Report of A2.2 Natural radioactive background characterization

Baltic Sea Underground Innovation Network (BSUIN)

Interreg Baltic Sea Region
EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND

BSUIN

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1. BSUIN project

The main goal of the BSUIN project is to create a network of underground laboratories (ULs) in the Baltic Sea Region providing users (small and medium-sized enterprises) with easy access and a convenient environment for business development and innovation. The task of the project is to develop the capacity of underground laboratories to improve their service offer as an innovative potential.

Scientific research is not the only way to fully use the infrastructure of underground laboratories. Underground laboratories can also provide a unique environment for a variety of businesses. Among others, they can allow the development of technologies for mining, tunnel construction, radiation shielding systems. ULs can be used for geophysical research, radiation detection and other measurements, as well as become production plants that are a new and developing field, especially in the field of heat production or facilitating food production.

The intention to create the BSUIN project was born from the fact that the underground laboratories of the Baltic Sea operated separately and their ability to offer services to enterprises was mainly limited to the regional or national level. Also their service concepts and marketing activities were directed mainly for scientific use, which was a factor limiting the capitalization of the potential to service business and other users.
In order to efficiently achieve the intended goals, the project was divided into five activities:

- WP1 project management and administration,
- WP2 characteristics of underground laboratories,
- WP3 design services,
- WP4 improvement of the environment condition of underground laboratories,
- WP5 networking of underground laboratories in the Baltic Sea region.

In the BSUIN project participate six Partner Underground Laboratories and two Associated Organization Laboratories around Baltic Sea Region (Fig. 1).

PARTNER LABORATORIES:

- Callio Lab, Pyhäsalmi (Finland),
- Äspö Hard Rock Laboratory, Oskarshamn (Sweden),
- TU-Freiberg's Research and Education Mine "Reiche Zeche" (Germany),
- Conceptual Lab development coordinated by KGHM Cuprum R&D center (Poland),
- Ruskeala, Karelia (Russia),
- Underground Laboratory of Khlopin Institute in St Petersburg (Russia).

ASSOCIATED ORGANIZATION LABORATORIES:

- Experimental mine Barbara (Poland),
- Hagerbach Test Gallery (Switzerland).

The Baltic Sea Underground Innovation Network is a collaboration between 13 partners from 8 countries in the Baltic Sea Region. Also 17 associate partners are participating in the project.

Fig. 1 Map of the Baltic Sea region with the underground laboratories involved in the project.

2. Purpose of the A2.2 activity

The goal of A.2.2 activity (***Natural radioactive background characterization***) is the description of natural background radiation (NBR) in BSUIN underground laboratories. The extremely accurate characterization of NBR is essential in order to enable the utilization of the ULs as low NBR environments for product R&D, such as development of nuclear measurement or production of materials for nuclear industry or applied scientific research.

The activity provided data and reports for the BSUIN network to offer the industrial and other users full natural radioactivity characterization of several ULs in Baltic Sea Region. Characterization of an UL have a standard form allowing for direct ULs comparison to fit properly industrial or scientific activities.

For this purpose, the following documents have been prepared:

- ***Table with available data on NBR in ULs,***
- ***Questionnaire with data devoted to NBR in ULs,***
- ***Types and methods of measurements required for characterization of NBR in Underground Laboratories for potential customers,***
- ***Standard form for UL characteristics in terms of NRB and use it to overview of ULs,***
- ***Scheme of Reiche Zeche mine devoted to natural background radiation (NBR) characterization,***
- ***Scheme of Callio Lab devoted to natural background radiation (NBR) characterization***.

3. Collection of all currently available data on NBR in particular UL

The first task of the A.2.2 activity was to collect all currently available data on natural background radiation in ULs. This task was consisted of three part:

a) overview of available information (from publications, internal reports, presentations, etc.),

b) developing and distribution of the questionnaire of UL description,

c) questionnaire data processing.

a. Overview of available information

All available data related to the NBR characteristics of underground laboratories were collected. Published scientific papers, reports and presentations on NBR measurements at UL have been reviewed. Based on the data obtained, a table in Excel sheet was created for all BSUIN ULs as well as for other ULs located in the world. The table is divided into four parts, taking into account the laboratories participating in BSUIN project, operating in Europe (including CELLAR (Collaboration of European Low-level underground LAboRatorie) organization), operating in Asia and operating in North America.

General information was considered for each laboratory, such as:

- Name of Underground Laboratory,
- Full name,
- Country,
- Localization,
- Access,
- Maximal size and weight of goods transported underground,
- Hall(s) dimension,
- Information about ULs,

- Minimum depth [m w.e.],
- Temperature,
- Humidity,

and also information devoted to NBR characterization such as:

- Muon flux [$m^{-2}s^{-1}$],
- Neutron flux [$m^{-2}s^{-1}$],
- Radionuclides contained of the rock,
- ^{238}U [ppm],
- ^{232}Th [ppm],
- ^{40}K [ppm],
- ^{222}Rn concentration,
- Method of measure,
- Rock density and its composition,

and

- References.

<u>Underground Laboratories in Europe</u> consist:

  - Baksan, Russia
  - Solotvina, Ukraine

<u>CELLAR (Collaboration of European Low-level underground LAboRatories)</u>

  - Modane, France
  - Gran Sasso, Italy
  - Canfranc, Spain
  - Boulby, United of Kingdom
  - ARCS, Austria
  - LLL, Germany
  - CAVE, Monaco
  - Felsenkeller, Germany
  - University of Iceland, Island

- HADES, Belgium
- UDO, Germany
- LEGOS, France
- IRSN, France
- LSCE, France
- LAFARA, France

<u>*Underground Laboratories in Asia* </u>consist*:*

- Kamioka, Japan
- OTO, Japan
- Ogoya, Japan
- Y2L, South Korea
- CJPL, China
- INO, India

<u>*Underground Laboratories in North America* </u>consist:

- SNO-laboratory, USA
- SUL, USA
- DUSEL, USA

The Excel table with the data described above, named the ***Table with available data on NBR in ULs***, is in the appendix.

b. Developing and distribution of the questionnaire of UL description

Based on the previous task of creating a table with the available NBR information at ULs, a questionnaire was developed on the natural background radiation in underground laboratories. The questionnaire named: ***"Questionnaire: natural background radiation (NBR) measurements in the Underground Laboratories (BSUIN project)"*** was distributed to all BSUIN laboratories in

July 2018. The questionnaire contained information not only so far collected data, but also planned measurements as well as available and planned installed equipment. Deadline for answers was established to 30.09.2018. We received response from all BSUIN Underground Laboratories (Callio Lab Pyhäsalmi/Finland; Conceptual Lab development co-ordinated by KGHM Cuprum R&D centre/Poland; Reiche Zeche-mine/Germany; Äspö Hard Rock Laboratory/Sweden; Ruskeala-marble mine/Russia; Underground Laboratory of Khlopin Institute, St Petersburg/Russia).

The questionnaire is presented below.

Questionnaire: natural background radiation (NBR) measurements in the Underground Laboratories (BSUIN project)

1. General information regarding the Underground Laboratory

Name:

Localization: ……………………………… (Country) ……………………………… (City)

2. Description of the location(s) where the NRB measurement(s) was performed

Hall ID	Dimensions of the cavern (height x length x width) [in meters]	Ventilation (gravitational only / mechanical / none /efficiency [m3/h])	Power supply (continuous / on request / none)	Internet connection wireless / remote access	Environmental conditions (average temperature / average humidity)	Depth below the surface [in meters]

Natural source of rock filtered water (yes / no / not accessible)

Access to bare / pure rock samples (yes / no / on request)

Wall materials from inside (kind, thickness [cm])

………………………………………………………………………. ……………………………………………………………….. …………………………………………………………………..

3. Measuring equipment

Already installed (Yes/No): ………………. (if yes, fill the table below)

	Type	model	measured quantity	date of installation (mm/yy)
1.				
2.				
3.				

Planned to be installed (Yes/No): ………………. (if yes, fill in the table below)

	Type	model	Physical quantity to be measured	Planning date of installation (mm/yy)
1.				
2.				
3.				

4. Environmental radioactivity characterization for individual hall (if below stated measurements were done in several halls, copy the table and fill in appropriately)

Hall ID (consistent with Table 2.

Radon concentration in air

Continuous monitoring (yes / no)	Measurement method	Equipment type	Collection period	Average result [Bq/m^3]:
	…………………………………… …………………………………… ……………………………………	………………………………… ………………………………… …………………………………	……………………………………	……………………………………

Radioisotopes content in water

Monitored (yes / no)	Measurement method	Equipment type	Collection period	Average result [Bq/L]:
	…………………………………… …………………………………… ……………………………………	………………………………… ………………………………… …………………………………	……………………………………	Uranium ……….. Radium ………… Other ……………

Radioisotopes content in rock

	Monitored (yes / no)	Measurement method	Equipment type	Collection period	Average result [Bq/kg]:
		…………………………………… …………………………………… ……………………………………	…………………………………… …………………………………… ……………………………………	……………………………………	^{40}K ………………….. ^{238}U ……………….. ^{232}Th …………….. Other ……………

Gamma rays

Monitored (yes / no)	Measurement method	Equipment type	Detection relative efficiency [%]	Energy range [keV]	Results:
	…………………………………… …………………………………… ……………………………………	…………………………………… …………………………………… ……………………………………	……………………………………	…………………………………………	[cps] ……………………………

Neutron flux

Monitored (yes / no)	Measurement method	Equipment type	Detection relative efficiency	Energy range (thermal/resonance / fast/ whole)	Results: [flux] [unit]
	…………………………………… …………………………………… ……………………………………	…………………………………… …………………………………… ……………………………………	……………………………………	……………………………………	………………………………

Muon flux

Monitored (yes / no)	Measurement method	Equipment type	Detection relative efficiency	Results: [flux] [unit]
	………………………………………	………………………………………	……………………………………..	……………………………..
	………………………………………	………………………………………		
	………………………………………	………………………………………		

c. Questionnaire data processing

Data from feedback questionnaire was collected in the table (an Excel document), in which the results of NBR measurements performed by groups from the University of Silesia (Poland) and National Center for Nuclear Research (Poland) were included. These NBR measurements have been performed in the Reiche Zeche mine (Germany) in March and December 2018, and in Callio Lab (Finland) in July 2018.

On the basis of the collected data, the following conclusions were drawn:

General information and description of the locations

- The Callio Lab2 (Pyhasalmi, Finland) is the deepest laboratory (1430-1436m below the surface), whereas the Ruskeala is the shallowest (20-30 m below the surface) among BUSIN laboratories.

- The lowest temperature - about 9^{o}C in the year is in the Callio Lab1 (Pyhasalmi, Finland), in the Äspö Hard Rock Laboratory - about 8-16^{o}C, and in the Ruskeala - about 10^{o}C.

- The access to the power supply (or power supply can be installed) is in all BSUIN Laboratories, apart from the Ruskeala.

- The Ruskeala has a hall with the biggest dimension: height 2.5m x length 2m x width 300m (Ruskeala Mining Park - underground and surface).

- The permanent access to the internet connection is not available in any of BSUIN laboratories. However, the internet connection can be established in the Callio Lab and Reiche Zeche, but not in the Ruskeala, in the Conceptual Lab development co-ordinated by KGHM Cuprum R&D centre and in Khlopin UL.

- The access to the bare/pure rock samples is possible in all BSUIN Laboratories except Khlopin UL.

- The walls in the laboratories are the pure rocks or are covered with concrete or bricks (Callio Lab and Reiche Zeche) and reinforced concrete linings (Khlopin UL).

Installed equipment related to the NRB measurements

- Measuring equipment was installed only in two laboratories - Callio Lab/Finland (for measurement of radon concentration in air) and Khlopin UL (for measurement gamma ray).

- Only the Äspö Hard Rock Laboratory planned to install a detector for measurement of radon concentration in air (in October 2018).

Radon concentration in air

- The radon concentration in air was measured in BSUIN laboratories by using different methods:
    - Tracefilm analysis
    - Single measurements at ventilation points in main and secondary drifts
    - Alpha spectroscopy
    - Radon detector
    - Activated carbon collectors
    - Pumping air

- The measurements were performed for different data collection periods. The longest measurement lasted 6 months, from October to April, and was performed at Äspö Hard Rock Laboratory by using Tracefilm detector. The shortest measurement (20 min) was performed in Ruskeala.

- The highest level of the radon concentration in air - about 10 kBq/m^3 was obtained in Ruskeala, whereas the lowest in the Conceptual Lab development co-ordinated by KGHM Cuprum R&D centre - 12-49 Bq/m^3.

- The high level of the radon concentration in air was also noticed in the Hall NASAO115A - 2760 Bq/m^3, in Stolenstole in Reiche Zeche mine - 1576 Bq/m^3, Lab1 in Callio Lab - about 1000 Bq/m^3 and in Khlopin UL – about 700 Bq/m^3. In the other localizations the radon concentration in air was about 300 Bq/m^3.

- The measurements of radon concentration in air within the BSUIN project were done in Reiche Zeche server room and Lab1 and Lab2 in Callio Lab.

- The measurements of radon concentration in air was performed in all BSUIN ULs, but the continuous monitoring was done only in at Äspö Hard Rock Laboratory by using Tracefilm detector, and in Lab4, Callio Lab for 30 days using activated carbon collectors.

Radioisotopes content in water

- The radioisotopes content in water was measured only in the Reiche Zeche mine and in the Callio Lab by using alpha spectrometry techniques and the LSC method by group from the University of Silesia, Poland within the project BSUIN.

- The water is not present in one Underground Laboratory, i.e. Conceptual Lab development co-ordinated by KGHM Cuprum R&D centre – it is a salt cavern.

- The concentration of ^{226}Ra and ^{228}Ra is below the Minimum Detectable Activity (MDA) in water samples from Reiche Zeche (Alte Elisabeth: ^{226}Ra <10 mBq/l and ^{228}Ra <30 mBq/l; outside server room in Reiche Zeche: ^{226}Ra <15 mBq/l and ^{228}Ra <40 mBq/l).

- The water samples from Callio Lab for measurement of the radium isotopes concentration were collected from three localization: PH-500907 (water collected directly from the rock outside Lab 2 in its nearby (~50 m before it)), PH-102 and PH-103 (water from two pipes which collect the water seeping through the rocks behind Hall 2 of Lab 2). The highest concentration of ^{226}Ra was obtained for the sample from PH-102 (116.7 Bq/l) and the lowest concentration of ^{226}Ra for PH-103 (15.1 Bq/l). The highest concentration ^{228}Ra was obtained for sample collected in PH-500907 (36.9 Bq/l) and the lowest concentration of ^{228}Ra for sample from PH-103 (6.1 Bq/l).

- The obtained concentrations of radium isotopes in water samples from Callio Lab are lower than average value for mine waters, which are about few kBq/l.

- The ^{238}U concentrations were measured in 3 localizations in the Reiche Zeche (Alte Elisabeth shaft, server room and outside server room) and 3 localizations Callio Lab (PH-500907, PH-102, PH-103).

- The ratio of uranium isotopes concentration ($^{234}U/^{238}U$) for sample from "Alte Elisabeth" and from server room in Reiche Zeche was about 1 (0.96 and 0.95 respectively), which is an evidence of the radioactive equilibrium in this samples. In sample "outside server room" the ratio is 1.58.

- In the sample from Callio Lab (PH-500907) the ratio of uranium isotopes $^{234}U/^{238}U$ is equal to 1.7 which is an evidence of the lack of radioactive equilibrium in this sample. The concentration of ^{234}U is higher than ^{238}U: the ^{234}U isotope is more mobile and therefore is able to penetrate to water from rocks.

- The concentration of ^{234}U from PH-102 and PH-103 was below Minimum Detectable Activity < 0.5 mBq/l.

Radioisotopes content in rock

- The radioisotopes content in rock was measured only in the Reiche Zeche mine and Callio Lab by group from University of Silesia (Poland) within the BSUIN project by using alpha and gamma spectroscopy techniques. Such measurements were performed also in the Conceptual Lab development co-ordinated by KGHM Cuprum R&D Centre.

- Measurements of radioisotopes concentration in rock were also performed in Ruskeala, but the analyses are still on going.

- The samples of rock were collected in 3 localizations in Reiche Zeche mine (Alte Elisabeth, server room Reiche Zeche and Reiche Zeche). The samples of rock in Callio Lab are from 9 localizations in Lab 2.

- The activity concentration of uranium, radium and thorium is similar in 3 localizations in Reiche Zeche: 30 Bq/kg, 40 Bq/kg, 30 Bq/kg respectively. The ratio of uranium isotopes ($^{234}U/^{238}U$) is about 1.

- The highest activity of ^{238}U in samples of rock from Lab 2 (Callio Lab) is 211 Bq/kg in PH-103 place. Whereas considerably lowest activity of uranium in rock is 1.4±0.2 Bq/kg in PH-102.

- High levels of uranium in concrete may be due to the production details of shotcrete cement.

- The highest activities of ^{226}Ra, ^{232}Th and ^{40}K were obtained for concrete samples from Lab 2, Callio Lab, 40.2-91.0 Bq/kg, 34.4-53.8 Bq/kg and 662-1136 Bq/kg respectively.

- The lowest values of radioisotopes activity in rock samples (among 3 underground laboratories: Reiche Zeche, Callio Lab and Conceptual Lab Cuprum) have been obtained for P1 salt cavern in Conceptual Lab development co-ordinated by KGHM Cuprum R&D centre.

Gamma spectrometry

- The gamma spectrometry was performed in Callio Lab (Lab1 and Lab2), Reiche Zeche (Alte Elisabeth shaft and server room), Ruskeala, Conceptual Lab development co-ordinated by KGHM Cuprum R&D centre (P1 salt cavern) and Khlopin UL.

- The highest level of counts in the gamma spectrum (given in counts per second – cps - in the energy range of 7-3150 keV) was observed in the Alte Elisabeth shaft about 700 cps and the lowest one in the P1 salt cavern in the Conceptual Lab development co-ordinated by KGHM Cuprum R&D centre (about 2 cps for energy range of 40 – 2700 keV) and in Khlopin UL (about 0.8 cps for energy range of 10-1600 keV (when the ventilation is on).

- The similar effective dose (about 0.04 µSv/h) was measured in Reiche Zeche (Alte Elisabeth shaft and server room) and in Ruskeala.

Neutron flux

- The neutron flux was measured in the Callio Lab (Lab, Lab3 and Lab4) and in the Reiche Zeche server room.

- The measurements were performed by using liquid organic scintillator in Lab3 and Lab4 (Callio Lab) and with the use of two helium proportional counters in Reiche Zeche (server room) and in Lab2 (Callio Lab).

- The measurements performed in Reiche Zeche and Lab2 in Callio Lab were done by the group from National Center Nuclear Research, Poland within the BSUIN project. The results from Reiche Zeche are published in Nuclear Instruments and Methods in Physics A, vol. 946 (2019) 162652, and results from the Callio Lab are published in Nuclear Instruments and Methods in Physics A, vol. 969 (2020) 164015.

- The thermal neutrons were measured in the Reiche Zeche (server room) and Lab2 of Callio Lab, whereas the fast neutrons were measured in Callio Lab (Lab3 and Lab4).

- The measured neutron flux is equal to $3.12 \cdot 10^{-6}$ $cm^{-2}s^{-1}$ (thermal neutrons) in the Reiche Zeche and $1.73 \cdot 10^{-5}$ $cm^{-2}s^{-1}$.

- The measured neutron flux at Callio Lab is $37.5 \cdot 10^{-7}$ $cm^{-2}s^{-1}$ (Lab3) and $20.8 \cdot 10^{-7}$ $cm^{-2}s^{-1}$ (Lab4) for energy range 0-1.5 MeV, and below $0.6 \cdot 10^{-7}$ $cm^{-2}s^{-1}$ (Lab3 and Lab4) for neutrons with energy above 25 MeV.

Muon flux

- The muon flux was measured only in the Callio Lab by using plastic scintillators. The values were in the range from $1.1 \cdot 10^{-4}$ m^{-2} s^{-1} (Lab2) to $6.2 \cdot 10^{-4}$ m^{-2} s^{-1} (Lab3).

The comparison of the gamma spectra from 3 Underground Laboratories: Reiche Zeche (Germany), Callio Lab (Finland) and Conceptual Lab development co-ordinated by KGHM Cuprum R&D centre (Poland) are presented in the Fig. 2 and Fig. 3.

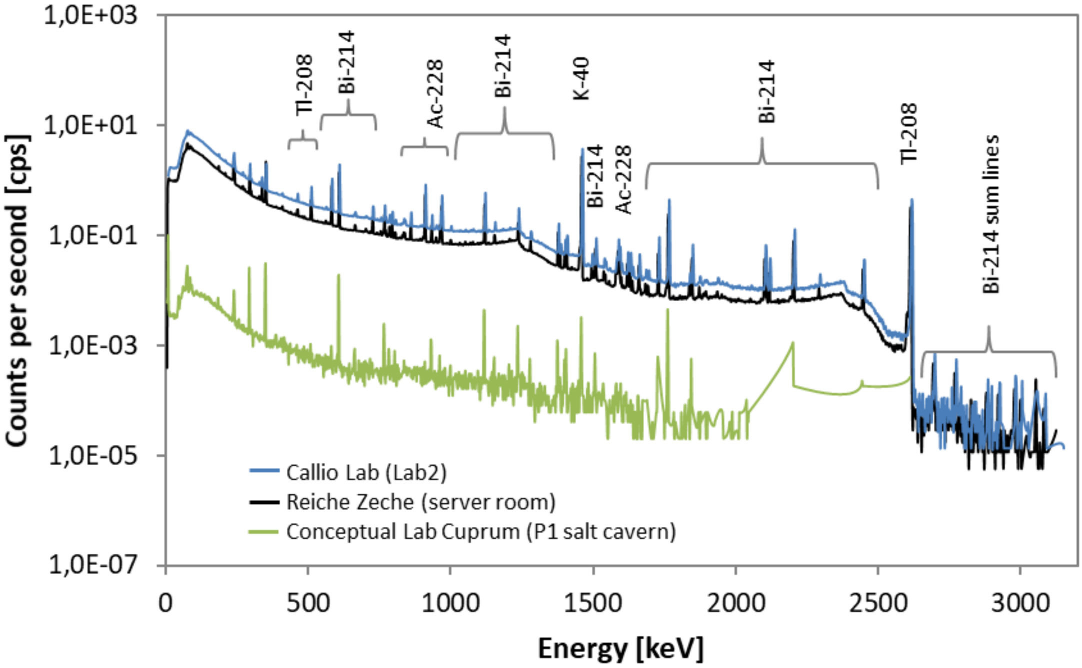

Fig. 2 Comparison of gamma-ray spectra from 3 BSUIN Underground Laboratories for the energy range 0-3150 keV.

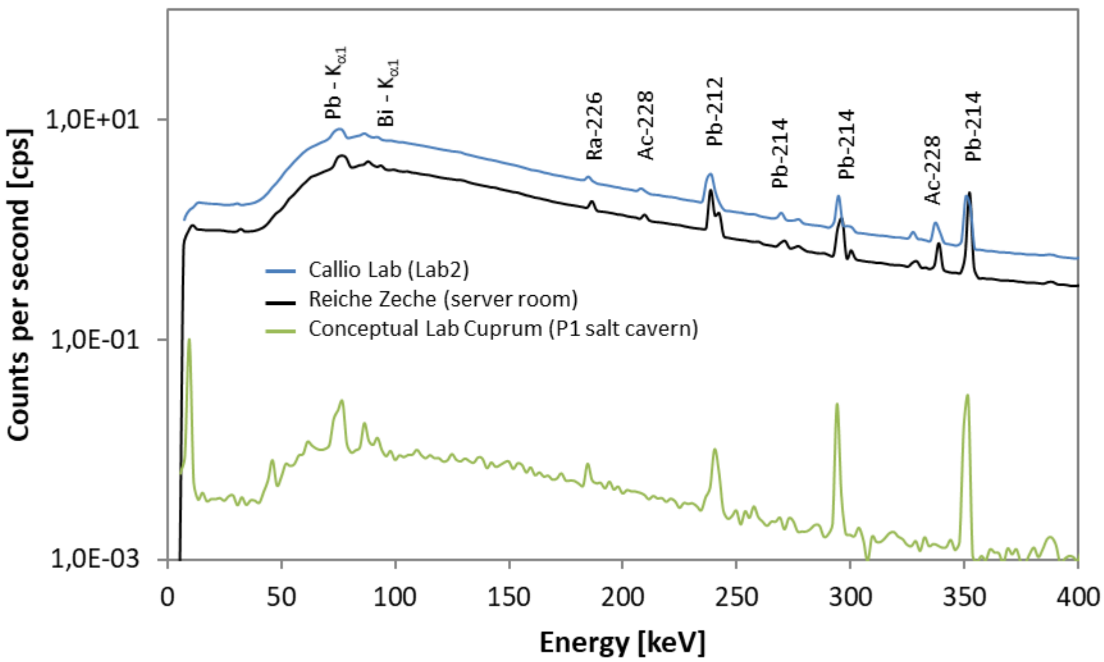

Fig. 3 Comparison of gamma-ray spectra from 3 BSUIN Underground Laboratories for the energy range 0-400 keV.

4. Recognition of type and methods of measurements required for UL NBR characterization, from the point of view of potential customer

a. Overview of available information

The data devoted to type and methods of measurements required for UL NBR characterization, from the point of view of potential customer has been collected from available publication, reports, presentations, books, etc. This report is divided into 10 chapters covering an introduction that provide general information about the natural background radiation, including the requirements stated by the radiation safety limits (in all country of partner laboratories), and required actions when working underground. In the next chapters the information about types and methods of NBR measurements in ULs are described. These chapters are following:

- Measurements of natural radioisotopes concentration in Underground Laboratories,
- Measurements of radon concentration in air,
- Measurements of natural radioisotopes in rock samples,
- Measurements of natural radioisotopes in water samples,
- Measurements of air kerma rate (K_{air}) from external ionizing radiation in cavern and absorbed dose rate in air,
- Measurements of the integral ambient dose equivalent H* and the rate $H^*_{(10)}$ in the laboratory area,
- Measurements muon flux in caverns in the ULs,
- Measurements of neutron flux in ULs.

The last chapter discusses the guidelines for the mandatory measurement of human exposure to natural isotopes found in underground workplaces, which are regulated by international and national law. In the last chapter was discussed guidelines for mandatory measurements of human exposure to natural isotopes found in underground workplaces, which are regulated by international and national laws.

b. Monitoring of current publications

The document containing information on the types and methods of NBR measurements was created in the 3rd and 4th period of the BSUIN project. The data was supplemented in subsequent periods. Data from published articles on the measurement results of natural background radiation at Callio Lab and the Reiche Zeche mine were also added. These measurements were made by research groups from the University of Silesia, the National Center for Nuclear Research and the Baltic Sea Instruments.

The appendix includes the document described above, named: ***Types and methods of measurements required for characterization of NBR in Underground Laboratories for potential customers.***

5. Development of a standard form for UL characteristics in terms of NBR and use it to overview of ULs

Information gathered from previous assignments helped to create and develop a standard form for underground laboratory characteristics in terms of NBR and use it to overview of ULs. The prepared standard form provides the information required to offer industrial and other users the full characterization of natural radioactivity at UL. This document consists the following information:

- General information
- Measurements of the NBR in Underground Laboratory
  - In-situ gamma-ray measurements
  - Measurement of the radon concentration in air
  - Measurement of the neutron flux
  - Measurement of the secondary cosmic ray muons flux
- Laboratory analyses of the water samples
  - Uranium concentration in water samples
  - Radium concentration in water samples
- Laboratory analyses of the rock samples
  - Radium, thorium and potassium concentration in rock samples
  - Uranium concentration in rock samples
  - Neutron activation of the rock samples

The document also contains tables with measurement results, alpha, beta and gamma radiation spectra of the tested samples, plots and information on recommended measurement methods, procedures and conditions during measurements.

The standard form described above is included in the appendix and has been called: ***Standard form for UL characteristics in terms of NRB and use it to overview of ULs***.

6. Design and perform a pilot measurement program

Measurements of natural background radiation in underground laboratories were planned and prepared in advance. For this purpose, an appropriate identification of the places where measurements should be made was made. The measuring equipment was also properly prepared. NBR measurements were carried out at Callio Lab and the Reiche Zeche mine by research groups from the University of Silesia (USK), the National Center for Nuclear Research (NCBJ) and the Baltic Sea Instruments (BSI).

In-situ measurements were carried out in the examined locations. Gamma-ray measurements and radon concentration in the air were performed at Callio Lab and the Reiche Zeche mine by a research group from the University of Silesia, and at Callio Lab by a group from Baltic Sea Instruments. While, the thermal neutron flux was measured by a research group from NCBJ in Callio Lab and the Reiche Zeche mine. Water and rock samples were also collected from the Reiche Zeche mine and Callio Lab for laboratory analysis in the Low-level Activity Research Laboratory of the Institute of Physics of the University of Silesia in Katowice.

a. Adaptation and modification of the measuring system

Gamma-ray measurements

Baltic Sea Instruments has its own production of HPGe detectors. Therefore, BSI scientists developed and manufactured a low-background HPGe gamma spectrometer for measurements at Callio Lab. This detector was produced in order to provide the necessary measurements to characterize the gamma-ray background in Callio Lab.

The HPGe spectrometer is based on a p-type crystal with a 50% detection efficiency and is cooled by a Stirling electric cooler. It allows to eliminate liquid nitrogen during work of this detector and as well as a problem with the transport of this gas to the underground laboratory. The energy resolutions is 1.20 and 1.95 keV at energies of 122 and 1332 keV, respectively. In order to performed measuring in Callio Lab, the measuring equipment were transported from the manufacturers to Callio Lab by using ground transportation for reduce activation by cosmic radiation. The material used for production of HPGe detector and cryostat were constructed of certified radiation-pure materials. The spectrometer is automated and allows access all long-term measurements to be controlled using Spectra Line software and also can be remotely operated from an external laboratory (by Internet). More information on the spectrometer described above is presented in the paper of V.Gostilo et al., 2020.

Neutron flux measurements

The neutron detection setup used for thermal neutron flux measurements at Callio Lab has been upgraded. The purpose of these improvements was to better adapt the measuring setup to long-term remote-controlled operation. The performed activities were useful in calibrating and adjusting helium counters. Among others the number of helium counters (from two to ten) was expanded compared to the previous measurements performed in Freiberg. Also the electronics were upgraded, the sampling rate was decreased to 1 MHz. Remote control of the trigger level and an analogue input amplifier gain were added. Remotely upgrade the firmware of the device via an internet connection was also possible. The description of the new neutron detection setup was described in the publication of K. Polaczek-Grelik et al., *2020.*

b. Measurement campaigns (reconnaissance, main measurements and additional measurements)

The first pilot NBR measurements were performed at the Education and Research Mine "Reiche Zeche" of the Technical University of Freiberg (Germany) during the SC meeting at a depth of 150 m (410 m w.e.) on March 7-8, 2018. These measurements included in-situ gamma-ray measurements in a rock cavern near the Alte Elisabeth shaft performed by a research group from the University of Silesia and thermal neutron flux measurements in a server room (Reiche Zeche) perform by a research group from National Centre for Nuclear Research. The thermal neutron flux at this location was measured by using two proportional ^{3}He counters. Subsequent in-situ gamma-ray measurements and measurements of the radon concentration in the air were made in the server room of the Reiche Zeche mine in December 2018 by the research group from USK. The locations of the measurements are shown in Fig. 4.

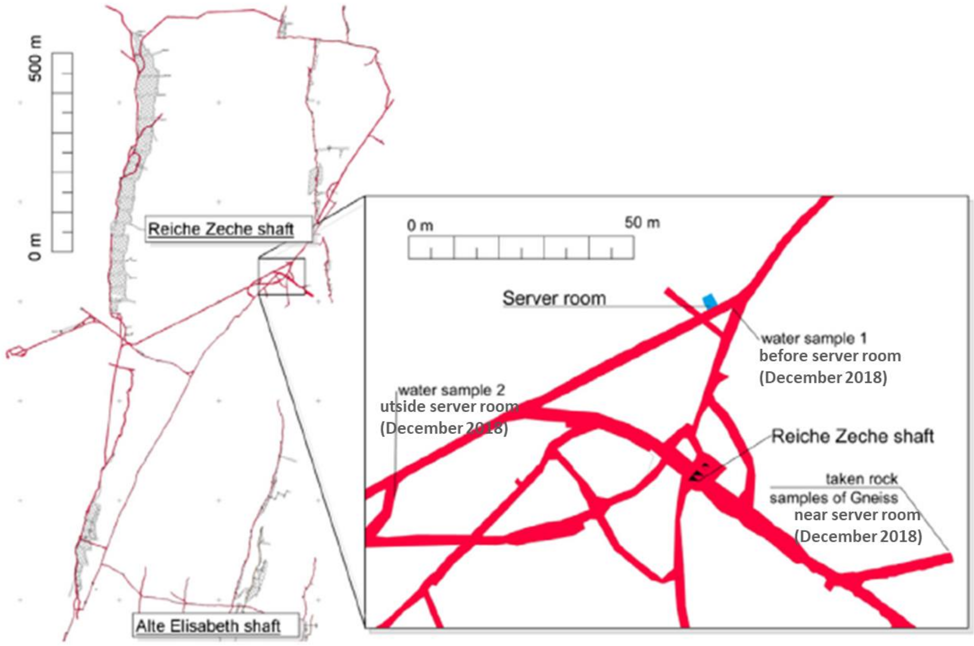

Fig. 4 First level of the Research and Teaching Mine of the TU Bergakademie Freiberg. The measurement location in the server room and sites of the collected samples near the Reiche Zeche shaft are marked (based on the excerpt of the mine layout provided in 2009 by Dr Ing Grund).

Four water samples and three rock samples from the Reiche Zeche and Alte Elisabeth shafts (in March and December 2018) were also collected for laboratory analysis at the Low-level Activity Research Laboratory of the University of Silesia (Fig. 4). In-situ gamma-ray measurements were carry out by using gamma spectrometry with GR4020 portable spectrometer (Canberra Industries, Inc., USA), a high purity n-type germanium (HPGe) coaxial detector. While the radon concentration in air were measured by RAD7 radon detector (Durridge Company, Inc.) at two locations in the server room (in the left and right corner of the server room). Laboratory analysis of the concentration of uranium ($^{234,238}U$) and radium ($^{226,228}Ra$) radioisotopes in water samples were performed by using alpha spectrometry technique (7401VR from Canberra (Packard)) and a liquid scintillation α/β LSC counter (WinSpectral α/β 1414 liquid scintillation counter from Wallac), respectively. The concentrations of uranium ($^{234,238}U$), radium (^{226}Ra), thorium (^{232}Th) and potassium (^{40}K) radioisotopes in the collected rock samples were measured using alpha (7401VR from Canberra (Packard) and gamma (HPGe detector from Canberra Industries, Inc., USA) spectrometry techniques. Before the laboratory measurements, the rock and water samples were properly prepared. Radiochemical procedures were applied to measure uranium and radium concentrations in the water and rock samples. While in order to analyzed radium, thorium and potassium radioisotopes concentration, the rock samples were dried, crushed, ground and stored in Marinelli container. Also, one rock sample were activated by neutron flux from ^{252}Cf source by period one month.

All procedures, conditions of the all measurements and the results of NBR measurements in the rock cavern near the Alte Elisabeth shaft and in the server room of the Reiche Zeche mine are described in **“Scheme of Reiche Zeche devoted to natural background radiation (NBR) characterizations”** as well as in the following publications:

- K. Polaczek-Grelik, A. Walencik-Lata, K. Szkliniarz, J. Kisiel, K. Jedrzejczak, J. Szabelski, T. Mueller, F. Schreiter, A. Djakonow, R. Lewandowski, J. Orzechowski, P. Tokarski, P. Jalas, J. Joutsenvaara, R. Hildebrandt. **Characterization of the radiation environment at TU Bergakademie in Freiberg, Saxony, Germany**, Nuclear Inst. and Methods in Physics Research, A 946 (2019) 162652, https://www.sciencedirect.com/science/article/pii/S0168900219311398

- Z. Dębicki, K. Jędrzejczak, M. Kasztelan, W. Marszał, J. Orzechowski, J. Szabelski, P. Tokarski, **The BSUIN project – overview and same results**. J. Phys.: Conf. Ser. 1181 (2019) 012071, https://iopscience.iop.org/article/10.1088/1742-6596/1181/1/012071/pdf

- K. Jędrzejczyk et al., **The BSUIN project**. Proceedings of Science (ICRC2019) 523, https://pos.sissa.it/358/523/pdf

- K. Szkliniarz, K. Polaczek-Grelik, A. Walencik-Łata, J. Kisiel, ***Characteristics of natural radioactivity at the Reiche Zeche mine, Germany,*** Acta Phys Pol B Proceedings Supplement 13 (2020) 4, 753
  https://www.actaphys.uj.edu.pl/fulltext?series=Sup&vol=13&page=753

The results of these measurements were also presented at regular SC meetings and Conferences:

Z. Dębicki, **The BSUIN project–overview and same results**, 26th Extended European Cosmic Ray Symposium, Russia, 6-10.07.2018

J. Kisiel, ***Natural radiation background measured within the BSUIN (Baltic Sea Underground Innovation Network),*** Seventh International Conference on Radiation in Various Fields of Research/ Montenegro, 10-14.06.2019

K. Jędrzejczyk, **The BSUIN project**, 36th International Cosmic Ray Conference (ICRC2019), Madison, Wisconsin, USA 24.07-01.08.2019

K. Szkliniarz, ***Charakterystyka naturalnej promieniotwórczości w wybranych podziemnych laboratoriach terenu Morza Bałtyckiego – projekt BSUIN***, 45 Zjazd Fizyków Polskich (45 Congress of Polish Physicists), Poland, 13-18.09.2019

K. Szkliniarz, **Characteristics of natural radiation background at the Research and Education mine Reiche Zeche (Germany) performed within the BSUIN project,** EGU General Assembly 2020, Online, 4–8.05.2020, EGU2020-2980

K. Jędrzejczak, **Characteristics of natural neutron radiation background performed within the BSUIN project,** EGU General Assembly 2020, Online, 4–8.05.2020, EGU2020-3353

The main NBR measurements were made at Lab 2 Callio Lab located in Pyhäsalmi mine (Finland) in July 2018 by a research group from USK and NCBJ. Measurements were performed at a depth of 1436 m (~4000 m w.e.) within the felsic volcanic bedrock occurs a volcanogenic massive sulphide deposit. Measurements of in-situ gamma-ray and radon concentration in air, as at the Reiche Zeche mine, were performed using a GR4020 portable spectrometer (Canberra Industries, Inc., USA), with an HPGe detector and RAD7 detector (Durridge Company, Inc.). In-situ gamma-ray measurements were made at seven locations in Lab2:

- MP1 - right corner of Hall 2,
- MP7 - left corner of Hall 2,
- MP2 - centre of Hall 2,
- MP6 - centre of Hall 2 - vertical downwards orientation of spectrometer,
- MP3 - centre of Hall 1,
- MP4 - near the concrete wall of Hall 2,
- MP5 - after drilling a hole showing the bare rock in Hall 2.

While, the concentration of radon in the air was measured in six locations::

- MP1 - right corner of Hall 2,
- MP7 - left corner of Hall 2,
- MP2 - centre of Hall 2,
- MP3 - centre of Hall 1,
- MP5 - in rock after drilling whole,
- Outside lab.

The thermal neutron flux was measured with ten bare helium proportional counters placed in a flat vertical tray parallel to the wall of Hall 2 (Lab 2), approximately 1 m from the wall (measuring point: MP). The location of the measurement points in Lab 2 is shown in Fig. 5.

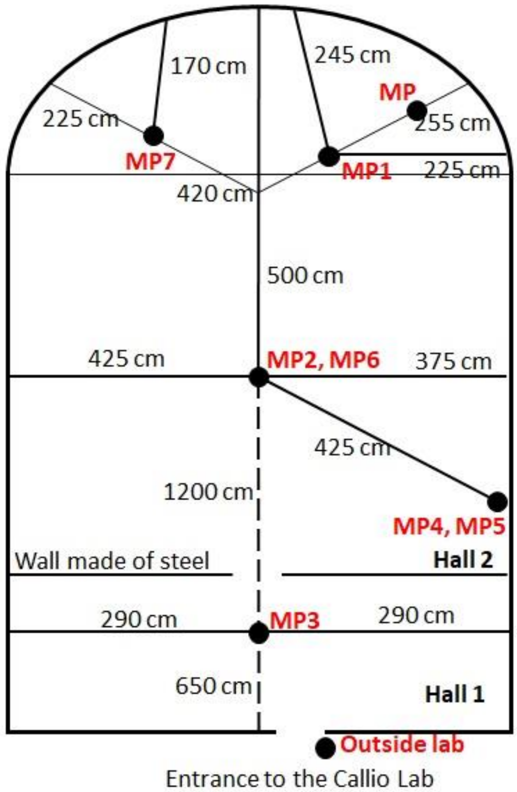

Fig. 5 Scheme of the Lab 2 with marked sites, where the in-situ measurements were performed.

Three water samples were taken for laboratory analyzes at the University of Silesia. Two water samples (PH-102, PH-103) from two pipes that collect water seeping through the rocks behind Hall 2 of Lab2 and one sample (PH-500907) taken directly from the rock outside Lab2 in its nearby (~50 m before it). Water samples were collected in polyethylene bottles.

Nine rock samples were also collected from Callio Lab for laboratory analysis at the USK::

- two samples contain rock from Hall 2 contain concrete from wall coverage and wall material itself (PH-102 and PH-103),
- concrete samples of the floor material used in Lab 2,

- wall shotcrete from left and right side of Lab 2,
- rock sample collected 50 m before the entrance to Lab 2 (left side of the corridor)- R2229,
- rock sample collected from the right side wall about 25 m from the door to Lab 2 (PH250907),
- two rock samples collected 50 m before the entrance to Lab 2 (right side of the corridor) – PH-500907 and PH-104.

Also, one rock sample was activated by a neutron flux from a ^{252}Cf source for a period of one month. As with the laboratory measurements of rock and water samples from the Reiche Zeche mine, all samples from Callio Lab were properly prepared before the measurements.

The places of rock and water sampling from Callio Lab for laboratory analysis are shown in Fig. 6.

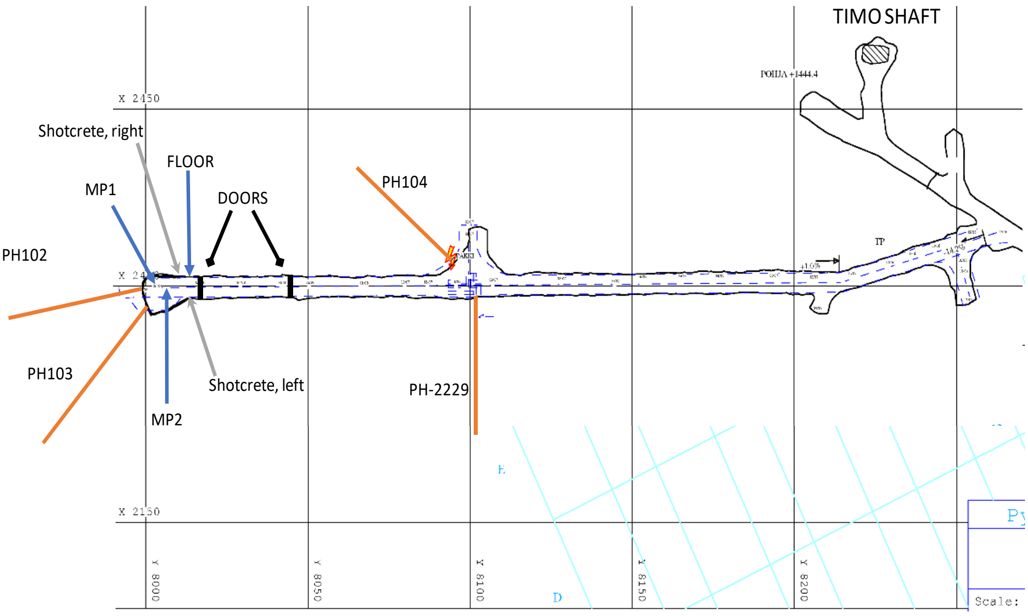

Fig. 6 The layout of Level -1436 m in Pyhäsalmi mine with marked sites where the samples of waters and rocks were collected.

Laboratory analysis of the concentration of uranium ($^{234,238}U$) and radium ($^{226,228}Ra$) radioisotopes in water samples was performed using the alpha spectrometry technique (7401VR from Canberra (Packard) and a liquid scintillation α/β LSC counter (WinSpectral α/β 1414 liquid scintillation counter from Wallac). The concentration of uranium ($^{234,238}U$), radium (^{226}Ra), thorium (^{232}Th) and potassium (^{40}K) radioisotopes in the collected rock samples was measured with alpha (7401VR from Canberra (Packard) and gamma (HPGe detector from Canberra Industries, Inc., USA) spectrometry techniques.

Similar in-situ gamma-ray measurements in Lab 2 and Lab 5 of the Callio Lab were performed by a research group from Baltic Sea Instruments. The gamma-ray measurements were carry out by using three portable spectrometers (portable HPGe spectrometer (NitroSPEC), clustered CdZnTe gamma-radiation spectrometer and scintillation spectrometer (BDEG-51-51-CeBr3)) as well as by using stationary low-background HPGe spectrometer. The measurements of the rock samples were done in Callio Lab by using planar HPGe detector (NitroSpec) installed at a shotcrete-free recess section of the wall and mounted close to the wall in an area lined with shotcrete. In order to more precise radionuclide analysis two rock samples (wall rock and shotcrete covering the walls) were measured in Marinelli container by using low-background HPGe spectrometer.

All procedures, conditions of the all measurements and the results of NBR measurements in the Callio Lab are described in ***"Scheme of Callio Lab devoted to natural background radiation (NBR) characterizations"*** as well as in the following publications:

- K. Jędrzejczyk et al., **The BSUIN project**, Proceedings of Science (ICRC2019) 523, https://pos.sissa.it/358/523/pdf

- K. Polaczek Grelik, A. Walencik Lata, K. Szkliniarz, J. Kisiel, K. Jedrzejczak, J. Szabelski, M. Kasztelan, J. Joutsenvaara, H.J. Puputti, M. Holma, T. Enqvist, ***Natural background radiation***

at Lab 2 of Callio Lab, Pyhäsalmi mine in Finland. Nuclear Inst. and Methods in Physics Research, A 969 (2020) 164015, https://www.sciencedirect.com/science/article/pii/S0168900220304630

- V. Gostilo, A. Sokolov, S. Pohuliai , J. Joutsenvaara, ***Characterisation of the natural gamma ray background in the underground Callio Lab facility***, Applied Radiation and Isotopes 156 (2020) 108987, https://www.sciencedirect.com/science/article/pii/S0969804319305998

- S. Pohuliai, A. Sokolov, V. Gostilo, J. Joutsenvaara, J. Puputti, ***Measurements of gamma ray background radiation in Pyhäsalmi mine***, Applied Radiation and Isotopes 161 (2020) 109166, https://www.sciencedirect.com/science/article/pii/S0969804320302955

The results of these measurements were also presented at regular SC meetings and Conferences:

K. Szkliniarz, ***Charakterystyka naturalnej promieniotwórczości w wybranych podziemnych laboratoriach terenu Morza Bałtyckiego – projekt BSUIN***, 45 Zjazd Fizyków Polskich (45th Congress of Polish Physicists) Poland, 13-18.09.2019

K. Jędrzejczyk, **The BSUIN project**. 36th International Cosmic Ray Conference (ICRC2019), Madison, Wisconsin, USA 24.07-01.08.2019

J. Kisiel, ***Characteristics of natural radiation background at the Callio Lab (Finland) performed within the BSUIN project***, EGU General Assembly 2020, Online, 4–8.05.2020, EGU2020-2979

K. Jędrzejczak, **Characteristics of natural neutron radiation background performed within the BSUIN project.,** EGU General Assembly 2020, Online, 4–8.05.2020, EGU2020-3353

c. Data processing to develop a scheme of UL's characterization

Based on the results of NBR measurements taken at the Reiche Zeche and Callio Lab mines, a scheme of the NBR characteristics for these Underground Laboratories was developed. Both schemes consist of several chapters containing information on measurement locations, in-situ measurements, and laboratory analyzes of water and rock samples. In addition, each scheme includes a schematic plan of the hall with a marked place in-situ measurements and photos during the measurements. Also, descriptions of chemical procedures for water and rock samples, measurement conditions, measurement equipment used and measurement results. The schemes consist of the following chapters and subsections:

1. **General information**

   With: Name of Underground Laboratory, localization, coordinates and altitude of the facility; Name of the responsible scientist/measurer; Place where the data is stored

2. **Measurements of the NBR in Underground Laboratory**

   With: Description of the site where the in-situ measurements were performed (Hall ID, Dimension of the cavern, Air volume exchange rate / Ventilation, Depth below surface, Environmental condition)

   a. **In-situ gamma-ray measurements**

      With: Information about measurements; Results of the in-situ gamma-ray measurements (contain e.g. Measurement method, Equipment type, Detection relative efficiency, integrated counts per second); The schematic plan of the hall with marked site where the in-situ gamma-ray measurement was performed; Qualitative analysis of gamma ray spectra registered in underground laboratory; The spectrum gamma-ray; Results of the gamma flux, gamma-ray dose and radioisotopes that have the main contributions in effective dose; Results of the effective dose rate from investigated localization; Apparent radioactivity calculated on the base of the gamma-ray spectrum.

b. Measurements of the radon concentration in air

With: Information about measurement (description of detector settings during measurement); The schematic plan of the hall with marked site where the measurement was performed and photo during measurements; Results of measurements of radon concentration in the air (Measurement method, Equipment type, Collection period, Average result), Plot of radon activity concentration.

c. Measurement of the neutron flux

With: Information about measurement (Type of counter, Setup description, Place of measurement); Results of the neutron flux measurements (Collection period, Average neutron counting rate, Dispersion of neutron counting rate, Calculated neutron flux witch error); Schematic plan of detector location in the chamber; Spectrum.

3. Laboratory analyses of the water samples

With: Description of the site where the water samples were collected (Hall ID, Depth below surface, Sites (wall, water gullets, water reservoir, other…..), Method of the sampling).

a. Uranium concentration in water samples

with: Description of the performed chemical procedure; Information about measurement and results (Hall ID (name of the sample), Measurement method, Equipment type, Collection period, Limit of detection, Average results (^{234}U, ^{238}U, ratio

$^{234}U/^{238}U$, U)); Spectra of all water samples.

b. Radium concentration in water samples

with: Description of the performed chemical procedure; Information about measurement and results (Hall ID (name of the sample), Measurement method, Equipment type, Collection period, Limit of detection, Average results (^{226}Ra, ^{228}Ra)); Spectra of all water samples.

4. Laboratory analyses of the rock samples

With: Description of the site where the rock samples were collected (Hall ID, Depth below surface, Sites (wall, floor, brick, concrete, other), Method of the sampling, Name of the sample).

a. Radium, thorium and potassium concentration in rock samples

With: Description of the procedure performed before measurements and conditions during measurements; Results of the radium, thorium and potassium radioisotopes concentration in rock samples (Hall ID (name of sample), Measurement method, Equipment type, Detection relative efficiency, Collection period, Average results (^{226}Ra, ^{232}Th, ^{40}K)); Spectra of all rock samples.

b. Uranium concentration in rock samples

With: Description of the performed chemical procedure; Information about measurement and results (Hall ID (name of the sample), Measurement method, Equipment type, Collection period, Limit of detection, Average results (^{234}U, ^{238}U, ratio $^{234}U/^{238}U$, U)); Spectra of all rock samples.

d. Neutron activation of the rock sample

With: Information about measurement and results (Hall ID (name of sample), Measurement method, Equipment type, Detection relative efficiency, Collection period, Source of neutron activation, Neutron flux of the source, Activated isotopes)); Spectrum gamma-ray.

The above-described schemes of UL's characterization for Reiche Zeche mine and Callio Lab are called: **"Scheme of Reiche Zeche mine devoted to natural background radiation (NBR) characterizations"** and **"Scheme of Callio Lab devoted to natural background radiation (NBR) characterizations"** and are found in the appendix.