collection of samples. Among more than 4000 minerals which are known today, some are highly radioactive e.g. uraninite, pitchblende, brannerite, coffinite or thorite. Even more, radioactive minerals are often present in museums and showrooms of minerals causing exposure of workers and the public. Private collectors of minerals very often handle natural radioactive materials. In addition, geological institutes usually keep geological samples during research projects which might be radioactive e.g. radioactive minerals or sands. Very often even after finishing research projects they keep such materials in their storages, which therefore can contain quite a lot of radioactive samples.

The radioactive samples are not only in a form of ores, minerals or sand, sometimes they are in form of petrified samples or even radioactive fossils. Such samples are for example handled outside geological departments of natural museums or faculties for natural sciences. Furthermore, radioactive samples can be a part of collections for a long period without noticing that they require special safety attention. They can be a part of private or institutional donations and they do not necessary have any connection to samples taken from local area, e.g. radioactive samples can be brought from very distant areas. The collectors from states with known areas of radioactive fossils or uranium mines could have higher probability to keep radioactive samples in museums, showrooms, storages of geological institutions and elsewhere where such samples were collected.

The persons handling such materials are very often not aware about the radiation risks they are exposed to when handling or storing such materials. Especially, when the above mentioned radioactive geological samples are not handled due to theirs characteristics related to radioactivity, users of such samples are not aware that they are actually handling radioactive materials and do not pay any attention to safety precautions.

Identification of radioactive samples

In order to establish the safety regime in institutions and other sites where radioactive geological samples are handled the identification of radioactive samples is necessary. A detailed analysis should follow regarding the main principles of radiation protection, namely justification, optimisation and dose limitation. According to the experiences radioactive samples are very often handled without basic knowledge of a justification principle and without any basic knowledge of safety measures. When the owners are faced radiation protection issues they often decide to reduce the number of exhibited samples. In such cases waste management issues also occur. Once the identification of samples is done the assessment of public and occupational doses when handling radioactive geological samples should be prepared and safety measures put in place.

The extensive campaign of identification conducted by the inspection of the Slovenian Nuclear Safety Administration in Slovenia, (SNSA, (http://www.ursjv.gov.si/en/), started a few years ago and the preliminary results of the campaign were published elsewhere (Janzekovic 2008). The SNSA is the responsible authority for control of radiation sources outside medicine and veterinary medicine. The campaign mainly focused on institutions which were also related to former uranium mine in Slovenia, the Zirovski vrh uranium mine. In a period 2007-2010 the SNSA identified many radioactive items in educational and research institutions, dealing with geological samples. The samples containing uranium and thorium can have different forms e.g. ores, minerals and petrified samples. The fossil of a mastodon tusk with elevated dose rate level at the contact was identified for instance and the analysis of its radioactivity is underway. Some samples inspected during the campaign are shown in Figure 1. The figures show a small portable radiation monitor named the radiation pager. The indication “9” shown on the pager indicates that the actual photon dose rate is above 38 µSv/h and the indication “4” indicates that the actual photon dose rate is above 12 µSv/h.

Fig. 1. Identification of elevated dose rates due to enhanced radioactivity of minerals (left, 2007) and a mastodon tusk (right, 2010).

The process of searching radioactive geological samples is similar to the process of detecting and finding other orphan sources described elsewhere (Janzekovic 2006). A well kept documentation regarding the origin of samples can facilitate the identification of radioactive material among usually a large number of non radioactive samples. The detection of photons originating from radioactive material was performed by detection

of external radiation using instruments like hand held gamma spectrometry unit Fieldspec shown in Figure 2, already mentioned radiation pager and even contamination monitor as a very sensitive instrument. It should be noted that in many cases inspection identified higher dose rate at the lower part of the showcases where actually radioactive minerals were stored and were not exhibited. In addition, the staff of the institutions frequently stored radioactive items in their office, frequently in a very vicinity of their own working place.

Fig. 2. Measurements of the photon dose rate of the geological specimen using Fielspec and a use of a radiation pager for identification of elevated dose rates in 2007.

The detected photon dose rates at the contact with samples could be a few orders of magnitude above the natural background and no provisions to avoid internal exposure are usually in place. Besides the presence of uranium and thorium and theirs daughters, elevated levels of ^{40}K can be present in some samples e.g. in coal samples.

The geological samples with enhanced radioactivity were stored in collections, laboratories, offices, halls and storages. Very seldom only one radioactive sample is present at a particular site and usually few tens of them were collected or exhibited together. The shapes of specimens are very different as well as their homogeneity. The shielding of radioactive object by other objects can be a considerable problem in order to identify radioactive geological samples. Slightly elevated levels of radiation at some distances from the showcases can indicated the presence of radioactive samples with high radioactivity.

After the inspections the majority of samples were carefully investigated by qualified experts while the investigation of others is still underway. Because of a huge amount of items, namely few hundreds, the identification of radioactive specimens, e.g. uraninite minerals specimens from local uranium mine and the worldwide uranium mines, was very difficult. It was based on the exemption levels valid for ^{238}U and ^{232}Th in secular equilibrium given in EU directive (EC 1996) which are given in Table 1. The qualified expert developed simplified identification methodology by using data on measured dose rate, mass of an object and conversion factor between photon dose rate and activity concentration in order to compare the estimated activity concentration and appropriate exemption level. Details are given in (Stepisnik 2007). According to data from this reference less than 5 % of potentially radioactive samples identified at inspections in 2007 were later not identified as radioactive specimens.

Table 1. Exemption levels for ^{238}U an ^{232}Th in secular equilibrium taken from (EC 1996).

Series	Exemption levels	
$^{238}U_{sec}$	1 kBq/kg	1kBq
$^{232}Th_{sec}$	1 kBq/kg	1kBq

As reported in (UNSCEAR 2000) the global average values of ^{238}U and ^{232}Th in soil are about 30-50 Bq/kg. In specific soil and rocks the concentration can be some orders of magnitude higher. While processing natural radioactive material in secular equilibrium some elements are usually extracted and no secular equilibrium is present any more.

The enhanced external dose rate due to presence of radioactive geological specimen was used as an indicator for presence of enhanced radioactivity in specimens during inspections. From radiation safety point of view the presence of radon and corresponding dose to inhalation should be controlled. The staff, e.g. guardians of showrooms are present actually whole working day in showrooms. The preliminary results of measurement radon concentration in showrooms with mineral collections and in a storage with radioactive samples showed that the maximum ^{222}Rn concentration exceeded 1000 Bq/m^3 in a room with a mineral collection and reach about 1800 Bq/m^3 in a storage in a basement. Additional measurements are necessary in order to investigate the actually concentrations. The concentrations were measured in springtime and could be even higher in winter. The concentrations should be at least compared to concentrations recommended by the EC from (EC 1990), the IAEA from (IAEA 1996) and WHO levels published in (WHO 2009) and given in Table 2. It shows that the reference level for workplaces given by the IAEA is lower than measured concentrations. It should be taken into account that geological radioactive specimens are sometimes exhibited in numerous private collections mostly in private houses. As a result the reference levels for the members of the public should be applied in such cases.

Table 2. EC, IAEA and WHO recommendations related to reference levels for consideration of remedial actions, details are given in (EC 1990), (IAEA 1996) and (WHO 2009).

Exhibition site	Reference	Reference levels of radon indoor concentration
Public museums (workers)	Occupational exposure (IAEA 1996)	1000 Bq/m^3
Private collections (members of the public)	Existing buildings (EC 1990)	400 Bq/m^3
	Future constructions (EC 1990)	200 Bq/m^3
	Buildings (WHO 2009)	100 Bq/m^3
	Buildings in special circumstances (WHO 2009)	300 Bq/m^3

After the campaign of the SNSA remedial actions took place, e.g. around altogether 100 kg of radioactive materials were transported from an old storage of geological samples to the Storage for radioactive waste and a few hundreds of kilograms of radioactive waste originated from the educational institution were stored in the Storage for radioactive waste. The specimens which are still in use at other sites, e.g. geological samples used at a faculty, are subjects of regulatory control.

After the SNSA campaign the actual exposures of workers, students, collectors and visitors were efficiently lowered because the majority of sources were put in suitable storages and many safety precautions were implemented.

Radiation safety and radioactive geological specimens

Many radiation safety requirements during handling and storing the samples were ignored because they were not identified as radioactive materials or sources. The risk associated with radioactive geological samples originates manly from:

- external exposure due to decay of ^{238}U and ^{232}Th series
- internal exposure due to presence of long-lived radionuclides in a sample and radon with its short-lived decay products.

Both components should be actually assessed prior the handling, preparing and exhibition of geological samples. The assessment should be done for all lifetime phases of a use of radioactive samples i.e. from "its cradle to its grave" in order to avoid unjustified exposure of workers, including guardians of showrooms, researchers, students, visitors or private collectors. While prevention from external exposure can be achieved without huge expenses, the presence of accumulation of ^{222}Rn can be an important and even major issue. In order to safely handle radioactive geological samples many measures can be applied, either administrative or physical, e.g.:

- exhibit replica specimens in museum collections and limit handling radioactive specimens as much as possible
- ventilate a room before or during, as appropriate, when entering storages with radioactive materials
- use protective glass as for example lead glass to prevent exposure from beta and gamma radiation
- use gloves and other personal protective belongings when handling radioactive samples
- encapsulate specimens in showrooms in order to prevent contamination and radon dispersion
- control the contamination when handling specimens which crumble
- use separate and suitable storages for radioactive geological samples
- define the specific area in laboratory or showrooms where radioactive samples are handled, make the dose mapping, assess the doses and control the area
- put radioactive samples at remote area also if they are present in private collections
- control the donation of specimens from radiological point of view
- prepare the waste management plan
- establish written working procedures and maintain the records of samples
- inform students, researchers, guardians of showrooms and other stakeholders about working procedures and importance of following established rules.

Conclusions

Regarding the fact that external radiation and internal exposure due to radon are mostly neglected when handling radioactive geological samples, the need for action provided by a regulator is unavoidable in order to keep the system of radiation protection effective. The countries use very different approaches when handling radioactive geological and other specimens in museum and showrooms. No international guidelines are given in order to harmonise the approaches.

Due to a fact that radioactive samples can be easily transferred from one state to another, harmonisation of national legislations can be very useful. In general, four approaches are identified.

a. The authorisation of practice is required and radioactive minerals and other geological radioactive specimens are controlled as all radioactive sources, according to requirement of the (EC 1996). Such approach requires substantial work of qualified experts and regulatory authorities in order to implement the requirements.
b. The practice is registered under specific conditions e.g. handling of only ten radioactive geological specimens while authorisation is required, for example, for more than ten specimens.
c. The handling of radioactive specimens in a workshop is an authorised practice and a full scope of authorisation is required. The exhibition of a single specimen requires less stringent requirements e.g. a dose rate at a place of a visitor should be less than 20 μSv/h because the exposure of a visitor is a "transient one" e.g. a person will receive only a small dose due to staying a short time at that place.
d. The practice is exempted from the legislation.

Approaches b and c are based on a graded approach and try to balance the burden posed by the full scope authorisation and neglecting of radiation safety.

In general, no international harmonisation is achieved in the area of natural radioactive specimens. While some countries pose full scope control as for any other radioactive material, some countries use graded approach. In addition, in some countries no precaution principles are applied when handling radioactive samples e. g. fossils. In view of a basic radiation protection principles and taking into account that in general collecting such specimens does not require huge effort it would be beneficial to prepare specific international standards or guidelines in this area. In addition, controlling numerous private collectors is even more challenging issue.

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Natural radiation background time series from gamma detector stations in Iceland

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Abstract
We present here for the first time data from four continuously monitoring gamma detector stations in Iceland along with basic analysis. The results from all four stations show an average dose rate of 44-49 nSv/hr, and standard deviation around 5 nSv/hr (10 minute sampling cycle), with a distribution consistent with a Gaussian one.

Introduction
In 2005, the Icelandic Radiation Safety Authority (IRSA) began operating two gamma monitoring stations. In 2007, two more were added so now there is one station in each of the island's four corners, all near sea level (see Figure 1). The stations are maintained in cooperation with the Icelandic Met Office. Each station also collects pressure, temperature, precipitation and wind data for its location. The gamma dose rate and accumulated rainfall data is continuously relayed to a web server and can be monitored by visiting IRSA's web page here[1]. The data is monitored for extreme values and sudden changes.

Iceland's rock foundation contains relatively little uranium and its daughter products. Hence the environmental radioactivity there is rather low. Dust and radon gas carried by global weather systems from the continents on either side of the Atlantic and brought to the ground with precipitation can have a measurable effect on the background radiation signal.

This is the first publication of the collected data, but these stations are being added to the European Radiological Data Exchange Platform (EURDEP) real time gamma monitoring station network to ease access to the data.

[1] http://www.gr.is/gammastodvar/

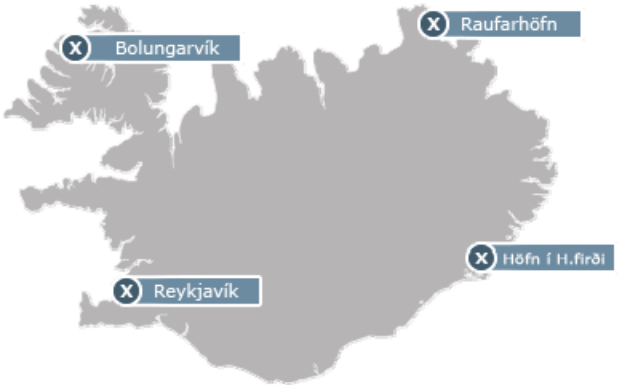

Fig. 1. Locations of IRSA's four gamma monitoring stations. Gamma background, rainfall, temperature, pressure, windspeed and wind direction is collected at these sites.

Material and methods

The gamma monitoring stations are equipped with a GammaTracer XL detectors from Saphymo[2]. Their measuring range is from 10 nSv/h - 10 Sv/h and their energy dependence is +/- 40% (over the range 45keV - 2MeV). The manufacturer provides the calibration (6% calibration error), and the tubes are recalibrated at each battery replacement (every 3-5 years). The measuring cycle is set to 10 minutes, with an estimated 1-sigma measuring error of approximately 5%. The gamma tracers are set to count for 10 minutes and write out to file.

The raw gamma dose rate data were at first cleaned to remove spurious data and obviously false readings. Further gaps (of order of a month and more) in the time stream are due to periods when the GammaTracer tubes undergo battery change and recalibration at the manufacturer's facilities. Due to growing pains (possibly a mistaken calibration) for the first year of operations, the first half year of data from the Reykjavik station has a clear upwards bias and was discarded off for the rest of the analysis. Cleaning these gaps out via automated algorithms proved tricky, so the time streams were trimmed 'by eye and hand'. Between 0.2 and 20% of the total data was thus discarded, most from the Reykjavik station.

For clarity and to reduce the effect of sampling irregularities, the data was collected into bins of 24 hours, and also into bins of 7 days.

We used the statistical computing environment R for this analysis.

Results

Summary statistics

The trimmed time streams are shown in figure 2 and a summary of the statistics from the cleaned data streams is given in Table 1. The bulk of the measurements values range from 40-60 nSv/hr, with a mean ranging from 44-49 nSv/hr and a standard deviation around 5 nSv/hr for the different stations.

[2] Manufacturer's information: `http://genitron.de/products/gamma_data_xl.html`

Table 1. Summary statistics of gamma dose rate data from the four stations. Note that data from each station come from strongly overlapping but not identical periods. All numbers in units of nSv/hr.

Station ID	Min	1Q	Median/Mean	3Q	Max
Bolungarvík	26	41	44 / 44.42	47	104
Höfn í Hornafirði	31	46	50 / 50.14	53	116
Raufarhöfn	30	47	50 / 49.97	53	161
Reykjavík	31	46	49 / 49.16	52	96

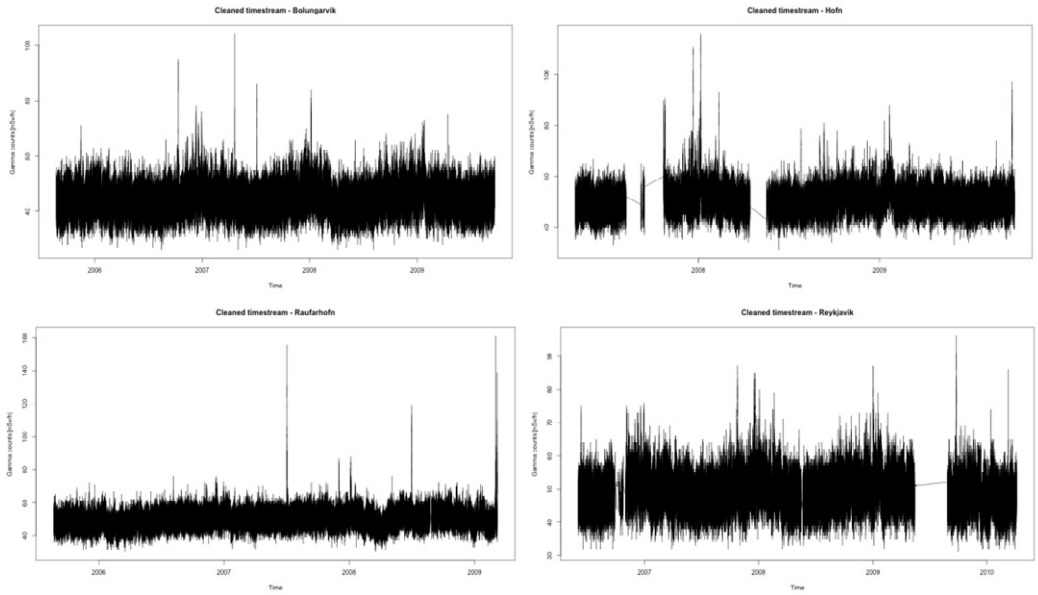

Fig. 2. Gamma dose rate time series data for the four stations, after pruning. The range can discerned, as can the larger gaps and some outlier values which were not obviously spurious.

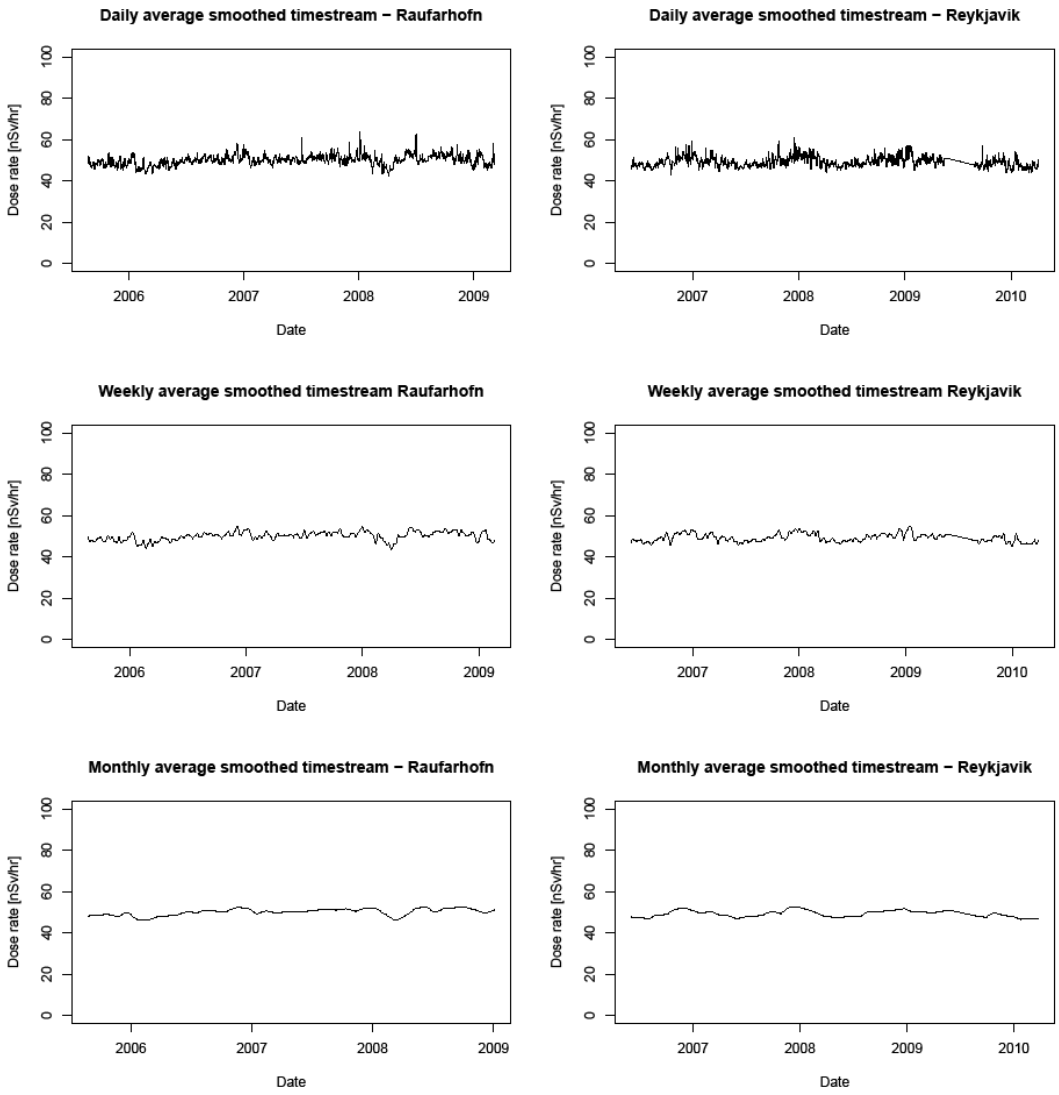

Fig. 3. 1-day, 7-day and 30-day moving average smoothing of cleaned gamma dose rate time series data for the Raufarhöfn (left) and Reykjavík (right) stations.

Dose rate distribution histograms

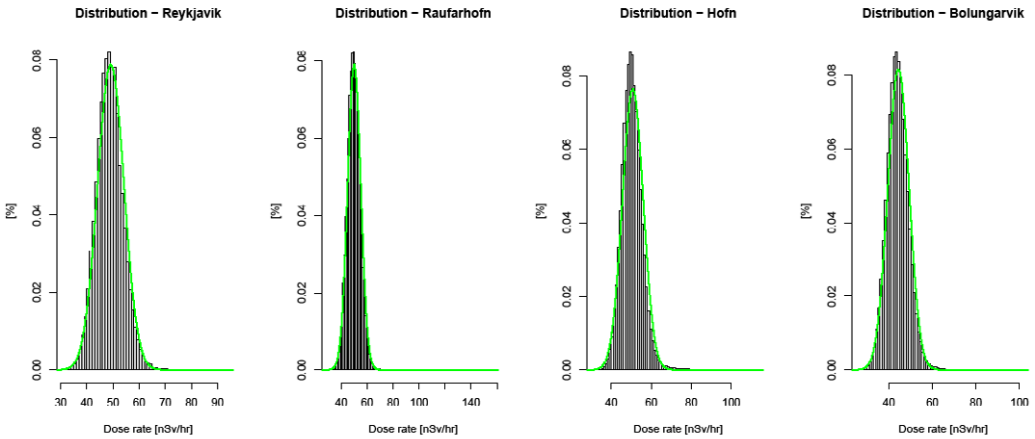

Fig. 4. Gamma dose rate distribution histograms for the four stations. The green line overlay shows a normal probability distribution with the data mean and standard deviation. The long tail towards higher values skews the distribution only slightly from a Gaussian.

Discussion & Conclusions

We see that environmental radioactivity levels are rather low and stable. The measurements are close to normally distributes, and the mild seasonality that can be spotted can be adequately explained with precipitation.

The data presented here will be made available to the network of gamma stations using the Eurdep data format. The data contain a many gaps and spurious values which need to be cleaned before a sensible analysis is made.

We thank Sigurður Emil Pálsson for his assistance and good advice.

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Localities in Montenegro with elevated terrestrial radiation

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Abstract
Research aimed to find localities in Montenegro with elevated terrestrial gamma background and recognize sources of their radiation was conducted during the period 2008-2009. For this purpose, 135 localities which have geological formations known to contain minerals with potentially high concentrations of U, Th and K, were selected throughout the country for dosimetric survey.

Knowing from earlier investigations that the average absorbed dose-rate in the air, 1 m above the ground, in Montenegro is 55 $nGyh^{-1}$, it was arbitrarily adopted that only localities with absorbed doses at least 50% above this average value will be considered as having relatively elevated radiation background. Field measurements have shown that 43 of the surveyed localities have such dose values. From these 43 localities, soil samples have been collected for further laboratory radiation characterization using a gamma spectrometry method. In that way, activity concentrations of ^{40}K, ^{232}Th, ^{235}U, ^{238}U, ^{226}Ra and ^{137}Cs were determined in the samples.

Among 10 sites with the highest radiation background in Montenegro (110-192 $nGyh^{-1}$), two sites are on andesite volcanic rock, one on fluvio-glacial sand and gravel, while the rest lie on bauxite deposits. Compared to the other known areas of high natural radiation background in the world, all these localities in Montenegro have a moderately elevated level of radiation background. Gamma spectrometry has revealed that a high content of K (up to 3341 $Bqkg^{-1}$) was the main source of elevated radiation at the sites on andesite rocks, and high U and Th content (up to 285 $Bqkg^{-1}$ of ^{238}U, and up to 201 $Bqkg^{-1}$ of ^{232}Th) at the sites on bauxite deposits.

Introduction
During the two-year period 2008-2009, within a project of the Montenegrin Academy of Sciences and Arts, a research was carried out with the aim to determine localities in Montenegro with relatively elevated terrestrial gamma background and to recognize sources of their radiation.

For planning field experiments, voluminous documentation on geology and pedology of Montenegro (Mirkovic et al. 1985; Djuretic et al. 1986) was used and analyzed. An earlier systematic investigation of terrestrial gamma radiation in Montenegro (Vukotic et al. 1997), performed 15 years ago, served as a base of this project. That investigation has shown that the average absorbed dose-rate in the air, 1 m above the ground, in Montenegro is 55 $nGyh^{-1}$ (according to the UNSCEAR 2000 Report, the average value for the other 7 countries of South-East Europe is 62 $nGyh^{-1}$). Therefore, we arbitrarily adopted that, within this project, a locality in Montenegro will be considered as having relatively elevated external radiation if the dose-rate in the air at that site is more than 50% higher than the country average, i.e. if the dose-rate is above 80 $nGyh^{-1}$. Soil samples were collected from such sites, and analyzed using a laboratory gamma spectrometry method.

In this article, only results for localities with dose-rates in the air which are at least twice higher than the country average ($D \geq 110$ $nGyh^{-1}$) are presented in detail.

Material and methods

Geological setting and selection of localities for survey

Before defining a sampling grid covering the territory of Montenegro and selection of localities where dosimetric measurements will be performed, a detailed analysis of structural-tectonic and structural-metallogenic regionalization of geological and ore formations was conducted. During this analysis, in planning field investigations, a special attention was directed towards the volcanic rocks and volcano-clastites of acid composition, Paleozoic sandstones and schists, flysh sediments, deposits of red and white bauxites, and Quaternary sediments (sands, clays, peats), for which there are indications they could contain minerals with elevated concentrations of U, Th and K. Less attention was given to carbonates (limestones, dolomites and marls) and to volcanic rocks of basic character.

Four geotectonic zones, with distinctive geological evolution during the last 200 million years, could be clearly recognized in Montenegro (Mirkovic et al. 1985), as presented in Figure 1. They are known as the Adriatic-Ionian Zone (JZ), the Budva-Cukali Zone (BZ), the High Karst Zone (VK), and the Durmitor Tectonic Unit (DTJ). The metallogenic zones in Montenegro correspond to these geotectonic units.

The coastal areas of the town of Ulcinj and partly of the towns of Tivat and Herceg Novi belong to the JZ zone, which is composed of Upper Cretaceous limestones, dolomites, dolomitic limestones; Middle Eocene foraminifer limestone and flysch; Middle and Upper Eocene flysch sediments and Middle Miocene sands, sandstones, clays and lithothamnium limestones.

The BZ zone encompasses the narrow coastal areas of the towns of Bar, Budva, Kotor and partly Tivat and Herceg Novi. Its geological structure consists of Mesozoic carbonates and eruptive rocks; Anisian and Paleogene flysch.

The central and southern parts of Montenegro belong to the VK geotectonic unit, whose geological structure is predominated by Mesozoic carbonate sediments, with occurrences of red and white bauxite formations, Triassic volcanic rocks, Paleogene flysch sediments and Quaternary sediments.

The DTJ zone encompasses the north-eastern part of Montenegro. Its terrains are composed of Paleozoic and Lower Triassic clastites; Triassic and Jurassic carbonates, with significant presence of Middle Triassic and Upper Jurassic volcanic rocks and volcano-clastites; sediments of Neogene age and Quaternary formations.

A sampling grid and a number of surveyed localities are planned for each of these four geotectonic unites individually. In total, 135 localities were selected in this manner for field investigations, 29 of them belonging to the JZ zone, 20 to the BZ, 38 to the VK zone and 48 to the DTJ, as it is presented in Figure 1. Geological, pedological and morphological characteristics of these localities were then described in detail.

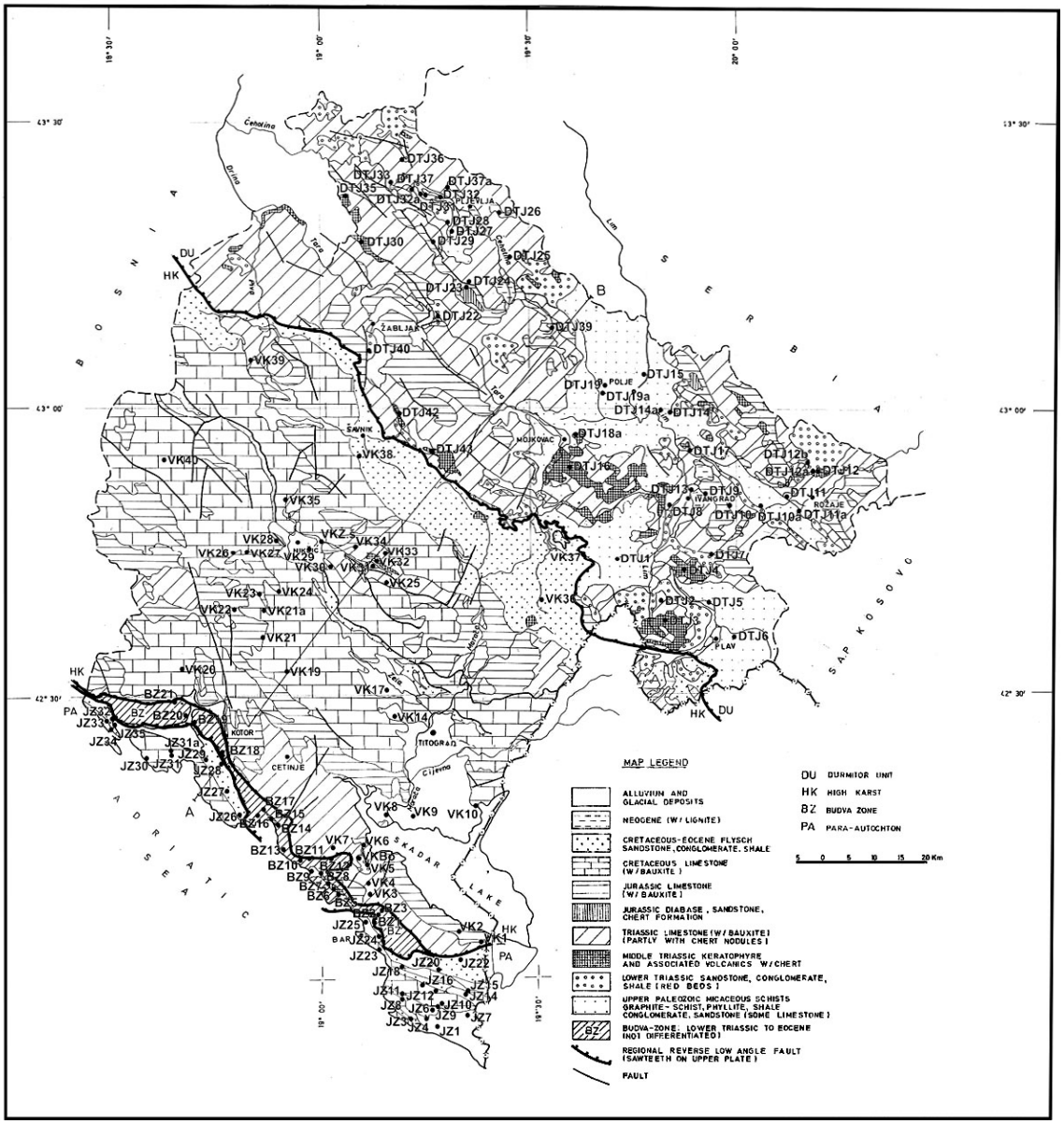

Fig. 1. Geological map of Montenegro, with indication of surveyed localities.

Dosimetry

Readouts of the gamma radiation count-rate meters CANBERRA Inspector (with NaI 1.5"x1.5" probe), VICTOREEN 190 SI (NaI 2"x2"), THERMO RadEye PRD (NaI probe) and THERMO FH 40 proportional counter were compared at several different sites under the same measuring conditions. This comparison has shown that the most consistent results were obtained with instruments VICTOREEN 190 SI and THERMO RadEye. Therefore, we decided to use the VICTOREEN 190 SI device for measurement of absorbed dose in the air, and to make control measurements, periodically, with the THERMO RadEye.

Dosimetry was then performed at all of the 135 selected localities, in the air 1m above the ground, during dry weather conditions. At each locality 10 measurements were carried out in an attempt to cover a broader area of the locality. The range of doses was then determined and the average dose-rate for the locality calculated on the basis of these 10 measurements. The GPS coordinates of the surveyed sites were also registered, as well as the geological and pedological observations.

Gamma spectrometry

Soil samples were taken, for a subsequent laboratory analysis, from all localities where an average dose-rate was found to be higher than 80 $nGyh^{-1}$. They were collected at the sites following a standard core sampling procedure (HASL-300). Sampled material was then ground, dried 8 hours at 100 °C, sieved through 2 mm mesh and packed into 1 liter Marinelli beakers. Analytical samples, prepared in this way, are counted 40 days later, after reaching radioactive equilibrium between ^{226}Ra and ^{222}Rn.

All these samples were analyzed using a low background gamma spectrometry system consisting of two HPGe detectors, which have 36% and 41% efficiency, 1.72 keV and 1.80 keV resolution (FWHM 1.33 MeV ^{60}Co), and 0.98 $imps^{-1}$ and 1.22 $imps^{-1}$ background count-rate at 40-2700 keV energy range, respectively. Activity concentrations of the following radioisotopes have been determined in the samples: ^{40}K (1460.75 keV), ^{232}Th (338.32 keV, 911.20 keV), ^{235}U (143.76 keV, 163.33 keV), ^{238}U (1001.03 keV), ^{226}Ra (295.22 keV, 351.93 keV, 609.31 keV, 1120.2 keV, 1764.4 keV), and ^{137}Cs (661.62 keV).

Results

An average dose-rate which is 50% higher than the country average was found at 43 localities: 5 in the JZ zone, 1 in the BZ, 18 in the VK, and 19 in the DTJ.

At only 10 of these localities the dose-rate is twice higher than the country average, i.e. $D \geq 110$ $nGyh^{-1}$. These localities and characteristics of their radioactivity - dose-rates in the air and activity concentrations in the ground, are given in Table 1.

Discussion

It is evident from Table 1 that all localities with the most elevated radiation background belong to the VK zone, except one which is in the DTJ. There are none in the geotectonic zones JZ and BZ, which completely cover the coastal area of Montenegro and its hinterland.

As the highest dose-rate in the air 1 m above the ground was found to be 192 $nGyh^{-1}$, and while all the others are bellow 150 $nGyh^{-1}$, it can be concluded that these

10 localities with the highest external radiation in Montenegro, in comparison with other known areas in the world with high natural radioactivity (UNSCEAR 2000), form part of those areas with a moderately elevated radiation background.

Table 1. Dose-rates in the air and activity concentrations in the ground at the localities with the highest terrestrial background radiation in Montenegro.

Locality	D (nGy/h)	^{40}K (Bq/kg)	^{232}Th (Bq/kg)	^{235}U (Bq/kg)	^{238}U (Bq/kg)	^{226}Ra (Bq/kg)	^{137}Cs (Bq/kg)
VK/7a	192	2329 ± 75	51.2 ± 1.8	2.3 ± 0.9	64.8 ± 13.1	31.2 ± 1.1	5.6 ± 0.2
VK/20	125	27.4 ± 1.8	194 ± 6	4.1 ± 1.2	113 ± 14	73.0 ± 2.3	20.2 ± 0.6
VK/21a	131	159 ± 5	126 ± 4	7.8 ± 0.8	137 ± 13	92.3 ± 3	20.2 ± 0.7
VK/23	137	109 ± 4	129 ± 4	4.1 ± 0.7	73.5 ± 15.5	76.1 ± 2.4	< 0.43
VK/24	134	164 ± 6	169 ± 5	9.4 ± 1.3	151 ± 20	151 ± 5	5.2 ± 0.3
VK/25	149	173 ± 6	196 ± 6	2.7 ± 0.5	66.0 ± 9.5	48.8 ± 1.6	0.79 ± 0.11
VK/27	115	145 ± 5	166 ± 5	16.2 ± 1.1	285 ± 19	239 ± 7	1.40 ± 0.15
VK/33	110	109 ± 4	201 ± 6	4.9 ± 0.7	114 ± 13	66.8 ± 2.2	2.95 ± 0.17
VK/35	112	146 ± 5	198 ± 6	2.0 ± 0.5	38.0 ± 9.6	43.4 ± 1.4	4.3 ± 0.2
DTJ/42	148	3341 ± 106	71.9 ± 2.5	2.8 ± 0.7	65.0 ± 34.4	33.2 ± 1.1	0.41 ± 0.15

Two of 10 localities with the highest terrestrial radiation background in Montenegro, VK/7a (Virpazar settlement) and DTJ/42 (Savnik settlement), are characteristic with the presence of andesite volcanic rock of Middle Triassic, one (VK/20 near the town of Niksic) with fluvio-glacial gravel and sand, while the other 7 localities are above deposits of white and red bauxites (VK/25, VK/27, VK/33, VK/35 in the surroundings of Niksic, and VK/21a, VK/23, VK/24 in the surroundings of the town of Cetinje, towards Niksic).

Table 1 shows, and the same is with the other 33 samples analyzed using gamma spectrometry, that activity concentrations of ^{137}Cs are relatively low, mostly far below a level of 20 Bqkg^{-1}, which was the contamination level of the territory of Montenegro before the Chernobyl accident. This means that cesium of Chernobyl origin, after more than two decades of presence in this terrain, partly decayed and significantly migrated from surface into deeper layers of soil, and it is definitely not a cause of elevated radiation doses at the investigated 43 localities.

The average activity concentrations of ^{40}K, ^{232}Th, ^{238}U and ^{226}Ra for 7 countries of South-East Europe are 433 Bqkg^{-1}, 35 Bqkg^{-1}, 52 Bqkg^{-1} (for 4 countries), 35.5 Bqkg^{-1}, respectively (UNSCEAR 2000), while these values for Montenegro are somewhat lower: 246 Bqkg^{-1} for ^{40}K, 24 Bqkg^{-1} for ^{232}Th and 29 Bqkg^{-1} for ^{238}U (Vukotic et al. 1997). Accordingly, Table 1 reveals that the source of elevated radiation doses at the localities VK/7a and DTJ/42, which are characterized with the presence of andesite rock, is a high concentration of K (up to 3341 Bqkg^{-1}) and, in a certain measure, of U in the ground. At the 7 localities, where the bauxite is predominant, the elevated contents of Th (up to 201 Bqkg^{-1}) and U (up to 285 Bqkg^{-1} of ^{238}U) in the ground are the cause. This is in accordance with an earlier investigation of radioactivity of Montenegrin bauxites (Vukotic 1981) which has proved high concentrations of U and Th in them, and also with investigations of radon (Antovic et al. 2007; Vukotic et

al. 2008) which have revealed that, in Montenegro, the highest indoor-radon level is in the town of Niksic (the main Montenegrin bauxite resources are on territory of this municipality), which is three times higher than the world average and two times higher than the average in the countries of South-East Europe.

Conclusions

The localities in Montenegro with the highest external radiation belong to those world areas with moderately elevated radiation background.

Cesium of Chernobyl origin, after more than two decades of presence in the terrains of Montenegro, partly decayed and migrated into deeper layers of soil, and is not a substantial cause of elevated radiation doses.

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Identifying the presence of orphan radioactive sources in dwellings from the vicinity of former uranium mines (Portugal): a methodological approach

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Abstract

Several radiological measurements were taken in two dwellings in the close vicinity of a former uranium mine (Urgeiriça, Central Portugal), in order to search for the presence of radioactive materials resulting from the mining activities. For the purpose, indoor radon concentration, gamma radiation flux, absorbed dose, radon gas flux from the floors and radon concentration measurements in crawl spaces were carried out.

The results showed important differences between the several parameters measured for both dwellings, reaching sometimes a few orders of magnitude. In one case, radioactive waste was identified in the crawl space, with the presence of these materials contributing to an excess dose of about 50 mSv/year, assuming as background the values measured in the second dwelling where no radioactive waste was found.

The methodology developed for this study proved to be a time/cost-effective procedure, capable of being applied in buildings of different construction types.

Introduction

For nearly one century, 61 uranium mines were exploited in central Portugal, generating 13 million tones of different kinds of wastes, accumulated normally in the vicinity of the exploitations. Over the years, some of these wastes were used as construction materials, usually in roads, but sometimes also in residential buildings; in this last case, the dose increase due to the exposure to ionizing radiation can be significant.

To assess the possible use of mining wastes in residential constructions, as well as the associated dose increase resulting from exposure to ionizing radiation, a methodology capable of being applied in buildings of different construction types and producing a time/cost-effective discriminating procedure was developed and tested. The methodology accounts for the challenge of discriminating between high radiation levels of purely natural origin, since the region is also radon prone, and those induced by the possible presence of radioactive materials resulting from mining activities.

Two dwellings located in the vicinity of the Urgeiriça mine (central Portugal) were used for test purposes. This was the most important uranium exploitation in Portugal, and also the place where industrial facilities were used to process ores extracted from all Portuguese mines. As a result, here can be found the largest amounts of mining wastes produced.

The uranium-bearing ore of Urgeiriça is of vein-type, striking N60ºE; it contains pitchblende and uraninite, as well as several secondary uranium minerals (Neiva, 1968). Hercynian porphyritic medium to coarse grained biotite granites are the dominant rocks observed in the area; non porphyritic two-mica granite rocks, as well as tertiary sedimentary, also occur in the region. Granites show uranium contents in the range 6 to 15 ppm, and soil gas radon measurements comprised between 29 and 593 kBq.m^{-3}, with a geometric mean of 110 kBq.m^{-3} (Neves et al. 2003). All granites are intersected by several sets of faults, with NNE to ENE dominant directions and frequently showing some degree of uranium enrichment (some dozens up to a few thousand ppm), resulting from the presence of secondary uranium phosphates (e.g. autunite, torbernite). In these faults and in their vicinity, soil gas radon measurements are frequently in the order of several hundred thousand up to a few million Bq.m^{-3}.

The referred geological setting results in a radon prone region, where indoor radon concentrations are in excess of recommended values for a large proportion of dwellings. In previous work, Neves et al. (2003) have studied 196 dwellings of the region with passive detectors, and obtained a geometric mean of 291 Bq.m^{-3} for indoor radon. Thus, distinguishing between natural or anthropogenic sources of indoor radon can be a challenge in this region.

Material and methods

In both dwellings used as a test case, a set of radiological data was collected, including the evaluation of indoor radon, gamma ray flux, absorbed dose, radon gas flux from the floors and also radon concentration in sub-slabs and crawl spaces.

Indoor radon concentrations were evaluated with CR39 detectors (n=7), exposed in several compartments for approximately 3 months; VOID labels were used to ensure that the detectors were not moved during the period of measurement (Fig. 1). After collection, the detectors were etched in a sodium-hydroxide solution during 270 minutes, at a temperature of 90ºC. The density of alpha impacts was estimated with an automated track-counting system (Radosys™), and the results converted to Bq.m^{-3} using appropriated factors, determined from the exposure of detectors in calibrated radon chambers.

Fig. 1. CR39 passive detector secured with a VOID label.

The gamma radiation flux from pavements, walls and ceiling materials of all rooms were measured using a NaI Saphymo™ SPP2-NF gamma scintillation detector. The density of measurement points obtained in each room was controlled by the absorbed dose data; where this value was high, indicating the possible presence of radioactive materials, a more accurate screening was carried out, thus locating radioactive sources, its intensity and size. A total of 102 measurements were taken; results are given in cps.

The determination of the absorbed dose (external radiation) was carried out with an Exploranium™ GR130G, positioned at a height of approximately 1 meter from the floor. The values are given in µGy.h-1 and each measurement is representative of approximately 16 m2. A total of 16 measurements were performed. The purpose of this technique was to obtain an estimate of the environment gamma radiation that can immediately indicate the presence of radioactive materials, in the floor or walls of the analyzed room.

To determine radon gas flux from the floors, a radon-box was used as an accumulator, which remained sealed to the floor for 24h with the open surface downwards. The radon concentration was then measured with a Genitron-Saphymo™ AlphaGuard Pro (Fig. 2, left side) and radon gas flux from the floor/atmosphere interface were subsequently calculated. A total of 5 measurements were taken; results are given in Bq.m-2.h-1.

Radon concentration in crawl spaces was also measured with a Genitron-Saphymo™ AlphaGuard Pro, using appropriate probes to collect air samples (from 1.5m to 4.5m) through the outside vents (Fig. 2, right side). A total of 6 measurements were taken and the results are given in $Bq.m^{-3}$.

Fig. 2. Radon-box technique measurement with Genitron-Saphymo™ AlphaGuard Pro (left) and radon concentration measurement in a crawl space (right).

Results

Both dwellings were built in the 1950's with the same materials, by the same constructor and suffered minor refurbishment work over the years. Their plans are slightly different as a result of their size, but the construction techniques and project are basically the same.

Since both houses have wooden floor, they were built with crawl spaces beneath the floor, in some places more than 2 meters high.

Dwelling #1 is a two storey-house with 8 rooms in the ground floor and 2 rooms in the first floor. Indoor radon concentration was measured with CR39 detectors in the ground floor rooms D1 (living room), D2 (bedroom), D3 (bedroom) and D4 (dining room); results shown in table 1.

The minimum values for the absorbed dose, gamma radiation flux, radon flux from the floor and radon concentration in crawl space values were 0.20 μGy.h^{-}1 (D3), 250 cps (D7), 38.6 Bq.m^{-2}.h^{-1} (D1) and 5720 Bq.m^{-3} (D1), respectively. The highest absorbed dose, gamma radiation flux, radon flux from the floor and radon concentration in crawl space values were 0.69 μGy.h^{-}1 (D1), 1600 cps (D1), 314.7 Bq.m^{-2}.h^{-1} (D4) and 14160 Bq.m^{-3} (D6), respectively.

Table 1. Summary of the values measured for each room (mean values) in dwelling #1; n.d.-not determined; A-external radiation; B-gamma radiation flux; C-radon flux; D-radon concentration in crawl space; E-indoor radon concentration.

Room	A [μGy.h^{-1}]	B [cps]	C [Bq.m^{-2}.h^{-1}]	D [Bq.m^{-3}]	E [Bq.m^{-3}]
D1	0.60	859	38.6	7614	2948
D2	0.37	537	154.7	11341	3405
D3	0.20	310	60.1	n.d.	2371
D4	0.25	310	314.7	n.d.	2435
D6	0.43	838	n.d.	14160	n.d.
D7	0.40	650	n.d.	n.d.	n.d.
D8	0.31	453	24.2	n.d.	n.d.

Dwelling #2 is a one storey-house with 5 rooms built over a crawl space. Indoor radon concentration was measured with CR39 detectors in rooms D1 (bedroom), D2 (kitchen), and D4 (living and dining room); results are shown in table 1.

The minimum values for absorbed dose, gamma radiation flux and radon concentration in crawl space values were 0.14 μGy.h^{-}1 (D5), 160 cps (D1 and D5) and 1528 Bq.m^{-3} (D2), respectively. The highest values for absorbed dose, gamma radiation flux and radon concentration in crawl space values were 0.17 μGy.h^{-}1 (D3), 200 cps (D3) and 1629 Bq.m^{-3} (D3), respectively.

Table 2. Summary of the values measured for each room (mean values) in dwelling #2; n.d.-not determined; A-external radiation; B-gamma radiation flux; C-radon flux; D-radon concentration in crawl space; E-indoor radon concentration.

Room	A [μGy.h^{-1}]	B [cps]	C [Bq.m^{-2}.h^{-1}]	D [Bq.m^{-3}]	E [Bq.m^{-3}]
D1	0.15	175	n.d.	n.d.	351
D2	0.15	175	n.d.	1528	356
D3	0.17	188	n.d.	1629	n.d.
D4	0.15	177	n.d.	n.d.	312
D5	0.14	177	n.d.	n.d.	n.d.

Discussion

Given these results, it was possible to identify the presence of allochthonous radioactive materials in dwelling #1. These were only used in the crawl spaces beneath the floor, specially on it's dirt floor, foundation walls and footing; it's detection was possible due to the measurements of gamma radiation flux (maximum of 1600cps) and external radiation data (maximum of 0.69 μGy.h^{-}1).

Radon concentration in crawl spaces also showed very high values (maximum of *ca*. 14000 Bq.m^{-3}), especially if we take into account the mean height of these spaces, which is around 2m, and the fact that some degree of natural ventilation exists.

Given that no indications of the presence of radioactive wastes was found in dwelling #2, its radiological values were assumed as representative of background values, since they also correlate well with results from others studies carried out in similar geological settings where no mining activities were carried out (Pereira et al. 2003).

Conclusions

The results showed important differences between the several radiological parameters measured, reaching sometimes a few orders of magnitude. In dwelling #1, radioactive waste was identified in the sub-slab, with the presence of these materials contributing to an excess in dose of about 50 mSv/year, assuming as background the values measured in the second dwelling, where no radioactive waste was found. The very high indoor radon levels are the main contributors to this excess value (more than 95% of the total dose).

The methodology developed for this study proved to be a time/cost-effective procedure, and was subsequently applied to more than 75 dwellings of the region with good results.

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Bioremediation of land contaminated by radioactive material

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Abstract

Objectives: Radionuclide pollution arises as a result of many activities, largely industrial, such as mining and the provision of nuclear energy. These pollutants are discharged into the atmosphere and aquatic and terrestrial environments and may reach high concentrations, especially near the site of entry for point source emissions, and/or be transported between different environmental compartments. Metallic radionuclide has also entered the environment as a result of weapons-testing and accidents such as Chernobyl. The effects of radionuclide in ecosystems are not well understood, although a degree of understanding exists over their fate; it is primarily concerns over transfer along aquatic and terrestrial food chains that are of current economic and public-health significance. Microbial biotransformations of metallic radionuclides are of great importance in the biosphere and several have additional applications for bioremediation. Reactions mediated by microorganisms include solubilization from organic and inorganic complexes, compounds and minerals by the production of acids or chelating agents. The aim of our study consisted in elaboration of the new biotechnological method for environmental pollution risk reducing.

Methods: Screening the importance of soil micro-organisms on radionuclides mobility have been performed.

Results and conclusions: The influence of microorganisms on the environmental fate of radionuclides was elucidated, using some nonpathogenic strains of Penicillium sp. and Mucor sp., active producers of extra cellular pectolitic enzymes. Higher degree of radio nuclides insoluble compounds solubilizition, especially cobalt compounds, was observed under the influence of investigated strains in vitro (Invention nr. 3657 MD). Such mechanisms are important components of radionuclide biogeochemical cycles and should be considered in any monitoring analyses of environmental radionuclide contamination.

Establishment of research network for natural radiation exposure studies in Asia

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Abstract

A new project entitled gConstruction of natural radiation exposure study network h has been recently adopted in the Program of Promotion of International Joint Research under the Special Coordination Funds for Promoting Science and Technology operated by the Ministry of Education, Culture, Sports, Science and Technology of Japan. Eight institutions are involved in this project and the project will continue until March, 2012. The aims of the project are to assess the dose for natural radiation exposures using state-of-the-art measurement techniques in four Asian countries (China, India, Korea and Thailand) and their outcomes will be distributed worldwide. Conventional measurement techniques will be improved and be optimized. More scientific data and results will be obtained throughout this project. In particular, the following advanced technologies for inhalation exposures will be introduced:

1. Discriminative measurements of radon (^{222}Rn) and thoron (^{220}Rn) gases,
2. Evaluation of thoron decay products concentration,
3. Simple but effective particle size distribution measurements.

The measurement of the natural radiation background in a salt mine

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Abstract

The Unirea Salt Mine is situated at a depth of 208 meters beneath the surface of the earth that corresponds to a water-equivalent thickness of about 560 meters. It has a remarkable stability of microenvironment, characterized by a constant temperature over the years of 12.5 ±0.5 ºC and a relative humidity of 60-65 %.

In order to set up a calibration laboratory in this mine, for the measuring systems dedicated to the dosimetric measurements and environment, the natural radiation background had to be measured.

The measurements were made using two different dosimetric systems: An electronic type, consisting from two ratemeters: an Eberline FH 40 GL 10 and an AUTOMESS 6150 dose ratemeter with external scintillation probes; A TLD dosimetric system SD-TL type, which consists of the TL laboratory reader-analyze, 770 A type and thermoluminiscent detectors by LiF:Mg, Cu, P. The results obtained with the two systems are in good agreement.

Introduction

The measurement of the absorbed dose or of the integral ambient dose equivalent, and their rates, at the level of natural radiation background is a basic aspect of the dosimetry of the environment. In this case, an important problem to be solved in the calibration of the dosimetric measuring systems, is the low level of the measuring range, which has to include the values corresponding to the natural radiation background (50÷100) nSv·h-1.

In order to reach the adequate conditions to perform such calibrations, an ultralow level background laboratory is necessary. So, the "Horia Hulubei National Institute R&D for Physics and Nuclear Engineering" (IFIN-HH) decided to develop an ultralow level radiation background in the former Unirea salt mine, located in the town Slanic, at a distance of about 100 km from Bucharest.

The Unirea Salt Mine is located at a depth of 208 meters beneath the surface of the earth; taking into account the geological structure of the soil in the area of the mine, is was found that this depth corresponds to a water equivalent thickness of about 560 m, Margineanu et al. (Margineanu, 2008).

The salt mine is characterized also by a remarkable stability of the microclimate: a constant temperature, measured over several years, of 12.5± 0.50C and constant

relative humidity, measured in the same conditions, of 60-65%. Of course, in order to set up a calibration laboratory in this mine, the first step was to perform accurate measurements of the absorbed dose and of the integral ambient dose equivalent and their rates, corresponding to the natural background in a hall where the new laboratory is located.

Material and methods

In order to perform accurate measurements of integral ambient dose equivalent $H^{*}_{(10)}$ expressed in mSv and of the rate $H^{*}_{(10)}$, expressed in nSv h-1 , in the area were the laboratory was located, two different dosimetric system were chosen:
Two electronic dose ratemeters, with external scintillation probes;
One TLD dosimetric system, SD-TL type.

a) As for electronic dose ratemeter, we used many instruments and finally we have selected two of them:
   - an Eberline FH 40 GL 10 dose ratemeter, with the external probe FHZ 5023E. This probe has a large scintillation NaI detector of 3x3 inch. We calibrated it in terms of absorbed dose per impulse, with a value of the calibration factor of: F = (0.17±0.03) nGy·imp-1. The energy dependence of the response instrument in the ratemeter mode, is of maxim ±30% for the whole measured energy range. The conversion of units from absorbed dose, Gy, to ambient equivalent dose, Sv, was done by considering a conversion factor f = 1 Sv/Gy. It was used only for preliminary measurements.
   - a thermo Automess 6150, with the external probe 6150 AD-6/H having also a scintillation detector.

This instrument, metrologically certified by its producer, has the following characteristics, according the technical specification
   - measuring range (digital): 0.01μSv·h-1÷9.99 mSv·h-1, with a declared uncertainty of 10%;
   - energy range: 60 keV-1.3MeV; energy dependence of the response in this range: ±30%.

   The reported results were obtained with this instrument.

   The TLD dosimetric system, SD-TL type, consists of TL reader-analyzer, model RA-94 and the thermoluminiscent dosemeters with commercial thermoluminescent detectors type LiF:Mg,Cu,P, known as GR 200A. The dosemeter for environmental monitoring, designed and made in our laboratory, consists of a plastic cylindrical container with the external dimensions: Φ=50 mm and h = 9 mm. Each dosemeter is provided with three detectors. A detailed description of the system and of its dosimetrical characteristics is given in the paper by Stochioiu et al. (Stochioiu, 2009).

Measurement conditions

The electronic dose ratemeters measuring directly the dose equivalent rate $\dot{H}^{*}_{(10)}$, were used in several pre established significant locations inside the laboratory. The TLD

system is calibrated in units of dose equivalent, $H^{*}_{(10)}$. The dose equivalent rate is calculated as the ratio of dose equivalent, mSv, and exposure time, h. In our case, two series of exposure, for periods of 39 d and 93 d were performed. In the case of the TL dosemeters, when processing the measured values, we took into account their irradiation during the transportation from Bucharest to the salt mine, and an appropriate correction was done. The reported values are the means obtained from the two exposition intervals.

For the purpose of the comparison of measurements and the establishment of consistence of results, the locations for the two types of measurements, electronic ratemeters and TLD system, were the same.

Results

Table 1 represents the measured values of the ambient equivalent dose rate [nSv·h-1], obtained with the two systems, respectively the electronic AUTOMESS 6150 and the TLD system SD-TL, in four representative locations and their comparison. These points were selected as the most representative from a large number of measurements areas of the mine.

Table 1. Mean ambient equivalent dose rate values , measured with the two systems and their comparison

Location	Mean ambient equivalent dose rate [nSv·h-1], AUTOMESS 6150 system	Mean ambient equivalent dose rate[nSv·h-1], TLD, SD-TL system	Difference, %
1	1.17±0.42	1.49±0.41	27
2	2.22±0.42	2.15±0.82	3
3	1.87±0.57	1.55±0.30	17
4	2.56±0.55	2.14±0.32	16

The reported uncertainties were calculated from the instruments' calibration factor uncertainties, respectively 10% and 7.5% and additional uncertainties: nonlinearity outside the certified interval, statistical uncertainty, etc.

Discussion

Such as it can be seen from the Table 1, two conclusions can be drawn:

1. The levels of background inside the underground laboratory are about 25 - 50 times less than the usual ground level, (50 -100) nSv h-1. The explanation is that the cosmic radiation is strongly attenuated by the rocks. The registered values are due to the residual content of radioactive elements existent in rocks, whose influence is also reduced by the existence of thick pure salt walls surrounding the laboratory. The influence of salt purity over the influence of 226Ra - 222Rn decay chain and of 40K was reported by Cristache and al. (Cristache, 2009), by using classical chemical analyses methods, Nenitescu (Nenitescu, 1982) and Neutron Activation Analysis.
2. The results obtained with two independent and different as operating principle dosimetric systems are in agreement within their measurement uncertainties.

Conclusions

– The low level of background in an underground laboratory was systematically studied, in order to characterize the environmental dose of the new laboratory.
– Two independent systems, an electronic and a TLD one were used. Their operating principles are different, but the results are in good agreement, what demonstrates the consistence of measurements.

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Personal monitoring of aircrew exposed to cosmic radiation

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Abstract

Everybody who flies frequently is exposed to elevated levels of cosmic radiation of galactic and solar origin and to secondary radiation produced in atmosphere. The annual average radiation dose to aircrew may become similar or even large than that of other occupationally exposed groups. The assessment of effective dose for aircrew members was performed by using programs EPCARD*. Altogether about 180 pilots were monitored during 2007 year and about 500 air crew members were monitored during 2008 years. In 2007 annual average effective dose (E) was 2.5 mSv and maximum personal dose was 4.0 mSv compared to next year annual average 2.3 mSv and maximum 3.7 mSv. Mobile Dosimeter Unit (MDU) Liulin Si spektrodosimeter and Exploranium GR 135 have been used for experimental measuring of levels of cosmic radiation on the airplane board.

Additionally to personal cosmic radiation monitoring, small human trial was conducted to monitor life style, nutrition and various clinical, biochemical, genotoxicity, immune and molecular markers from blood samples of exposed as well as control subjects and to investigate the possible effects of radiation exposure on human health.

Introduction

The recommendation of International Commission on Radiological Protection (ICRP) No. 60 from 1991 year (ICRP 60) included the exposure of the aircrew from the cosmic radiation among the occupational exposure. Council Directive 96/29/Euratom (CD96/29), the Basic Safety Standards (BSS) has been published on May 13, 1996 laying down basic safety standards for the health of workers and members of the general public against the dangers arising from ionizing radiation(BSS 1996). Article 42 of the directive on the protection of aircrews from EU member states have been transposed into the national legislation directives. The directive has been also incorporated into the Slovak regulation since 2000. Ministry of Health of Slovak

Republic funded the project "Radiation load of aircrew and biomonitoring of health risk of combined exposure to radiation and stress factor" which was conducted from 2006 to 2008. The main aims of the project were to introduce radiation monitoring (periodical monitoring system build on experimentally measurements as well as theoretically confirmed effective dose assessment) and to identify the effect of exposure on biological markers of genetic stability, DNA repair, oxidative stress and on immune markers. This contribution presents results of radiation monitoring.

Material and methods

The EPCARD* calculation program was used for evaluation of aviation personnel radiation load exposure. We created software for computing of data from large number of monitored members of aircrew. The interactive database was created for data on occupational exposure the aviation crew members for every month, as well as for annual exposure. This database enables data elaboration and analysis, the statistical evaluation, and the assessment of other radiation protection quantities.

Onboard aircraft exposure measurements were provided by Mobile Dosimeter Unit (MDU) – Liulin Si diode based spectrodosimeter and gamma spectrometer Exploranium GR 135. Measurements have been performed on an B737 aircraft Sky Europe Airlines at an altitude 12 000 m.

Results

Estimate of personnel radiation load

In 2007 we observed the radiation load of 181 pilots. The results show that the average annual effective dose is 2.5 mSv, the maximum annual effective dose is 4.0 mSv and the collective dose is 460.6 mSv.

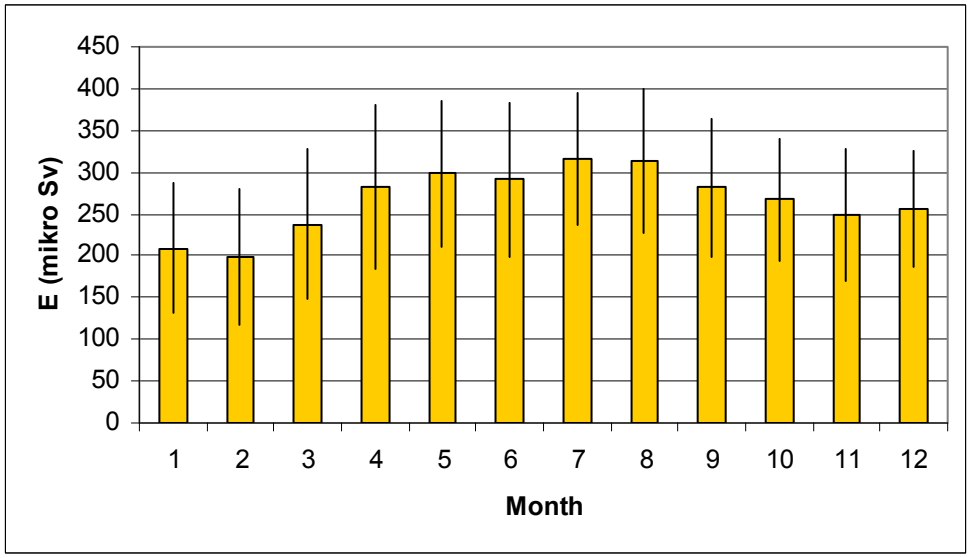

Fig. 1. Average monthly effective dose – pilots 2007.

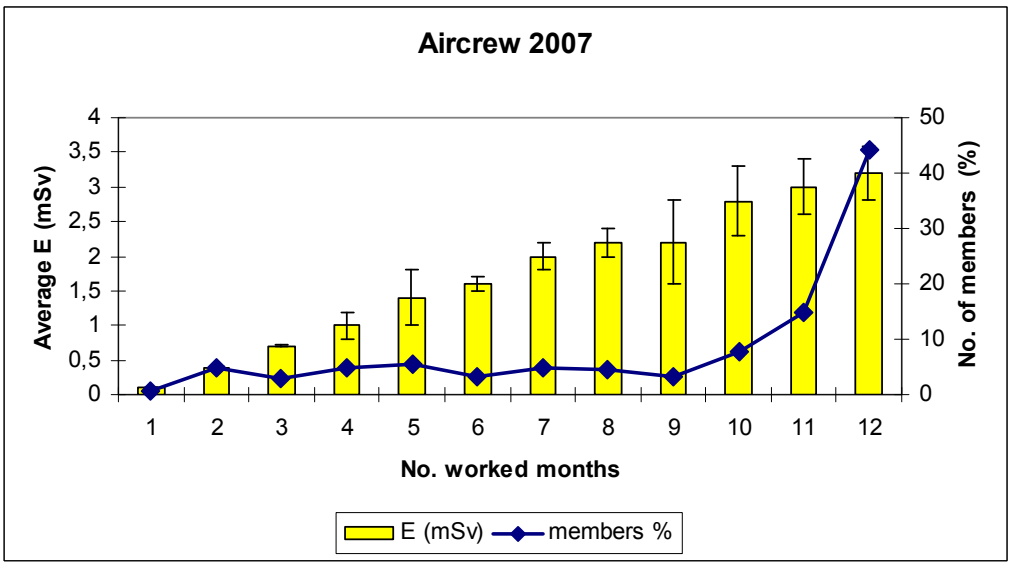

Fig. 2. The average effective dose by the number of months worked during the year 2007.

In 2008, we monitored the radiation load of 183 pilots. The results show that the average annual effective dose is 2.5 mSv, the maximum annual effective dose is 3.7 mSv and the collective dose is 463.6 mSv.

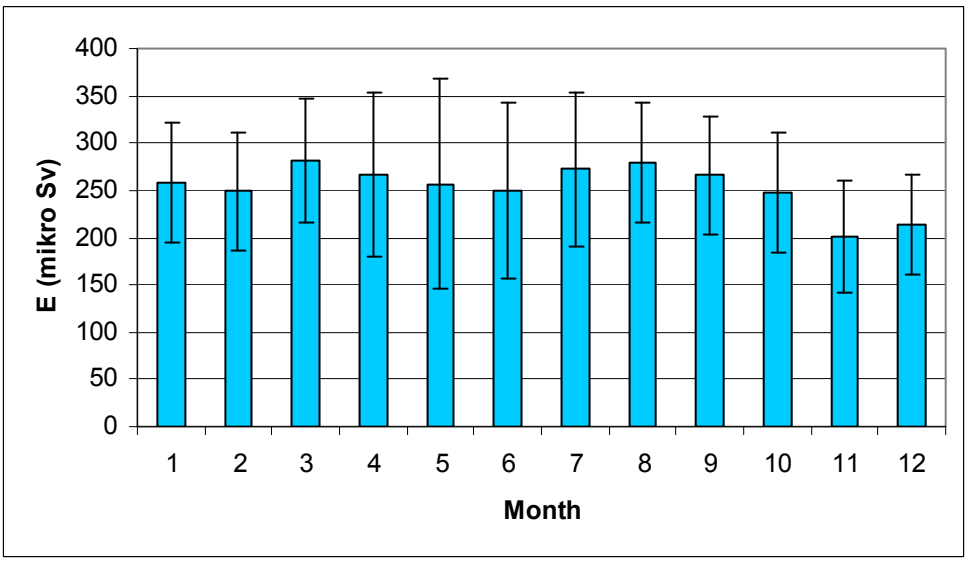

Fig. 3. Average monthly effective dose – pilots 2008.

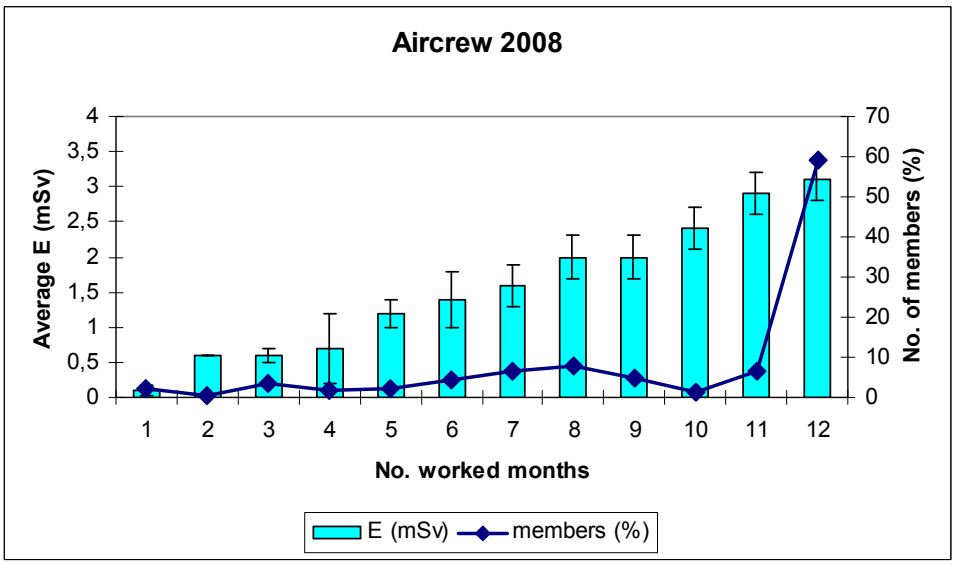

Fig. 4. The average effective dose by the number of months worked during the year 2007.

In 2008 we watched the radiation load 316 stewards too. The results show that the average annual effective dose is 2.2 mSv, the maximum annual effective dose 3.7 mSv and the collective dose is 693.1 mSv.

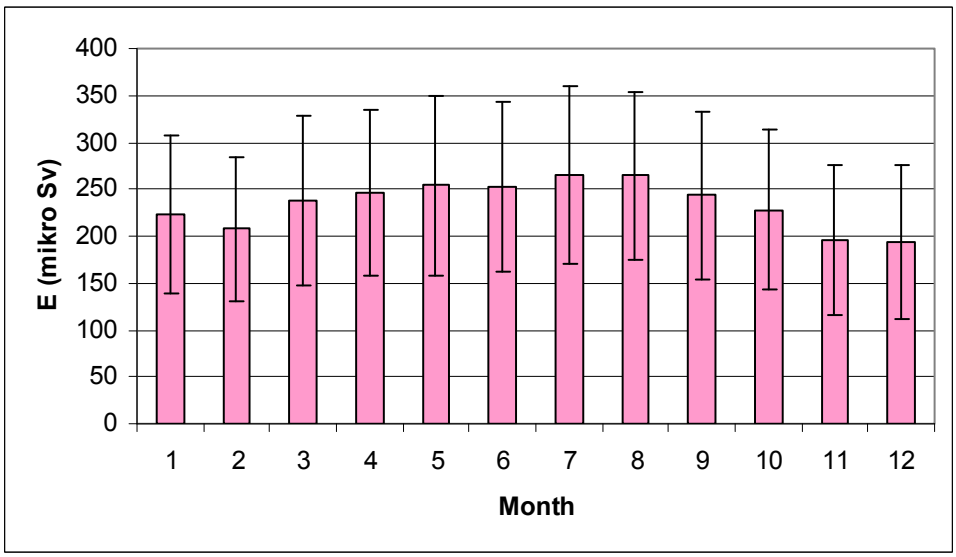

Fig. 5. Average monthly effective dose – stewards 2008.

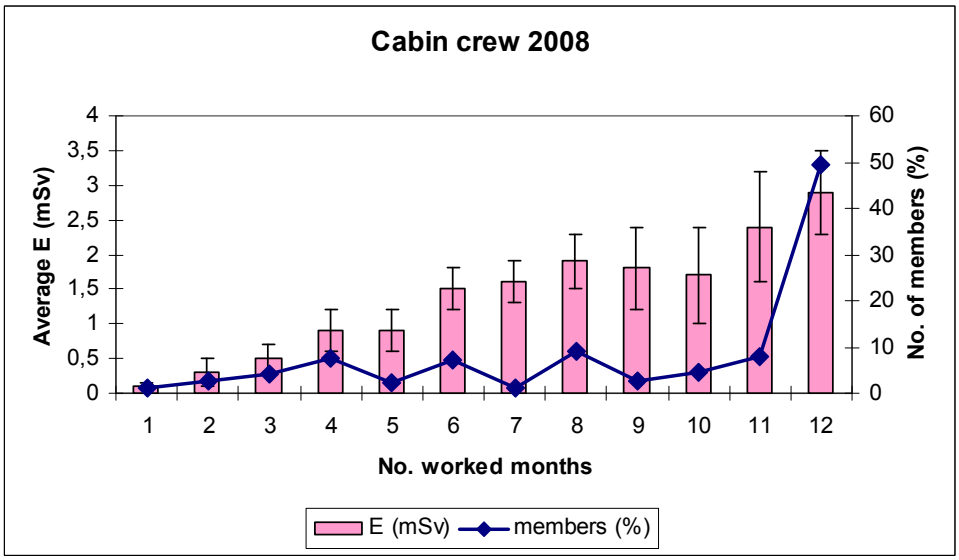

Fig. 6. The average effective dose by the number of months worked during the year 2008.

Table 1. Radiation load of aircrew members.

Year	Air crew Members	No members	Average E ± STD [mSv]	Maximum E [mSv]	Collective E [mSv]
2007	Pilots	181	2.5 ± 1.0	4.0	460.6
2008	Pilots	183	2.5 ± 0.9	3.7	463.6
2008	Stewards	316	2.2 ± 1.0	3.7	693.1

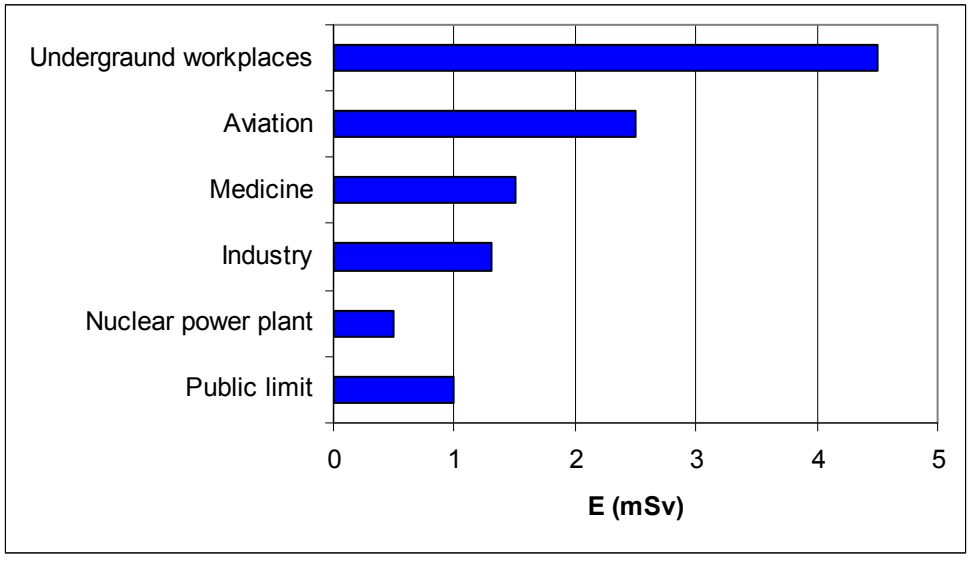

Fig. 7. Comparison of annual effective dose from different occupational exposure in Slovakia (Böhm 2007).

Experimental results

Table 2. Experimental data of ambient dose equivalent (May 2008).

Fly	Departure	Arrival	Cruise	H*1 [nSv]	H*1 [nSv]
BTS – FCO	12:52 13.05	14:12 13.05	1 h 20 min	200	1 747
BTS – LTN	17:40 13.05	19:45 13.05	2 h 05 min	410	4 208
BTS – MAN	12:37 14.05	14:50 14.05	2 h 13 min	500	4 382
BTS – KSC	09:03 15.05	09:33 15.05	0 h 30 min	25	283
KSC - DUB	10:20 15.05	13:20 15.05	3 h 00 min	780	7 025
BTS - BHX	12:00 16.05	14:10 16.05	2 h 10 min	470	3 824
BTS – HRG	20:10 17.05	23:45 17.05	3 h 35 min	640	5 231
HRG - BTS	01:10 18.05	05:15 18.05	4 h 05 min	730	5 869
BTS - ORY	06:38 26.05	08:50 26.05	2 h 18 min	460	3 460
BTS - ORK	09:45 27.05	12:22 27.05	2 h 37 min	710	6 123
ORK - BTS	13:30 27.05	16:00 27.05	2 h 30 min	690	5 771

BTS, FCO, etc - IATA code of airport (BTS – Bratislava, FCO – Rome, LTN – London, MAN - Manchester, KSC – Košice, DUB – Dublin, BHX – Birmingham, HRG – Hurgada, ORY – Paris, VIE – Vienna, ORK – Cork
Departure GMT +2
*H*1 – ambient dose equivalent gama rays (Exploranium 135)*
*H*2 - ambient dose equivalent neutrons and heavy charged particles (Liulin)*

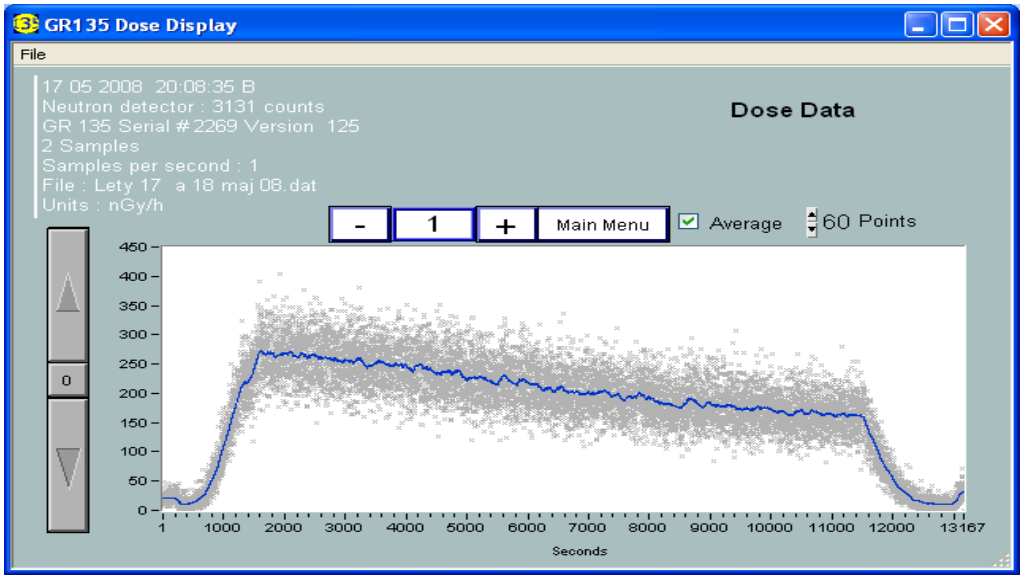

Fig. 8. Data from Exploranium 135, fly Bratislava – Hurgada.

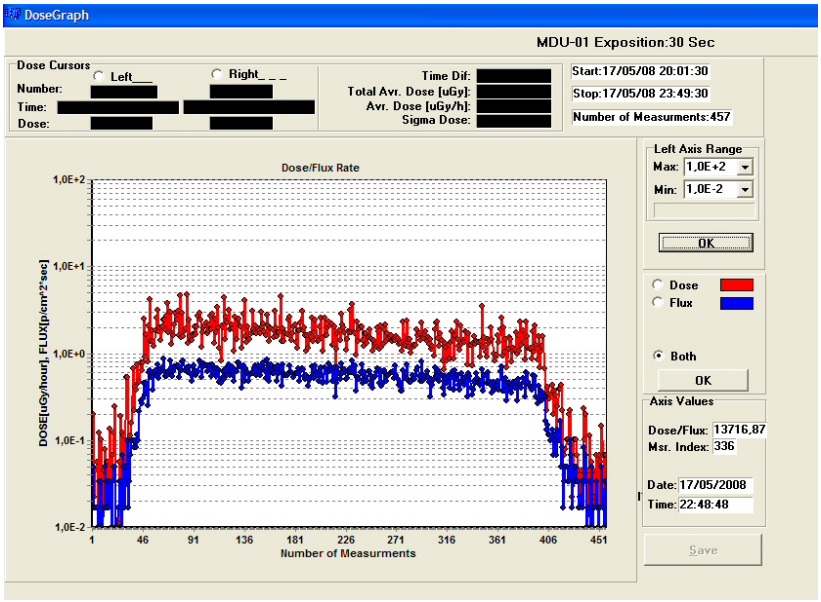

Fig. 9. Data fromMDU Liulin, fly Bratislava – Hurgada.

Discussion

Annual effective dose to aircrew members who had been working more than 3 months during the year always exceeds 1 mSv. In accordance with Article 42 Directive 96/29 Euratom - Each Member State shall make arrangements for undertakings operating aircraft to take account of exposure to cosmic radiation of air crew who are liable to be subject to exposure to more than 1 mSv per year. Experimental measurements and estimates of personal radiation load from exposure to cosmic radiation were carried out during the period of minimum solar activity. We assume that during the period of increased solar activity may be higher annual effective dose. The graphic outputs from used devices show that the measured ambient dose equivalent and the intensity of cosmic radiation are dependent not only on traffic levels but also on the geographical location. Cosmic ray intensity increases towards the magnetic poles of the Earth and decreases toward the equator in the same altitudes. This is due to the different intensity geomagnetic field at the Earth's equator and poles. Magnetic field of Earth protects us from the increased intensity of cosmic radiation. We use this fact to a large extent possible to optimize the radiation load of personnel planning for deployment of staff to the route. Reducing of radiation load of aircrew members cannot be achieved by shielding in aircraft construction or using of protective shielding devices. There is the only way optimization - to take into account the assessed exposure when organizing working schedules with a view to reducing the doses of highly exposed aircrew. During the flight planning it should be take into account that a dose rate of cosmic radiation grows with the increase of latitude and flight level.

Conclusions

The project allowed for the first time in Slovakia to carry out monitoring of personnel radiation load from cosmic radiation. The results obtained confirm the eligibility of the start up of radiation monitoring Slovak air carriers and justify the need for its continuation. The obtained results show that annual effective dose to members of air

crews is highly significantly higher in comparison with radiation dose of workers exposed in other workplaces.

Acknowledgements

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