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Characteristics of the natural radioactivity of the underground laboratories in the Baltic Sea Region participating in the BSUIN and EUL projects

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Abstract. Underground laboratories (ULs) offer more and more opportunities for their usage. Still, one of the most critical parameters describing ULs is their natural radioactivity. Therefore, the article compares the six ULs of the BSUIN (Baltic Sea Underground Innovation Network) and EUL (Empowering Underground Laboratories Network Usage) projects regarding their natural radioactivity. Measurements include in situ and laboratory analysis of the collected rock and water samples, using various nuclear spectrometry techniques. The lowest level of natural radioactivity characterizes salt deposit is in the Conceptual Lab development coordinated by KGHM Cuprum R&D centre.

1 Introduction

Underground laboratories are currently gaining great interest. They are used not only for research in physics and biology but also for the production of plants and mushrooms and for mining, industry, business, and tourism purposes (Bettini, 2007, 2012; Pandola, 2011; Coccia, 2010; Ianni, 2017; Lampe et al., 2016; Laubenstein, 2017; Boreham et al., 2015; Paling, 2020). However, in order for such places to be used safely, they must be adequately tested for several issues (natural radioactivity, structural stability, human safety). One of the most critical parameters characterizing underground locations is their natural radioactivity. It is essential not only because various experiments in physics and astrophysics (i.e., searching for dark matter, double beta decay studies) could be conducted there but also from the point of view of safety and radiological protection of people staying and working there.

For this purpose, the BSUIN (Baltic Sea Underground Innovation Network) project (BSUIN, 2021) was created in 2017, bringing together six partner underground laboratories and two ULs of associated organizations located in the Baltic Sea region. Its main goal was to develop the possibilities of underground laboratories to improve their innovative potential service and create a network in the Baltic Sea Region providing users, including small and medium-sized enterprises, with easy access and the environment business development and innovation. This project was completed with great success in 2020, and its continuation is currently carried out in the EUL (Empowering Underground Laboratories Network Usage) project (EUL, 2021). INTERREG Baltic Sea Region funds fund both projects (INTERREG, 2021). Figure 1 shows the Baltic Sea region map with the underground laboratories participating in the BSUIN and EUL projects marked.

This paper presents an overview of the underground laboratories participating in the BSUIN and EUL projects, emphasizing the characterization of natural radioactivity.

2 Underground laboratories BSUIN and EUL projects

2.1 Äspö Hard Rock Laboratory, Sweden

Äspö Hard Rock Laboratory is located at Äspö north of Oskarshamn (in the Simpevarp area in the municipality of Oskarshamn). The main task of Äspö HRL is to conduct research on the storage of spent nuclear fuel from all nuclear power plants operating on the territory of Sweden. Therefore, UL resembles a place where such nuclear fuel is stored (although it is not there) at a depth of 500 m underground

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Figure 1. The map of the Baltic Sea Region showing the partner underground laboratories involved in the BSUIN and EUL projects (BSUIN, 2021).

in specially designed copper canisters surrounded by bentonite clay. Äspö cooperates with many institutions in the world operating in a similar industry. The owner of Äspö HRL is a Swedish Nuclear Fuel and Waste Management Co (SKB) (BSUIN, 2021; FQ, unpublished data, 2020; Äspö HRL, 2021).

There are many tunnels and rooms on several levels in the laboratory. The main 5 km long Äspö HRL tunnel spirals down to a depth of 460 m from the Simpevarp peninsula to the southern part of Äspö (FQ, unpublished data, 2020). The laboratory can be accessed via elevator shaft lifting to 2 t or 20 people or via the entrance ramp (mine vehicles are used to transport materials and people). The Äspö offers, among others: workshops, stores, and crew shed at Äspö and at the tunnel entrance, offices and meeting rooms, radio frequency identification system, power supply (continuous), good ventilation tunnel, rescue chamber, operating and monitoring systems. The laboratory has a mechanical ventilation system (14–30 $m^3\,s^{-1}$).

There are two main types of rock in Äspö: Äspö diorite (quartz monzodiorite to granodiorite, porphyritic) and Ävrö granodiorite (granite to quartz monzodiorite, generally porphyritic). The entire lab is covered with pure rock except for the rescue chamber, which has a tunnel sealing (1–2 mm) (BSUIN, 2021; FQ, unpublished data, 2020; Äspö HRL, 2021).

2.2 Callio Lab, Finland

Callio Lab is located in active zinc, copper, and pyrite mine (Pyhäsalmi Mine) in the town of Pyhäjärvi in central Finland. It is coordinated by the University of Oulu Kerttu Saalasti Institute. The Pyhäsalmi mine is the oldest and deepest base metal mine in Europe, and mining is expected to end in the fall of 2021. Currently, Callio Lab belongs to the larger CALLIO-Mine for Business concept aimed at transforming the mine area into an economically feasible multidisciplinary operating environment. Access to the underground laboratory is possible through a vertical shaft (elevator for about 20 people) and a long, inclined tunnel, also accessible for trucks, which leads to the bottom of the mine (BSUIN, 2021).

In Callio Lab, there are seven underground halls and an extensive tunnel network, good infrastructure, and equipment, including electrical workshops, maintenance halls, restaurants, offices, and safe high-speed internet access (CALLIO LAB, 2021).

The main underground laboratories in Callio Lab, sorted by depth, are: Lab 1 where the EMMA experiment on cosmic-ray muons is being conducted; Lab 4 used for underground production of plants; Lab 3 used for underground information modelling; and Lab 2 and Lab 5 where the researches in the field of elementary particle physics requiring a low cosmic background are conducted (Joutsenvaara, 2019; FQ, unpublished data, 2020; Pohuliai et al., 2020). Ventilation in Lab 1 is gravitational, while in Lab 2, Lab 3, and Lab 5 mechanical (10–20 $m^3\,s^{-1}$), and in Lab 4 additionally controlled by temperature and gas content (FQ, unpublished data, 2020). Lab 5 is on the main level and is part of a much more efficient air ventilation system.

The Pyhäsalmi mine is located in a belt containing two large volcanogenic deposits of massive sulphides. The ore contains the following precious metals on average 0.92 % Cu, 2.45 % Zn, 37.4 % S, 0.4 $g\,t^{-1}$ Au and 14 $g\,t^{-1}$ Ag (Mäki et al., 2015). The walls of the underground halls are covered with shotcrete of 5–10 cm thick, and the floor is reinforced.

2.3 Conceptual Lab development co-ordinated by KGHM Cuprum R&D centre, Poland

Conceptual Lab development co-ordinated by KGHM Cuprum R&D center is located in the Polkowice-Sieroszowice mine in the Lower Silesia province in south-western Poland. The mine belongs to KGHM Polska Miedź S.A., holding copper mines and metallurgic plants. KGHM Polska Miedź S.A. is a State Treasury owned company. KGHM Cuprum R&D center is one of 21 entities of KGHM Polska Miedź S.A. and acts as a research and development center (BSUIN, 2021). Mainly copper is mined in the mine, but there are also seams with admixtures of other metals and a salt seam. The mine is one of the largest copper mines in the world.

Due to the long-term operation of the mine, the mine's infrastructure is highly developed. It includes several large access shafts (up to 7.5 m in diameter), an extensive network of underground roads, a ventilation system, machines for fully mechanized mining, and underground transport vehicles (Zalewska, et al., 2010; Kisiel et al., 2010a). At KGHM Polska Miedź S.A. there are no typical underground laboratories, but the company has hundreds of kilometers of existing excavation pits easily accessible and passable. Such sites can be used as underground laboratories. Excavations can be used, for example, to improve the technology of excavation, blasting, or ground support, best suited to local mining and geological conditions (BSUIN, 2021).

There are several layers in the mine. The dolomite layer is above the production level, which is 900 to 1200 m deep. Above the dolomite layer, there is a layer of anhydrite 150 m thick. The next layer is rock salt and Motley fine sandstone. There are also layers of quartz sandstones and hard Rotliegendes sandstones in the mine (BSUIN, 2021; Szkliniarz et al., 2021).

2.4 Research and Education Mine "Reiche Zeche", Germany

Research and Education Mine "Reiche Zeche" belongs to the Bergakademie Freiberg University of Technology (TUBAF), Germany. The mine is located in the Eastern Erzgebirge Mountains in the center of Saxony. Reiche Zeche is a historic ore mine with several kilometers of openings available that are periodically inspected (Weyer, unpublished data, 2015; BSUIN, 2021). Access to the mine is possible via two active vertical shafts (Reiche Zeche and Alte Elisabeth). There are no larger measurement halls in the mine (there are i.a. an old water wheel room, a lecture room, a room for events, and several utility spaces). The mine is available up to 230 m, while the level up to 750 m is flooded. The mine includes 129 km long drifts, 19 km of which are safely accessible and frequently used. There are three main levels in the underground location: Adit level (depth 100 m) with narrow openings mainly for visitors and teaching, Level 1 (depth 150 m): main level for teaching and visitors, recently also main level for research; Level 3 (depth 200 m): future main level for research. In the mine, in some central places, high-speed internet, power supply, telephone, and lighting are available. The mine is ventilated by a forced ventilation system, which the Mining Authority requires due to aspects of radiation protection. Approximately 10–15 $\mathrm{m^3\,s^{-1}}$ of fresh air flows into the mine (Weyer, unpublished data, 2015).

There is a zinc-lead deposit in the mine, and the main minerals are: galena, sphalerite, pyrite, chalcopyrite, arsenopyrite, and quartz. The walls in the pit are usually pure bedrock, while in some rooms (for example, in the server room), the walls and the floor are bricks, whereas the ceiling and the floor are made of concrete of unknown thickness (Weyer, unpublished data, 2015).

2.5 Ruskeala marble mine, Russia

The Ruskeala Underground Laboratory is located in the Ruskeala area of the Sortavala municipality of Karelia, Russia (south-west of the Republic of Karelia) in the Ruskeala Mining Park. The UL is located in an inactive marble mine with huge underground spaces. Geotechnological and photogrammetric research is carried out there. One of the main goals of the underground laboratory is to test, design, and build tourist sites in old lost quarries and mines. Access to the UL is via a slightly inclined tunnel from the surface. The underground laboratory consists of several extensive tunnels, a lake, and a larger area with chambers (BSUIN, 2021; FQ, unpublished data, 2020; RUSKEALA, 2021). Power, internet access, and ventilation are not available. The walls are bare rock-natural source marble.

2.6 Underground Low-Background Laboratory of Khlopin Radium Institute, Russia

The low-background underground laboratory belongs to the Khlopin Radium Institute and is located in the northwest of Russia in Saint Petersburg. Khlopin Radium Institute is a research and production institution specializing in nuclear physics, radio- and geochemistry, ecological issues related to nuclear energy, radioecology, and isotope production (BSUIN, 2021; Stepanov, 2018). The UL can be accessed directly from the interchange tunnel between Nevsky Prospekt and Gostiny Dvor metro stations in St. Petersburg. There are three transport options to UL: (1) in-stream escalator with subway passengers, (2) separate escalator under the supervision of subway workers, (3) via loading platform (at night) – additional request required (FQ, unpublished data, 2020). UL is relatively small and includes two workrooms and an additional technical corridor. In the underground rooms, a power supply is available.

The laboratory is located at a depth of about 60 m and is surrounded by the Cambrian Clay. The walls of the working rooms are covered with reinforced concrete cladding. As for room ventilation, it is only mechanical on request (FQ, unpublished data, 2020; Stepanov, 2018).

Table 1 summarizes the main underground spaces in ULs, while Table 2 the natural condition parameters in BSUIN and EUL ULs.

3 Natural background radiation in ULs

During the BSUIN and EUL projects, measurements of natural radioactivity were carried out at the Reiche Zeche mine, Callio Lab and Conceptual Lab (Cuprum) which included: in situ measurements (gamma, radon concentration in air, neu-

Table 1. Characteristics of BSUIN and EUL ULs underground rooms. The rooms are listed in order of depth.

UL name	Room name	Depth (m)	Dimension (high × length × width) (m) / Area (m^2)
Äspö HRL	NASA0115A	115	4 × 20 × 8 / 80
	Tunnel 1650 m	220	4 × 3600 × 8 / 14 400
	Stannplan220		4 × 3600 × 8 / 14 400
	Stannplan340	340	4 × 3600 × 8 / 14 400
	TASU	410	4 × 70 × 8 / 280
	TASP		4 × 80 × 8 / 320
	TASD	420	4 × 100 × 8 / 400
	Rescue Chamber		4 × 15 × 11 / 60
	Stanplan450	450	4 × 3600 × 8 / 14 400
	TASI		4 × 25 × 8 / 100
Callio Lab	Lab 1	75	5 × 5 cross-section tunnels, 70 m in total
	Lab 4	660	4 × 13–14 × 5 / 52–56
	Lab 3	990	4 × 12 × 7 / 48
	Lab 5	1410	5–6 × 53 × 11–13 / 265–318
	Lab 2	1436	5–7.5 × 18 × 6–10 / 90–135
Conceptual Lab (Cuprum)	Hundreds of kilometers of existing excavation	650–1300	– / –
Reiche Zeche mine	Several utility spaces	100–200	2.20 × 2.30 / 5
Ruskeala	Underground space	36	2.5 × 300 × 2 / 750
	Chamber		– / 15
Khlopin UL	Workroom 1	60	– / 64
	Workroom 2		– / 32
	Technical corridor		– / 6–8

Table 2. Characteristics of BSUIN and EUL ULs environmental conditions.

UL name	Max depth (m)	Max depth (m w.e.)[a]	Temperature (°C)	Relative humidity (%)	Mine rock type / average density (g cm^{-3})
Äspö HRL	460	1250	8–16[b]	–	Äspö diorite / 2.72 Ävrö granodiorite / 2.67
Callio Lab	1440	4100	9–27[c]	43–100 [c]	volcanogenic deposits of massive sulphides / 2.8
Reiche Zeche mine	230	600	10–12	97–98	lead–zinc deposit / 2.6 (at gneiss)
Conceptual Lab (Cuprum)	1300	3600	28–37[c]	very low	dolomite, anhydrite, salt / 2–2.8
Ruskeala	36	100	10	–	marble / 2.72
Khlopin UL	60	120	21–23	75–90 60 with dehumidifier	Cambrian Clay / 2.0

[a] Meters of water equivalent; [b] depends on the season; [c] depends on the depth.

Table 3. Results of in situ measurements of natural radioactivity in BSUIN and EUL ULs.

UL name	Room name / Depth (m)	Gamma-ray flux ($cm^{-2}\,s^{-1}$)	Count rate ($keV^{-1}\,s^{-1}\,kg_{Ge}^{-1}$) in energy range 40–2700 keV	Effective dose rate ($\mu Sv\,h^{-1}$)	^{222}Rn ($Bq\,m^{-3}$)	Neutron flux ($cm^{-2}\,s^{-1}$)	Muon flux ($cm^{-2}\,s^{-1}$)
Äspö HRL	NASA0115A / 115	–	–	–	$2760^{a,r}$	–	–
	Tunell 1650m / 220	–	–	–	$1080^{a,r}$	–	–
	Stannplan220 / 220	–	–	–	$500^{a,r}$	–	–
	Stannplan340 / 340	–	–	–	$520^{a,r}$	–	–
	TASU / 410	–	–	–	$810^{a,r}$	–	–
	TASP / 410	–	–	–	$940^{a,r}$	–	–
	TASD / 420	–	–	–	$500^{a,r}$	–	–
	Rescue Chamber / 420	–	–	–	$620^{a,r}$	–	–
	Stanplan450 / 450	–	–	–	$200^{a,r}$	–	–
	TASI / 450	–	–	–	$90^{a,r}$	–	–
Callio Lab	– / 400	–	–	–	–	$(26.1 \pm 1.7) \times 10^{-7}$ (< 1.5 MeV) $(5.7 \pm 0.7) \times 10^{-7}$ (1.5–12 MeV)^{h,s}	$(2.1 \pm 0.2) \times 10^{-6\,j,t}$
	Lab 1 / 75	–	–	–	$700–1000^{d,r}$		
	Lab 4 / 660	–	–	–	$300^{e,r}$	$(20.8 \pm 1.6) \times 10^{-7}$ (< 1.5 MeV) $(5.6 \pm 0.5) \times 10^{-7}$ (1.5–12 MeV)^{h,s}	$(3.2 \pm 0.3) \times 10^{-7\,j,t}$
	Lab 3 / 990	–	–	–	$300^{f,r}$	$(37.5 \pm 1.7) \times 10^{-7}$ (< 1.5 MeV) $(9.5 \pm 0.7) \times 10^{-7}$ (1.5–12 MeV)^{h,s}	$(6.2 \pm 0.6) \times 10^{-8\,j,t}$
	– / 1390	–	–	–	–	–	$(1.1 \pm 0.1) \times 10^{-8\,j,t}$
	Lab 5 / 1410	–	$23.54^{c,u}$		21.9 ± 1.3^{w} (related to cooling and air exchange system)	$(42.2 \pm 5.0) \times 10^{-7}$ (< 1.5 MeV) $(16.8 \pm 5.8) \times 10^{-7}$ (1.5–12 MeV)^{h,s}	
	Lab 2 / 1436	$12.7 \pm 1.5^{b,x,y}$	$347.57 \pm 0.03^{b,x}$ $48.4^{c,u}$	$0.158 \pm 0.029^{b,x,y}$	$213.3 \pm 11\,\%$–$270.4 \pm 10\,\%^{g,x,y}$	$(1.73 \pm 0.10) \times 10^{-5\,i,x}$ (thermal)	$(8.21 \pm 3.15) \times 10^{-10\,k,x}$

Table 3. Continued.

UL name	Room name / Depth (m)	Gamma-ray flux ($\text{cm}^{-2}\,\text{s}^{-1}$)	Count rate ($\text{keV}^{-1}\,\text{s}^{-1}\,\text{kg}_{\text{Ge}}^{-1}$) in energy range 40–2700 keV	Effective dose rate ($\mu\text{Sv}\,\text{h}^{-1}$)	^{222}Rn ($\text{Bq}\,\text{m}^{-3}$)	Neutron flux ($\text{cm}^{-2}\,\text{s}^{-1}$)	Muon flux ($\text{cm}^{-2}\,\text{s}^{-1}$)
Reiche	– / 90	–	–	–	257–1576[l,r]	–	–
Zeche	– / 150	–	–	–	237–981[l,r]	–	–
mine	Reiche Zeche, server room / 150	2.8 ± 0.8[b,z,y]	191.71 ± 0.03[b,z]	0.036 ± 0.008[b,z,y]	805.1 ± 10.4[g,z,y]	$(3.12 \pm 0.10) \times 10^{-6}$[i,z] (thermal)	$(5.2 \pm 1.9) \times 10^{-7}$[k,z]
	Alte Elisabeth, rock cavity / 150	2.6 ± 0.5[b,z]	326.20 ± 0.03[b,z]	0.035 ± 0.008[b,z]	–	–	–
Conceptual Lab	salt cavern P1 / 930	0.124 ± 0.002[b,aa]	2.30 ± 0.02[m,ab] 3.13 ± 0.01[b,aa]	0.0018[n,ab]	12 ± 4–49 ± 8[o,ab]	–	–
(Cuprum)	Anhydrite gallery / 1014.4	0.64 ± 0.20[b,ac]	114.25 ± 0.05[b,ac]	0.008 ± 0.001[b,ac]	6.6[g,ac]	$(2.0 \pm 0.2) \times 10^{-6}$[i,ac] (thermal)	approx. 1000 m $(2.8–5.5) \times 10^{-8}$[k,ab]
Ruskeala		–	–	0.04[p,r]	10 000 ± 5[q,r]	–	–
Khlopin UL		–	–	–	60–700 without ventilation, 15–70 with ventilation[o,r]	–	–

[a] Trace film detector (WLM-30 from Nucletron), [b] gamma spectrometry and the HPGe detector with 40 % detection relative efficiency, [c] stationary low–background HPGe spectrometer with open lid (50 % detection efficiency), [d] the radon collector, [e] activated carbon collectors, [f] semiconductor monitor, [g] radon monitor – RAD7, [h] liquid organic scintillator with three photomultipliers (PMT) and nineteen proportional counters filled with ^{3}He, [i] helium counters, [j] plastic scintillator telescope, [k] estimated based on empirical formulas, [l] at the ventilation measurement points in the main and secondary drifts using the Doseman Pro RTM 1688, [m] gamma spectrometry and the HPGe detector with 30 % detection relative efficiency, [n] 78 pieces of high sensitive thermoluminescent MCP–N (LiF: Mg, Cu, P) detectors located on the chamber walls in several places, [o] radon monitor – AlphaGuard, [p] complex of radiation investigation "Pioneer", consisting of a netbook, recording the readings connected to it the block of detection of gamma–radiation *БДКГ–03* and GPS–navigator, [q] portable radiometer (PPA-01M-03), [r] FQ, unpublished data (2020), [s] Abdurashitova et al. (2006), [t] Enqvist et al. (2005), [u] Gostilo et al. (2021), [w] Pohuliai et al. (2020), [x] Polaczek-Grelik et al. (2020), [y] Szkliniarz (2021), [z] Polaczek-Grelik et al. (2019), [aa] Polaczek-Grelik et al. (2016), [ab] Kisiel et al. (2010b), [ac] Szkliniarz et al. (2021).

tron flux) and detailed analysis of water and rock samples (concentration of radium, uranium and potassium radioisotopes) (Polaczek-Grelik et al., 2019, 2020; Szkliniarz et al., 2020, 2021). In other underground laboratories, data was collected from existing publications, reports, and information obtained in response to a specially prepared questionnaire that was sent to all underground laboratories participating in the project. Tables 3–5 gather information on natural radioactivity in underground laboratories. Some physical quantities have not been measured in all underground laboratories. The quantities describing natural radioactivity presented here are: gamma-ray flux, count rate in the gamma radiation spectrum, effective dose rate, the radon concentration in air, neutron flux, and muon flux.

Additionally, attention was paid to the concentration of radioisotopes in rock and water samples taken from the investigated locations. Such tests were performed in external laboratories dealing with this type of research. The collected data are presented in Tables 4 and 5. The radioisotopes tested in the rock samples are isotopes of radium (^{226}Ra), radium (^{228}Ra(^{232}Th)), potassium (^{40}K), and uranium (^{234}U, ^{238}U). The analyzed radioisotopes in water samples are isotopes of radium (^{226}Ra, ^{228}Ra) and uranium (^{234}U, ^{238}U). Radioisotopes in water samples were studied using alpha spectrometry and LSC (liquid scintillator counter) techniques, while in rock samples using alpha and gamma spectrometry. In the case of in situ tests in underground laboratories, the measurements of radon concentration in the air were carried out using: radon monitors (RAD7, AlphaGuard, Doseman Pro RTM 1688), activated carbon collectors, and trace film detector. Gamma-ray flux and count rate were mainly measured using gamma spectrometry (and HPGe detector) as well as a portable radiometer (PPA-01M-03). However, the effective dose rate was measured with the sensitive thermoluminescent MCP-N detectors, gamma spectrometry, and the Complex of radiation investigation "Pioneer". As for the neutron flux measurements, the research was carried out using helium counters and liquid organic scintillator, while the muon flux was determined using a plastic scintillator telescope or was estimated based on empirical formulas.

Radioisotope concentrations in rock and water samples have been measured in most BSUIN and EUL ULs, except for the Ruskeala marble mine. Samples of the rock surrounding the Khlopin UL and the construction materials (cement, sand) used to shield the walls, as well as the shielding materials (various grades of lead, cast iron, steel, tin, copper), were tested using gamma spectrometry in the 1970–1980s. The results were published in internal reports of the Radium Institute in Russian (EUL, 2021). There is no water in the Conceptual Lab (Cuprum).

Figure 2 presents a comparison of gamma radiation spectra measured in three underground laboratories of the BSUIN project (Reiche Zeche mine – at a depth 150 m in the server room (Polaczek-Grelik et al., 2019), Callio Lab – at a depth 1436 m in Lab 2 (Polaczek-Grelik et al., 2020), the Concep-

Table 4. Results of radioisotope concentrations in rock samples in BSUIN and EUL ULs.

UL name	Rock name	^{226}Ra (Bq kg^{-1})	^{228}Ra(^{232}Th) (Bq kg^{-1})	^{40}K (Bq kg^{-1})	^{234}U (Bq kg^{-1})	^{238}U (Bq kg^{-1})
Äspö HRL	Ävrögranite	–	$67.4 \pm 26.8^{a,e}$	$1116 \pm 62^{a,e}$	–	$60.5 \pm 9.9^{a,e}$
	Äspödiorite	–	$74.3 \pm 16.6^{a,f}$	$1054 \pm 124^{a,f}$	–	$54.3 \pm 9.9^{a,f}$
Callio Lab	Concrete (Lab 2)	40.2 ± 1.6–$161.7 \pm 14.5^{b,g,h}$	34.4 ± 1.5–$100.3 \pm 11^{b,g,h}$	662 ± 53–$1171 \pm 257^{b,g,h}$	53.9 ± 3.5–$89.2 \pm 3.7^{c,g}$	57.4 ± 3.7–$87.1 \pm 3.6^{c,g}$
	Rock (Lab 2)	8.1 ± 0.4–$83.1 \pm 7.47^{b,g,h}$	2.6 ± 0.3–$47.6 \pm 5.2^{b,g,h}$	104 ± 10–$1513 \pm 333^{b,g,h}$	1.6 ± 0.2–$10.3 \pm 1.3^{c,g}$	1.4 ± 0.2–$11.4 \pm 1.4^{c,g}$
	Concrete (Lab 5)	31.7 ± 9.5–$37.2 \pm 11^{b,i}$	17.8 ± 5.3–$27.3 \pm 8^{b,i}$	402.8 ± 120.8–$614 \pm 184^{b,i}$		
Reiche Zeche mine	Rock (Alte Elisabeth)	$39.4 \pm 0.9^{b,j}$	$33.1 \pm 0.5^{b,j}$	$1399 \pm 21^{b,j}$	$26.1 \pm 1.7^{c,j}$	$25.5 \pm 1.7^{c,j}$
	Rock (Reiche Zeche)	$43.8 \pm 0.4^{b,j,k}$	$31.5 \pm 0.6^{b,j,k}$	$1049 \pm 17^{b,j,k}$	$34.4 \pm 2.4^{c,j,k}$	$32.4 \pm 2.3^{c,j,k}$
Conceptual Lab (Cuprum)	Salt (P1 cavern)	$3.1 \pm 0.3^{d,l}$	0.008–$0.110 \pm 0.004^{c,l}$	2.1 ± 0.3–4.0 and in a few other samples, ^{40}K potassium was not identified^{b,l,m}	0.021–$0.38 \pm 0.05^{c,l}$	0.016 ± 0.003–$0.40 \pm 0.06^{c,l}$
	Anhydrite	–	$0.52^{c,l}$	not identified^{b,l}	$0.76 \pm 0.24^{c,l}$	$0.82 \pm 0.09^{c,l}$
	Anhydrite (gallery)	0.63 ± 0.03–$21.1 \pm 0.7^{b,n}$	0.19 ± 0.03–$0.60 \pm 0.10^{b,n}$	6.1 ± 0.2–$15.4 \pm 0.3^{b,n}$	0.84 ± 0.08–$24.75 \pm 0.74^{c,n}$	0.82 ± 0.08–$24.37 \pm 0.73^{c,n}$

[a] In situ gamma-ray spectrometry with the internal NaI detector, [b] gamma spectrometry with HPGe detector, [c] alpha spectrometry, [d] gamma spectrometry with HPGe detector, value estimated based on in situ spectra, [e] Mattsson et al. (2004), [f] Mattsson et al. (2003), [g] Polaczek-Grelik et al. (2020), [h] Gostilo et al. (2020), [i] Pohuliai et al. (2020), [j] Polaczek-Grelik et al. (2019), [k] Szkliniarz et al. (2020), [l] Kisiel et al. (2010b), [m] Mietelski et al. (2005), [n] Szkliniarz et al. (2021).

Table 5. Results of radioisotope concentrations in water samples in BSUIN and EUL ULs.

UL name	Water name	^{226}Ra (mBq L^{-1})	^{228}Ra(^{232}Th) (mBq L^{-1})	^{234}U (mBq L^{-1})	^{238}U (mBq L^{-1})
Äspö HRL	Boreholes KAS04, KAS06, HAS13	–	–	26.1–4950^{a,c}	5.8–685^{a,c}
Callio Lab	Water (Lab 2)	15.1 ± 0.4–$116.6 \pm 2.7^{b,d}$	6.1 ± 0.9–$10.7 \pm 4.5^{b,d}$	0.8 ± 0.2–$4.9 \pm 0.7^{a,d}$	$< 0.5^{a,d}$
Reiche Zeche mine	Water (Alte Elisabeth) Water (Reiche Zeche)	$< 10^{b,e}$ $< 15^{b,e}$	$< 30^{b,e}$ $< 40^{b,e}$	$12.8 \pm 0.8^{a,e}$ $142.4 \pm 4.9^{a,e}$	$13.4 \pm 0.8^{a,e}$ $150.4 \pm 5.2^{a,e}$

[a] Alpha spectrometry, [b] LSC technique, [c] Smellie and Laaksoharju (1992), [d] Polaczek-Grelik et al. (2020), [e] Polaczek-Grelik et al. (2019).

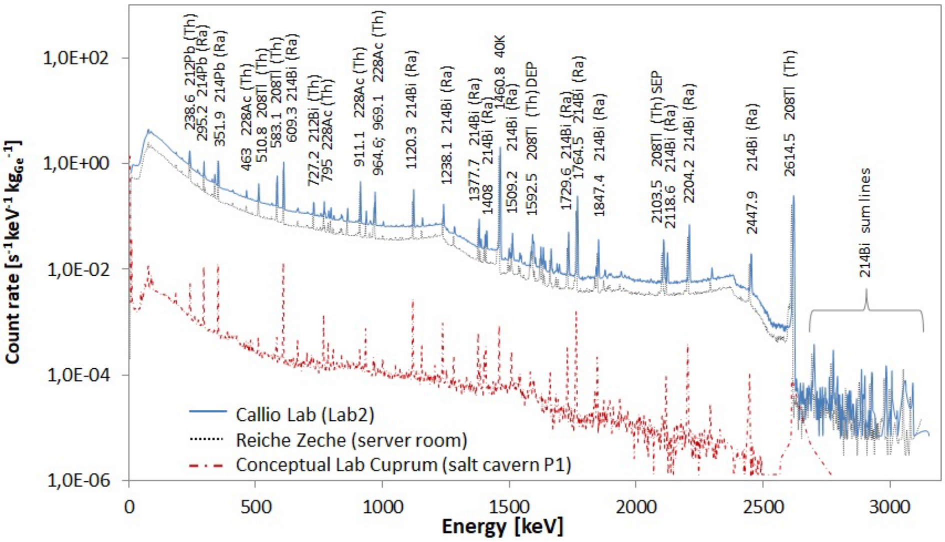

Figure 2. Comparison of background gamma-ray spectra collected at Reiche Zeche mine – server room (Polaczek-Grelik et al., 2019), Callio Lab – Lab 2 (Polaczek-Grelik et al., 2020), and Conceptual Lab development co-ordinated by KGHM Cuprum R&D centre – salt cavern P1 (Polaczek-Grelik et al., 2016), using gamma spectrometry and the same HPGe GR4020 detector.

tual Lab development co-ordinated by KGHM Cuprum R&D centre – at a depth 930 m in salt cavern P1 (Polaczek-Grelik et al., 2016) using the same HPGe GR4020 detector (Canberra Industries, Inc., USA, with 40 % detection relative efficiency). Based on the performed measurements, the gamma radiation spectrum (counts per second per energy per mass of germanium crystal) is estimated to be two orders of magnitude smaller in the salt cavern P1 of the Conceptual Lab development co-ordinated by KGHM Cuprum R&D centre than in Callio Lab and Reiche Zeche mine.

In underground laboratories, the main factor influencing natural radioactivity is the geology of the site in which it is located. Geochemistry and physical conditions such as shielding, ventilation, and depth are further factors. Based on the collected data, considering the above conditions, it can be concluded that the lowest level of natural radioactivity was observed in the Conceptual Lab (Cuprum). The underground location where the measurements were taken (salt chamber) is characterized by a very low concentrations of uranium (^{234,238}U up to 0.40 ± 0.06 Bq kg^{-1}), thorium (^{228}Ra(^{232}Th) up to 0.110 ± 0.004 Bq kg^{-1}), and potassium (^{40}K up to 4 Bq kg^{-1}) (Table 4), as well as the radon level of 12 ± 4–49 ± 8 Bq m^{-3} (Table 3), which is comparable to the concentration on the ground surface. This proves the origin of radon (^{222}Rn) and its decay products mainly from the ventilation air and not from the surrounding salt layer (Kisiel et al., 2010b).

The value of the muon flux decreases with the UL depth. The lowest located room is Lab 2 (1436 m) in Callio Lab, where the muon flux is two orders of magnitude smaller than in the Conceptual Lab (Cuprum). However, Callio Lab is located in sulphide deposit in felsic volcanic bedrock that are more radioactive than the salt layer. Additionally, the walls and floor of the hall in Lab 2 are covered with concrete and shotcrete, which are more radioactive than the surrounding rock (Polaczek-Grelik et al., 2020). This radioactivity comes mainly from uranium ^{234}U and ^{238}U (Table 4). This phenomenon is quite common due to the addition of mine west to building materials such as cement or concrete. Additionally, in some of the tested samples from Reiche Zeche mine and Callio Lab, there is a noticeable radioactive disequilibrium between the isotopes of radium ^{226}Ra and uranium ^{238}U. Secular breaking for uranium is caused by a difference in geochemical properties between radium (^{226}Ra) and uranium (^{238}U) and the greater mobility of radium in the environment.

The radon level (^{222}Rn) in Lab 2 reaches up to $270.4 \pm 10\,\%\,\mathrm{Bq\,m^{-3}}$, which is much higher than in Conceptual Lab (Cuprum) and in leading underground laboratories in the world (about 30–120 $\mathrm{Bq\,m^{-3}}$; Bettini, 2007). The highest radon level in the BSUIN underground laboratories was recorded in NASA0115A (Äspö HRL, 2021) at a depth of 115 m, where it was 2760 $\mathrm{Bq\,m^{-3}}$ (Table 3). The Reiche Zeche mine also has a higher natural radioactivity level than the Conceptual Lab (Cuprum). The measured radon concentration in the server room is $805.1 \pm 10.4\,\mathrm{Bq\,m^{-3}}$. Measurements in the Reiche Zeche mine were made at a depth of 150 m in the gneiss formation in the server room (walls are covered with bricks, and the floor is concrete) and in a rock cavity near the Alte Elisabeth shaft. The gamma-ray flux for both sites was similar (about $2.7 \pm 0.7\,\mathrm{cm^{-2}\,s^{-1}}$; Table 3) and about five times lower than in Lab 2 (Callio Lab). However, the concentration of uranium (^{234,238}U) in the collected rock and water samples is higher than for the samples from Callio Lab. The highest concentrations of radium ^{228}Ra and uranium ^{238}U were recorded in water samples from Äspö HRL (Tables 4–5).

The neutron flux in underground sites mainly comes from the (α, n) and fission (U and Th) processes in rock (local geology) and concrete used to strengthen underground spaces. To a lesser extent, the neutron flux depends on the depth because neutrons are produced in the interactions of cosmic muons (the neutron flux is about 3–4 orders of magnitude smaller than the flux from rocks and concrete). The highest level of thermal neutrons was measured in Lab 2 (Callio Lab) and is $(17.3 \pm 1.0) \times 10^{-6}\,\mathrm{cm^{-2}\,s^{-1}}$, and the lowest in Conceptual Lab (Cuprum) $(2.0 \pm 0.2) \times 10^{-6}\,\mathrm{cm^{-2}\,s^{-1}}$ (Table 3). The lower level of neutron flux was measured, among others, in Gran Sasso (Italy) $(0.56 \pm 0.22) \times 10^{-6}\,\mathrm{cm^{-2}\,s^{-1}}$ and in the salt layer in Slanic Prahova (Romania) $(0.12 \pm 0.05) \times 10^{-6}\,\mathrm{cm^{-2}\,s^{-1}}$ (Szkliniarz et al., 2021).

4 Summary

The first part of the article presents a brief description of the location, underground conditions, and structure of six underground laboratories in the Baltic Sea region (Äspö HRL, Callio Lab, and Conceptual Lab development co-ordinated by KGHM Cuprum R&D centre, Reiche Zeche mine, Ruskeala, Khlopin UL) participating in the BSUIN and EUL projects. The second part of the article presents the characteristics of the natural radioactivity of ULs. Particular attention was paid to the results of in situ measurements, including gamma-ray flux, count rate, effective dose rate, the radon concentration in air, neutron and muon flux, and the results of the analysis of uranium (^{234,238}U), thorium (^{232}Th), radium (^{226,228}Ra) and potassium (^{40}K) concentration in rock and water samples taken from ULs. These results are summarized in Tables 3–5. The concentrations of radioisotopes in water and rock samples differ significantly from each other. It is undoubtedly related to the geology of UL and the type of rocks. The lowest concentrations of radioisotopes were recorded in salt samples from Conceptual Lab development co-ordinated by KGHM Cuprum R&D centre. Additionally, Fig. 2 shows a comparison of gamma-ray spectra obtained from in situ gamma spectrometry measurements from three ULs: Callio Lab, Reiche Zeche mine, and Conceptual Lab development co-ordinated by KGHM Cuprum R&D centre. Based on the collected data, it can be concluded that the lowest level of natural radioactivity characterizes salt deposit, whereas in sites located in orthogneiss and sulphide deposit in felsic volcanic bedrock it is about two orders of magnitude higher.

Data availability. The data supporting the findings of this publication are available in the references given and from the corresponding author on request.

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