# Investigations of novel technologies for safeguarding geological repositories

K. Khrustalev[1], R. Plenteda[1], C. Ames[1], I. Tsvetkov[1], J. Emmer[1], W.-S. Park[1]

[1]International Atomic Energy Agency (IAEA), Vienna, Austria

## Abstract

Safeguarding a geological repository may benefit from technologies which have not been utilized in an international safeguards context until now. Based on ideas discussed in the Member States expert groups Programme for Development of Safeguards for the Final Disposal of Spent Fuel in Geological Repositories (SAGOR) and Application of Safeguards To Geological Repositories (ASTOR) over the last 30 years, the International Atomic Energy Agency (IAEA) is now investigating practical applications of some of these technologies, including their cost/benefit analysis in the establishment of an effective and efficient safeguards regime for a first-of-a-kind facility being constructed in Finland, scheduled to start operations in 2025. Some of the technologies investigated are well established in industrial applications (e.g., ground penetrating radar, microseismic monitoring), but their practicality and implications for deriving safeguards conclusion have not yet been evaluated, and some of the technologies are genuinely novel (e.g., low-level Kr-85 stack emissions monitoring). This paper will provide an overview of IAEA efforts in this area, specific issues associated with individual technologies, and future plans.

## Keywords

International Safeguards, Geological repository, spent nuclear fuel, design information verification, ground penetrating radar, microseismic monitoring, noble gas stack monitoring

## Introduction

Geological repositories (GR) for spent nuclear fuel (SNF) are slowly becoming reality after a long development stage. The first of its kind, the Finnish GR at Eurajoki, Western Finland, near the Olkiluoto NPP, is being constructed and is scheduled to enter active operation (disposal of SNF) in 2025, with an operational life time projected at 100 years.

The Member State expert groups ‘Programme for Development of Safeguards for the Final Disposal of Spent Fuel in Geological Repositories’ (SAGOR) and ‘Application of Safeguards To Geological Repositories’ (ASTOR) addressed the implementation of safeguards for GRs starting in the late 80s, identifying a broad range of technologies of various technological readiness states with the aim at providing “deterrence in depth” – penetrations monitoring, disposal tunnels integrity (GPR - Ground Penetrating Radar, visual observations), gravitometry, magnetic survey, seismic, hydraulic head monitoring, environmental sampling (traditional ES on air ducts/filters as well as stack monitoring for Kr-85) [1, 2].

Taking the particular implementation of the GR in Finland as well as the technological readiness into account, the IAEA decided to investigate practical and operational applications for some of the techniques identified by the expert groups: seismic monitoring, GPR and possibly ventilation stack monitoring for Kr-85, which may help in the establishment of an efficient and effective implementation of safeguards objectives: timely detection of nuclear material diversion from peaceful use and detection of undeclared activities (e.g. reprocessing) in a declared facility.

## Geological repository design and operation

GRs have penetrations into the underground part such as vehicle access tunnel(s) and various access shafts (personnel lift, canister lift, ventilation shafts). Those can be safeguarded by a combination of traditional SG measures such as surveillance, seals and radiation detectors.

However, the ‘**Geological containment’** part requires some novel techniques. ‘**Geological containment’** applies the concept of facility containment to the natural barrier of the underground component of the GR. For safeguards purposes the integrity of that containment, which extends outwards the walls of the tunnels and deposition holes where the canisters are deposed, need to be independently confirmed.

The design information verification includes 3D laser scanning, which contributes to assurance that the GR infrastructure and tunnels are constructed as declared and have not been altered over the course of the facility operations.

Other methods, such as geophysical monitoring of the hydraulic head levels (ground water), have also been considered [3] and may provide an indicator of undeclared digging activities when a ground water horizon is penetrated, causing changes in the hydraulic head levels. These levels are monitored for environmental safety, and thus the information about such changes is readily available; however, this information is not sufficiently location-specific within the GR and therefore has limited safeguards value.

The IAEA decided to investigate the practical applications of two well-established industrial techniques - microseismic monitoring and GPR technologies – to address some of the safeguards challenges of the geological containment. Both technologies are being used extensively in commercial industrial applications and are well understood, but have not yet been considered for practical safeguards use, with the exception of limited GPR use for investigation of concrete building structures as part of the design verification activities. In general, both of these technologies would be used for any GR by the facility operator for seismic safety and to ensure that the natural rock barrier around the deposited canister does not contain any major cracks and therefore is unsuitable for deposition. Thus, the IAEA can potentially synergize safeguards objectives with existing safety and security measures where possible.

In addition, to detect potential undeclared activities involving the disposal canisters such as opening of the canisters and removal of SNF from them within the GR, indirect methods such as Kr-85 emission monitoring are being investigated.

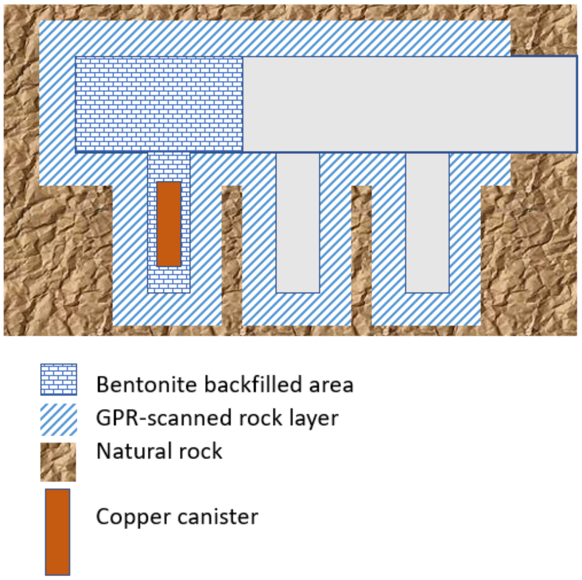
The objectives of the IAEA’s investigations are the following:

1. To analyse the feasibility of monitoring the integrity of the geological containment using the existing seismic safety monitoring network;
2. To analyse whether it is possible to create a layer of GPR-scanned rock around the disposed canisters which can then be monitored for undeclared breaches using

the seismic monitoring network (see Fig.1), thus increasing the probability of containment breach detection; and

3. To analyse the feasibility of early detection of undeclared disposal canister opening within the GR using Kr-85 as an indicator of spent fuel.

*Figure 1: Schematic vertical cross-section of a GR deposition tunnel with emplacement holes*



## Seismic monitoring of the GR

Seismic monitoring has been identified as one of the key geophysical techniques capable of providing information about the geological repositories and activities therein [1, 2, 3]. Most underground activities are associated with energy dissipation which can then be detected by seismic sensors in the form of waves propagating through the ground (mainly P – compressional and S – transverse waves).

Using differences in the arrival times of the waves between various sensors, wave forms and velocity model of the rock volume, one can accurately locate and categorize various seismic events and map them to known activities, even for very low-level signals (induced earthquakes with the magnitude level down to -3.2 have been identified using advanced seismic data analysis [4, 5]).

Seismic monitoring has been recognized early on as part of the safeguards project of the Radiation and Nuclear Safety Authority of Finland (STUK). The nuclear non-proliferation control for the GR is based on the following sub-areas [4]:

- Preliminary data: plans and drawings
- Implementation data: verification measurements, as built drawings, inspections and operating records
- Monitoring data: Micro-seismic monitoring

The seismic network at the Finland GR site has been in operation since 2002, first to establish the baseline seismicity of the area, and later to monitor the seismic GR block – cube of 2x2x2 km$^3$ encompassing the GR, with additional semi-regional stations monitoring the larger area and capable of detecting teleseismic events. The network has been continuously improved and now consists of 18 permanent stations and three mini-arrays equipped with geophones and accelerometers [5]. The sensors, data acquisition and the analysis system are provided by the Institute of Mine Seismology (IMS) – one of the major industrial providers of microseismic monitoring technology to mines.

GR facility operator (Posiva Oy) is publishing annual rock mechanics monitoring reports, where seismic events are categorized and correlated with the excavation activities and associated induced seismicity.

With support from the Posiva, its subcontractors responsible for the seismic network data collection and analysis, as well as STUK and Euratom as observers, the IAEA-SG developed a plan to evaluate the usability of the existing network for safeguards purposes.

The project started with a feasibility study conducted by an independent industry consultant. The consultant was hired by the IAEA in order to perform a practical assessment of the implementation of the micro-seismic monitoring for GR containment integrity:

- Provide initial data assessment from Posiva's seismic monitoring data;
- Estimate the sensitivity of containment monitoring;
- Provide recommendations on the network optimization and data authentication; and
- Estimate the associated costs for the establishment and maintenance of technical capabilities for regular micro-seismic monitoring.

Sample raw seismic data (converted to miniSEED format) provided typical examples of various activities in the GR: explosions, microearthquakes, raise boring, teleseismic events and noise.

The sample data was processed and analyzed using state-of-the-art seismic software and the results compared with published Posiva reports.

In order to better estimate the network sensitivity during various stages of GR operations (active excavation campaigns vs. more "quiet" operational phases), continuous seismic data acquisition would be required (see below).

Various scenarios for seismic data authentication were discussed and developed, along with their respective cost analysis:

1. Maximum Security Scenario: There are already existing applications of seismic data authentication which use a specialised card integrated into the datalogger to provide end-to-end security from the remote location to the data recording facility. This solution has the highest level of reliability; however, it requires modification to the hardware at each station, and has the highest cost and impact on key operations infrastructure required for safety. Therefore, this scenario is the least likely to be implemented.
2. Minimalistic Scenario: Uses data-based authentication by calculating internal data metrics for fingerprinting and tamper-indication (e.g. waveform amplitude RMS variation

over time, known teleseismic or regional events outside the boundary). This option equates to a research project with a promising, but uncertain outcome.

3. Intermediate Scenario: Install 2-3 stations with data authentication indicated in scenario 1 to be operated by IAEA. These would be emplaced in easy access tunnels of the repository or on the surface near existing stations. The waveforms from these co-located sensors would be correlated with those of the existing network to confirm proper operation and data authenticity. This would be limited by the number of co-located stations installed and the sites would be selected based on optimal coverage of the GR block boundary. This solution appears to be the most realistic and cost-effective.

Based on the outcome of the feasibility study presented to all stakeholders in the project, the IAEA decided to proceed with a small-scale seismic data acquisition analysis project using an independent contractor with support from Posiva, STUK and with Euratom as an observer.

In order to establish the technical requirements for the seismic data analysis, interviews were conducted with inspectors in charge of the GR project to develop a set of key objectives:

1. The analysis shall be able to detect undeclared activities/access to the deposited SNF canisters – that is, to provide location and categorization of events (natural vs. human-made, including not only impulse type events but also continuous machinery type of activities), as well as determine the detection limits on magnitude and location threshold in terms of magnitude and error ellipse dimensions for the locations where the canisters are deposited;
2. Determine the criteria for sensitivity to various types of events based on the network's noise level – need for continuous data acquisition and cutting-edge processing technology to find hidden waveforms that have not been observed by the traditional data analysis methods.
3. Automate the detection of a boundary penetration – if we define a region of interest (ROI) around a deposition tunnel which has been backfilled, can we automatically detect if there any events which penetrate this ROI? Template matching/machine learning cross-correlation with the continuous data can be used for looking at known patterns (drilling, blasting, raise boring).
4. Acceptable level of data review automation/manual review.
5. General requirements for the analysis software - open source is preferable
6. How to trust the data – finding the optimal cost-benefit solution for data authentication

The sensors in the network are capable to provide continuous data collection, but this capability is mostly used for diagnostic purposes and the data is stored only temporarily. The regular network data storage and processing is setup in a triggered mode optimized for the safety-related events [5]. In order to collect the continuous data and store it for the IAEA analysis additional IT infrastructure and software modifications will be needed for the planned small-scale test.

### Investigation of the Ground Penetrating Radar

GPR technique uses pulses of electromagnetic radiation in the microwave band of the radio spectrum (10s MHz to 3 GHz), and reads the reflected signal to detect subsurface structures and objects without drilling, probing or otherwise breaking the ground surface. GPR uses transmitting and receiving antennae. The transmitting antenna radiates short pulses of the high-frequency radio waves into the ground. When the wave hits a buried object or a boundary with different electrical properties, the receiving antenna records variations in the reflected return signal. Using the time-differences in the reflected waves it is possible to reconstruct images of subsurface structure and look for voids, cracks or other inhomogeneities.

GPR has been used by the IAEA since 2006 for design information verification and for inspection of concrete during the construction of new nuclear facilities, but has never been used in a GR on a bare rock before.

The technique is quite-labor intensive: the antennas used for the scanning are bulky (proportional to the emitted wavelengths on the order of .5-2m length) and need to be dragged or carried manually in close contact to the uneven rock surface in order to achieve good coupling. The scans need to be performed in a relatively dense grid (every 50 cm) in order to create a 3D image of the subsurface from individual scan profiles.

There are a number of commercial companies which make GPR systems for various purposes, such as buildings and road inspections, archeology, and burial site investigations. The manufacturers provide software for data collection and image reconstruction, but there are also dedicated software packages which can work with data formats produced by different vendors.

The interpretation of the reconstructed images requires expert knowledge, especially in cases when the scanned media is inhomogeneous, such as the natural rock of a GR.

In Finland, a license issued by the state telecom authority is required in order to operate a GPR system. Furthermore, a site-specific permit is required from the facility operator since the GPR system may interfere with the existing radiofrequency emitting devices in use. [6]

With support from Posiva and STUK, the IAEA has engaged a commercial company with the required licences and permits and previous experience of specific operational constraints of the GR. The system used there was the GSSI’s SIR-4000 GPR unit.

The selection of the GPR antenna frequency is always a compromise between the resolution and the penetration depth: higher frequency means less deep penetration, but better spatial resolution. Also, the GPR signal attenuation varies depending on the measured medium. In low conductivity material (e.g. dry sand), the achieved penetration depths are much higher than in high conductivity material (e.g. sulphide rock). Water content affects the GPR penetration as well, since water is an almost perfect reflector for the microwave radiation.

GPR signal attenuation is challenging in the Finnish GR which is a mix of pegmatitic and gneissic rock (higher conductivity and permittivity than pegmatite). Rock type (e.g. mineral composition and texture), fracture zones, fracture intensity, fracture fillings and water content effect strongly the signal attenuation. Generally high conductivity and high dielectric value (permittivity) of the medium (rock) strongly attenuates the GPR signal.

During the measurement campaigns, IAEA safeguards inspectors and technicians had the opportunity to obtain hands-on training on the modern GPR equipment and software analysis tools. Antennae with the following frequencies were tested – 100 MHz, 270 MHz, 350 MHz (digital HyperStacking© antenna - HS) and 400 MHz. The 350 MHz HS antenna proved to be most optimal for the GR rock providing the best penetration depth (up to 7-9 meters) and spatial resolution combination.

Sample scans of the deposition tunnel's floors (with empty emplacement holes) and walls have been performed.

Based on the measurement campaign, including the practical training on the use of the GPR in the field and subsequent data analysis sessions, the IAEA safeguards inspectors and technicians were able to estimate the amount of efforts needed for effective GPR use and level of expertise required for the data interpretation. This experience will help the IAEA to decide if GPR shall be used independently on a case by case basis in the future using our own equipment and expertise.

## Stack monitoring for Kr-85 in the GR

Krypton is a noble gas whose isotope Kr-85 is a major fission product. Previous estimates show that for an average burnup LWR fuel, the Kr-85 source term can be on the order of 160 TBq/1SQ Pu [7 and references therein provide excellent overview]. Main emitters of Kr-85 are reprocessing plants and, considering the ~11y half-life of Kr-85, the last 75 years of nuclear technological development lead to a growing background concentration of Kr-85 around the world on the order of 1.2 Bq/m3 in the northern hemisphere at present day levels [7].

Nuclear power plants also emit Kr-85 (along with other radioactive noble gases) during normal operation. Even for intact SNF, part of the Kr-85 inventory slowly diffuses out of the assemblies, leading to a constant increased Kr-85 background in the vicinity of an NPP which spikes during regular refueling when the reactor core is opened. These emissions are regulated by the state authorities and ventilation stack monitoring is an integral part of any nuclear installation. However, the release limits set by state regulators for radioactive noble gases are generally set rather high since their health impact is very small. For example, the total noble gases release limit for Olkilouto NPP is ~18 PBq/year with the actual emission measured on the order of 5-50 TBq/year – Kr-87 equivalent [9, 10].

Considering the SNF Kr-85 inventory and the isotope's relatively long half-life, its diffusion out of the SNF assemblies will lead to the fission gases accumulation in the canister, with canister's walls being 5cm thick copper and welded shut. Thus, it can be assumed that a detection of Kr-85 in the exhaust air of the GR ventilation system may indicate undeclared activities involving the spent nuclear fuel such as disposal canister opening.

Key advantages of Kr-85 monitoring:

- Non-invasive monitoring for undeclared activities (canister opening/reprocessing)
- May reduce inspector's days in the field in a hazardous environment (operational mine)
- Increased likelihood of detection – sampling also from physically inaccessible areas
- Well-established monitoring technology since 1970s

However, there are certain challenges which require careful consideration.

First, there are ways to capture Kr-85 in a scrubbing system. However, literature analysis [13] shows that such scrubbing system's efficiency does not exceed 99.9%, which may seem high enough but still sets a sizeable amount of activity free. Scrubbing technologies employed in the past include capturing Kr-85 on activated charcoal, cryogenic cooling and storage of liquified gas in tanks, or capturing on various adsorbents (molecular sieves or organic). All of these scrubbing techniques and the associated infrastructure is bulky, energy intensive and expensive and will be hard to hide.

Second, there are legitimate sources of increased Kr-85 concentrations in air. These sources can be local – such as Kr-85 emissions from a nearby nuclear power plants (NPP) or declared spent fuel handling in an encapsulation plant where the SNF is transferred from the transport cask into the disposal canisters. Sources can be also regional, such as emissions from fuel reprocessing or medical isotope production facilities in Europe, plumes from which may reach the site and temporarily increase ambient Kr-85 background. The impact of such plumes shall be further investigated.

In order to mitigate the influence of external sources, one can monitor not only exhaust air of the GR ventilation stack but also its intake air, and study the balance between intake and exhaust concentrations. The interpretation of this data will require careful study with modelling and experiments with neutral trace gases (such as $SF_6$) in order to understand the dwell and intermixing times of the ventilation air masses within the GR.

Third, the existing Kr-85 commercially available monitors are designed for regulatory purposes and do not have sufficient sensitivity for detecting such low concentrations as can be expected based on preliminary analysis.

A hypothetical scenario has been used to estimate the volumetric concentration of Kr-85 in the exhaust air considering the above-mentioned factors, based on the known parameters of the GR ventilation system and some assumptions on the Kr-85 inventory and release scenario. While the resulting estimated Kr-85 concentration is too low for the existing gross-beta stack monitoring detectors, it is still 100x higher than the normal Kr-85 background and therefore can be reliably detected above the background level.

A conceptual Kr-85 sampling system can be very similar in design to some of the existing CTBTO IMS xenon monitoring systems [11], essentially comprising a large-scale preparatory gas chromatograph coupled to a beta-gamma coincidence detector. The design of the krypton collection system can be greatly simplified in comparison to the xenon system, thanks to relatively high krypton concentration in the atmosphere compared to xenon (1.14 ppmv for Kr vs 0.087 ppmv for Xe) and much higher expected concentrations (for radioxenon monitoring systems the design criteria is to be able to detect concentrations of 1 mBq/m3). Furthermore, xenon systems have to successfully separate radon which is competing for the adsorption with xenon, whereas krypton is free of such interference. Thus, the scale and complexity of the sampling and purification system can be reduced considerably and the overall system can be of a size of a household appliance comprising a small air pump/compressor with a dust filter, humidity scrubber and krypton enrichment column based on suitable molecular sieves.

Such a system can work either in a continuous sampling mode with sample flow through a shielded beta detector, or in a fixed sampling interval similar to CTBTO IMS NG systems (6/12/24 hour sampling cycle). Samples can be also collected and analyzed off-site at random intervals. The exact sampling strategies shall be studied based on modelling and experimental data. And the system has to comply with the usual tamper-indicating requirements as other IAEA SG instruments, to ensure that the collected air is a representative sample of the ventilation air flow.

Kr-85 disintegrates primarily by beta minus decay [12]. Thus, a gross-beta scintillator detector with the purified krypton sample inside, surrounded by an anti-coincidence cosmic muon veto system can be used for quantifying the Kr-85 activity concentration in air. The anti-coincidence cosmic muon veto system could be based, for example, on a NaI crystal (SAUNA [11] type detector). The sensitivity of the detector shall be adapted to the expected background concentrations of Kr-85 so that the ambient background can be used as a quality control check source in order to make sure that the detector is operating properly. Furthermore, when designing a detector for Kr-85, the so called “memory effect” of the scintillator (embedding of Kr-85 atoms into the detector material) shall be carefully considered and materials used which minimize it. Otherwise the detector will become gradually contaminated by Kr-85 which will increase the background counts and render the detector less and less sensitive with time.

## Conclusion

Combined with other monitoring methods (such as portal monitoring for neutron signals, micro seismic surface monitoring for undeclared underground activities) and an automated evaluation tool capable of creating correlated events (Near Real Time monitoring software, under development by IAEA-SG), such comprehensive safeguards systems can provide a robust deterrent against possible undeclared activities within a geological SNF repository facility.

## References:

1. Application of Safeguards to Geological Repositories (ASTOR) Group of Experts proceedings and reports, 2006-2017 https://www.iaea.org/resources/databases/application-of-safeguards-to-geological-repositories, retrieved on July 31, 2021, access through respective Member State Support Program coordinators
2. R. Mongiello, R. Finch, G. Baldwin, Safeguards Approaches for Geological Repositories: Status And Gap Analysis, Sandia National Laboratories, 2013, SAND 2013-5185P
3. O. Okko, J. Rautjarvi, Evaluation of Monitoring Methods Available for Safeguards Use at Olkiluoto Geological Repository, Report on Task FIN C 1527 of the Finnish Support Programme to IAEA Safeguards, STUK Technical Report STUK-YTO-TR 216, August 2006
4. J. Saari, A. Lakio. Local Seismic Network at the Olkiluoto Site, Annual Report for 2006, Posiva Working Report 2007-55

5. O. Kaisko, M. Malm, Microearthquakes During the Construction and Excavation of the Final Repository for the Spent Nuclear Fuel at Olkiluoto in 2002-2018, Posiva Working Report 2019-05, Retrieved from https://www.posiva.fi/en/index/media/reports.html on July 31, 2021
6. TRAFICOM (Finnish Transport and Communication Agency), Guide on the Licence Policy on Ground and Wall Probing Radars (GPR/WPR) Intended for Professional Use, Retrieved from https://www.traficom.fi/sites/default/files/media/file/Tiedote%20maatutkaopas%20%28en%29%20%281%29.pdf on July 31, 2021.
7. M. Schoeppner, A. Glaser, Present and future potential of krypton-85 for the detection of clandestine reprocessing plants for treaty verification, Journal of Environmental Radioactivity, Volumes 162–163, October 2016, Pages 300-309 https://doi.org/10.1016/j.jenvrad.2016.06.001
8. C. Schlosser, A. Bollhöfer, S. Schmid, R. Krais, J. Bieringer, M. Konrad, Analysis of radioxenon and Krypton-85 at the BfS noble gas laboratory, Applied Radiation and Isotopes 126 (2017) 16–19, http://dx.doi.org/10.1016/j.apradiso.2016.12.043
9. S. Van der Stricht, A. Janssens. Radiation protection 127 - Radioactive effluents from nuclear power stations and nuclear fuel reprocessing plants in the European Union, 1995-1999, European Commission, Directorate C, Environment and Health, Unit C.4, Radiation Protection, 2001
10. RADD - Radioactive Discharges Database, European Commission, Brussels, Belgium, 2021, Retrieved from: https://europa.eu/radd/standardReports.dox?pageID=StandardReports with the following parameters: Finland, Olkiluoto, Airborne Releases – Noble Gases, Retrieved on: July 31, 2021
11. A. Ringbom, T. Larson, A. Axelsson, K. Elmgren, C. Johansson, Sauna—a system for automatic sampling, processing, and analysis of radioactive xenon, Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip., 508 (3) (2003), pp. 542-553, https://doi.org/10.1016/S0168-9002(03)01657-7
12. Decay Data Evaluation Project, Laboratoire National Henri Becquerel, http://www.nucleide.org/DDEP_WG/DDEPdata_by_Z.htm, retrieved on July 31, 2021
13. P. Paviet-Hartmann, W. Kerlin, S. Bakhtiar, Treatment of Gaseous Effluents Issued from Recycling – A Review of the Current Practices and Prospective Improvements, INL/CON-10-19961, 11th Actinide and Fission Product Partitioning and Transmutation Exchange Meeting, 2010