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Usability of Monitoring at the Olkiluoto Repository Site for Safeguards

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Abstract:

At the Olkiluoto repository site, the operator Posiva Oy runs a multidisciplinary monitoring programme targeted at studying environmental impact, improving the understanding of the natural properties of the site, verifying favourable conditions for long-term safety, and developing methods for monitoring the performance of engineered barriers. The usability of the data produced by the monitoring programme for the implementation of nuclear safeguards is assessed, primarily to detect the excavation of any undeclared underground premises.

Microseismic monitoring is currently the only method whose results, located seismic events in Olkiluoto and surroundings, are already used in implementing national safeguards. It is concluded that automatic hydraulic head measurements in deep drillholes and land use monitoring also produce relevant data and findings for safeguards purposes.

Hydraulic head is monitored in several drillholes that penetrate the rock volume where the repository will be excavated. These holes are divided into sections, so that head can be measured separately at different depths. The monitored sections are often situated in hydrogeological zones, where fractures in the crystalline bedrock allow groundwater to flow significantly more freely than elsewhere. In some of these zones, a groundwater leak into a new tunnel or drillhole gives rise to a significant decrease of hydraulic head at such a large distance that it can be readily detected in several monitoring sections.

Monitoring of land use is based on aerial photographs and maintaining a land use record. These sources are used to regularly update a land use grid covering the whole of Olkiluoto. The aerial photographs and land use grid can supplement other imagery used to verify the declaration of surface constructions.

The inclusion of the results of hydraulic head and land use monitoring in the input for the implementation of national safeguards could apparently be achieved by examining material and reports that Posiva already delivers for other purposes. The IAEA can use these reports as open source information.

Keywords: monitoring; repository; safeguards; seismicity; hydrogeology

1. Introduction

Monitoring is required to be performed at a repository as recommended in IAEA TECDOC 1208 [1], and required by STUK Regulatory Guide YVL D.5 [2]. Therefore, Posiva Oy, the company responsible of the final deposition project for the spent nuclear fuel in Finland, has been running an extensive multi-disciplinary monitoring programme at the Olkiluoto repository site. The aims include studying the impact for the repository project on the environment, improving the understanding of the conditions at the site, and supporting the analysis of the long-term safety of the repository.

Before applying for the nuclear construction licence Posiva has constructed an underground rock characterization facility called the ONKALO at the Olkiluoto repository site. It extends to the planned repository depth of about 430 m and includes an access ramp, shafts and technical underground rooms that will eventually also serve as the actual repository. Figure 1 shows the repository site of Olkiluoto, the horizontal extent of the ONKALO in 2017, drillholes and other monitoring points, and in an insert, the location of the site in Finland.

In this article, we discuss the usability of the monitoring programme for implementing national nuclear safeguards at the Olkiluoto site during the construction phase and, as regards detecting undeclared excavation, also during the operational phase. The implementation of nuclear safeguards in an underground repository for spent nuclear fuel mainly concerns the verification of two issues: first, that the construction of underground facilities corresponds to the reported, declared and licenced design, and second, that full accountability for all nuclear material is maintained in the process of transport, encapsulation and final deposition of spent nuclear fuel or any other nuclear material. Of these two issues, the monitoring programme mainly contributes to the first one, because the surveillance of the operation of the facility is not within its scope. The international safeguards requires the declaration of the Design Information, i.e., the layout of the site and the fuel transfer routes per Safeguards Agreement, and according to the Additional Protocol also the buildings, i.e., volumes of underground rooms, but not the monitoring of the stability of the buildings, rooms or premises. These issues have been addressed by the IAEA Expert's Group SAGOR / ASTOR when developing generic safeguards approaches in the

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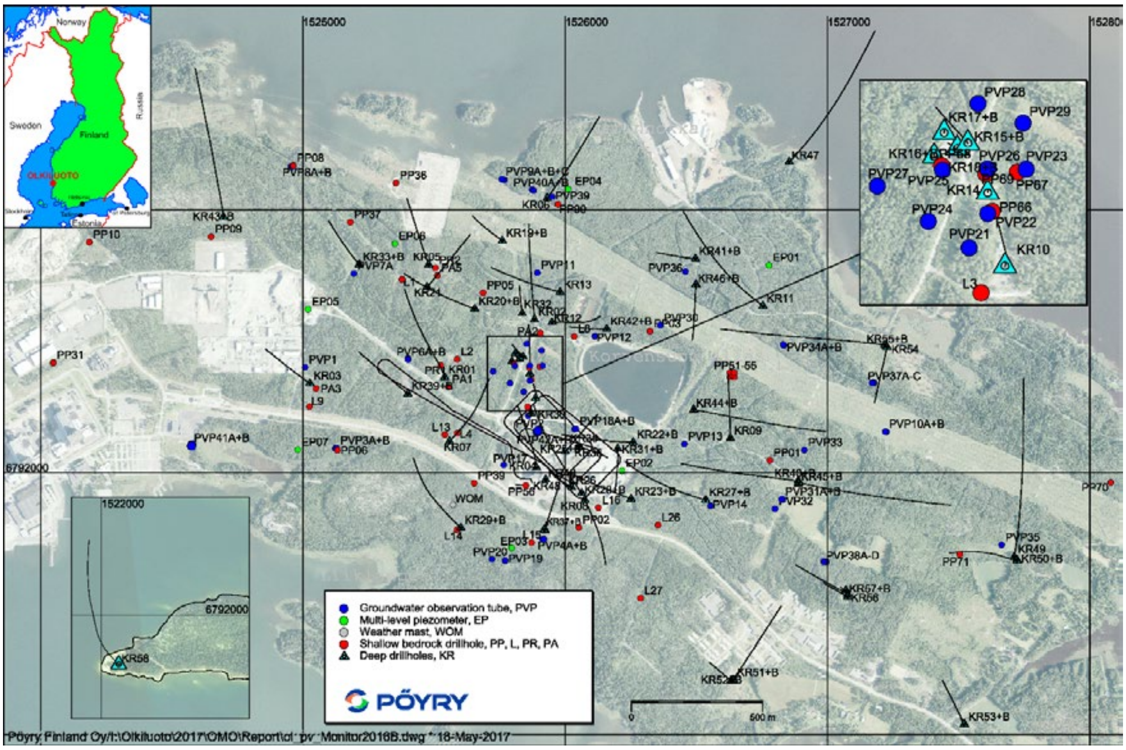

Figure 1. Aerial photograph of the Olkiluoto repository site with drillholes and other monitoring points. The surface projections of deep “KR” drillholes are shown as black curves. Grid size 1 km. Insert in the upper left-hand-side corner presents the location of Olkiluoto in Finland.

SAGOR phase [3] and identifying potential technologies for safeguarding geological repositories [4]. The safeguards-safety interface was indicated already by the SAGOR group [5], but the use of operator’s data and safety analysis instead of independent verification has been an obstacle for the IAEA to apply the these methods and data available at the repository site.

The operator Posiva runs a safeguards programme since the early stages of the site investigations and the excavation of the ONKALO. Under that programme, the design information is generated e.g. by laser-scanning and maintained in the safeguards-by-design process, and site declarations are updated for the IAEA verification. In addition, detected microseismic events in Olkiluoto have been regularly reported to STUK as the contribution of the monitoring programme to national safeguards implementation. The monitoring results can be used to generate state findings to be ascertained by the IAEA according to the Safeguards Agreement, and moreover, the public results can be included in the IAEA data analytics and in included in the state-level evaluation on the fuel cycle-related activities.

The aim of this study is not to develop a independent verification methods for the IAEA, but to facilitate its and in particular STUK’s safeguards assessment by increasing Olkiluoto site understanding using all information available as proposed already in 2006 [6]. The geoscientific monitoring programme at the Olkiluoto repository site was updated in 2016. Therefore the reassessment of its safeguards relevance was carried out in 2017 [7].

2. Monitoring programme and its potential in safeguards implementation

Olkiluoto Monitoring Programme (in Finnish: Olkiluodon monitorointiohjelma, OMO) has formally existed since 2004 [8], when Posiva started the excavation of the ONKALO, although some of the measurements were started more than a decade earlier. The programme has gradually evolved over time on the basis of experience gathered and changes in the needs for research. An updated programme was introduced in 2012 [9] and in 2016, some further adjustments were made and the duration of the programme extended to include the years 2017–2019 by publishing separate updating memos for the six sub-programmes or disciplines: rock mechanics [10], hydrology and hydrogeology [11], hydrogeochemistry [12], surface environment [13], engineered barrier system [14], and foreign materials [15].

2.1 Rock mechanics monitoring

Rock mechanics monitoring concentrates on the assessment of tectonic movement and bedrock stability in Olkiluoto and the surrounding area. For the most recent annual monitoring report on rock mechanics, see Haapalehto et al. [16]. Table 1 presents the two methods in the programme that are assessed relevant for the implementation

Process	Method	Location	Frequency	Relevance to safeguards
Seismicity, reactivation of bedrock structures	Microseismic monitoring	18 automatic stations	Continuous	Located seismic events indicate excavation by blasting
Thermal evolution	Monitoring of temperature	Temperature profiles in drillholes	During geophysical and flow loggings	Anomaly in temperature profile may indicate open space near the drillhole

Table 1. Targets of rock mechanics monitoring assessed relevant for safeguards.

of safeguards. The first one, microseismic monitoring, is currently the only part of the monitoring programme whose results Posiva submits for safeguard purposes. In addition to the methods in the table, rock mechanics monitoring includes a number of studies that are not considered relevant for safeguards. The tectonic movement of bedrock is monitored by GPS measurements of the relative positions of fixed pillars, and the post-glacial isostatic uplift by precise levelling. In the underground premises, the stability of the excavated rock is monitored by visual observation of spalling and by using extensometry to investigate rock stress redistribution in newly excavated spaces and the possible reactivation of bedrock structures at fracture zone intersections. Tunnel air temperature is also continuously monitored.

Microseismic monitoring is actually aimed at studying natural seismicity and detecting any activation of bedrock fractures that the construction of the repository may induce. However, the bulk of the recorded events are blasts from excavation. The events can be located with sufficient spatial accuracy to ensure that they are related to the licenced construction. As an example of microseismic monitoring data accumulated during one year, Figure 2 presents the seismic events detected in 2010 within the seismic “ONKALO block”, a 2 km × 2 km × 2 km cube surrounding the repository. Most of the events were blasts related to the excavation of the lowest straight section of the access ramp; the marks are coloured on the basis of time, so that the progress of excavation is clearly visible. There also occurred seismic events on or near the ground surface that were associated with construction of pipelines and buildings.

Experience from the time of the excavation of ONKALO has proven that microseismic monitoring is able to detect tunnelling by blasting reliably and accurately. Sensitivity to excavation by boring has also been demonstrated by Saari and Malm [17], as well as the ability to distinguish simultaneous blasting at an undeclared location from declared excavation. The obvious advantages of microseismic monitoring in detecting clandestine tunnelling are that, firstly, it covers the entire volume of host rock between and beyond the network of drillholes and other monitoring locations, and secondly, that blasts are detected immediately. On the other hand, because of the large sampling frequency of seismic sensors, the measurement data cannot be stored as a continuous time series, but the measuring stations are programmed to store and transmit only the sequences of data where a seismic event occurs according to certain triggering criteria.

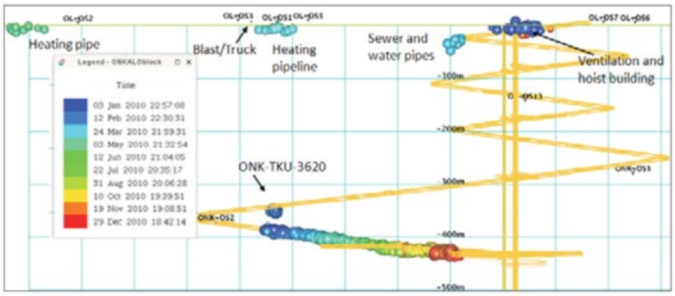

Figure 2. Microseismic events detected near the ONKALO in 2010 [13]. Grid size is 100 m ×100 m and the colour scale indicates time of the event from January (blue) to December (red). The ONKALO access ramp and shafts are shown in orange.

The second method of rock mechanics monitoring that is assessed to have relevance to safeguards is the monitoring of thermal evolution of bedrock by temperature measurements in drillholes. This assessment is based on the observation of Johansson et al. [19] that the excavation of the tunnel has affected the temperature profiles measured in a deep characterisation drillhole. In the temperature profile acquired in 2015, there are two clearly observable anomalies at depths where the access ramp passes the drillhole at distances of about 20 and 35 metres. The excavation reached these closest points in March 2009 and May 2010, so that the observed temperature effect has taken 5–6 years to develop. Although this demonstrates that thermal monitoring can potentially detect unknown tunnels, the method is evidently very slow and uncertain for the following reasons: the tunnel has to pass a drillhole relatively closely, it takes a long time before the existence of the tunnel alters the temperature of the surrounding rock mass sufficiently for detection (depends on distance but typically order of years), and temperature profile measurements are not carried out systematically in all drillholes but only in those that are selected, by other criteria, for groundwater flow logging.

Process	Method	Location	Frequency	Relevance to safeguards
Evolution of hydraulic head	Hydraulic head monitoring	Packed-off surface drillholes and ONKALO drillholes	Hourly	Detects tunnel excavation in case it causes a change in the flow of groundwater from a monitored hydrogeological structure.
	Analysis of pressure responses	Hydraulic head data	During geophysical and flow loggings	

Table 2. Targets of hydrogeological monitoring assessed relevant for safeguards.

2.2 Hydrological and hydrogeological monitoring

Hydrological and hydrogeological monitoring comprises of studies of groundwater level, hydraulic properties of the bedrock and overburden, hydraulic head and flow of groundwater in the bedrock, inflow into tunnels, and the influence of the Korvensuo Reservoir, the only remarkable body of surface water in Olkiluoto. For the most recent annual monitoring report on hydrology and hydrogeology, see Vaittinen et al. [20]. Of all the related measurements, only the automatic monitoring of hydraulic head of groundwater in packed-off deep drillholes, and the analysis of pressure responses in the head data, are assessed relevant for the implementation of safeguards (see Table 2). Hydraulic head is a quantity used in hydrogeology to express groundwater pressure, equal to the elevation of the (real or theoretical) surface of a column of water connected to the groundwater system. It is more practical than the actual pressure because it is the gradient of head, not of pressure, that determines the flow velocity of groundwater.

In addition to hydraulic head monitoring, some other methods of hydrogeological monitoring can also yield indications of excavation or construction on ground surface, but with such uncertainty and long delay that their relevance to the implementation of safeguards is merely hypothetical. These methods include the monitoring of groundwater level in shallow drillholes and groundwater observation tubes, and the monitoring of groundwater flow and hydraulic properties in deep drillholes by flow logging. In a few cases during the construction of the ONKALO, earthwork on the surface and tunnel excavation have affected groundwater level to an observable extent, but with a delay and at a short range only, so that the activity has evidently been first observed visually.

Hydraulic head is monitored in most of the almost 60 deep (up to a depth of 1 km) characterization drillholes in Olkiluoto. To enable head monitoring and to prevent artificial hydraulic connections in the vertical direction, the drillholes have been packed-off, in other words equipped with a set of inflatable packers that divide the drillhole into hydraulically isolated sections. A maximum of eight packer sections in one drillhole can be connected to the top of the drillhole with a hose so that the water level in the hose and, therefore, the hydraulic head in the section can be measured. Hydraulic head data together with results on groundwater flow and hydraulic conductivity are used to study the effect of excavation on the groundwater system, in hydrogeological modelling of Olkiluoto, and in the interpretation of hydrogeochemical observations.

The ability of hydraulic head monitoring to detect tunnel excavation and other underground activity results from the repository being constructed in crystalline bedrock, where fracturing and thus also hydraulic conductivity is concentrated in deformation zones that have formed during the geological evolution of Olkiluoto. For a detailed description of the geology of the site, see Aaltonen et al. [21]. The data on the geology and hydrogeology of Olkiluoto, gathered by various methods including monitoring measurements, has been used to compile a hydrogeological structure model of the site [22]. It describes the hydraulic properties of the bedrock with approximately planar hydrogeological zones, along which groundwater is able to flow significantly more easily than in the rock volumes in between. Figure 3 presents a 3D visualisation of the current hydrogeological structure model of the Olkiluoto area. Monitoring of hydraulic head mostly concentrates on the modelled zones, because they are essential for both the planning and the long-term safety analysis of the repository.

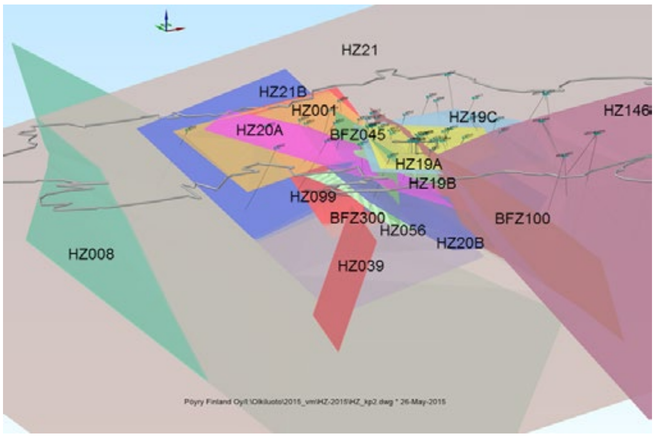

Figure 3. Visualisation of the hydrogeological structure model of Olkiluoto. Coloured polygons represent hydrogeological zones (HZ+number) or brittle deformation zones (BFZ+number), the thick grey line the shoreline of Olkiluoto, and thin black lines deep drillholes. View from the south-west.

The sensitivity of hydraulic head monitoring to excavation is most clearly demonstrated by data from the time when the construction of the ramp reached the hydrogeological HZ20 system, consisting of zones HZ20A and HZ20B of the structure model, in the summer of 2008. Figure 4 shows these zones, the ONKALO in the extent in 2017, and some of the drillholes with hydraulic head monitoring sections. Before blasting through the zone, a core-drilled pilot hole was made into the planned tunnel profile for investigations. The pilot hole penetrated the HZ20 system, causing a leak that lasted for over two weeks. Figure 5 presents a plot of the change of hydraulic head during the leak in selected monitoring sections of drillholes intersecting the HZ20 system. The largest head response occurred in section L4 of drillhole OL-KR4, which lies only a few dozen metres from the leaking point. The interruption in the data from that section, as well as the almost as strongly affected L2 of OL-KR22, results from the water level in the measuring hoses in the drillholes falling below the pressure sensor. Uninterrupted data exists from section L2 of OL-KR25 (230 m from the leaking point), where the head decreased by about 8.5 m before the leak stopped. In other monitored drillhole sections in the HZ20 zone, the response decreases with distance still being about 1 m in section L8 of OL-KR5, which lies about 900 m to the north-west of the leak point, and 1.6 m in L1 of OL-KR44, 1,000 m to the east.

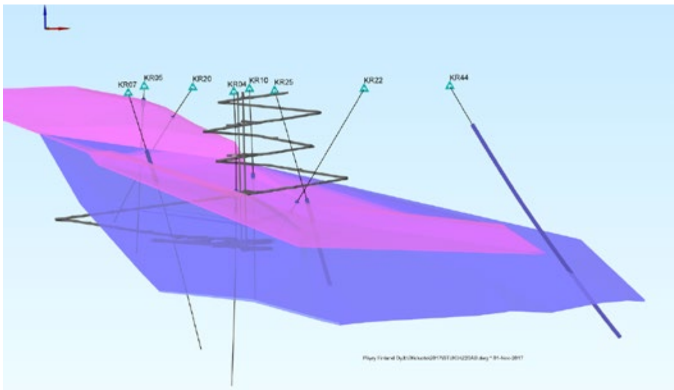

Figure 4. 3D illustration of the ONKALO (grey), hydrogeological zones HZ20A (purple) and HZ20B (blue), and some head monitoring sections of drillholes where responses to the leaks discussed in the text were detected. The drillholes are presented with black lines and the selected monitoring sections with thick blue lines. The spiralling access tunnel is about 5 km long and reaches the depth of 450 m from ground surface. View from the south.

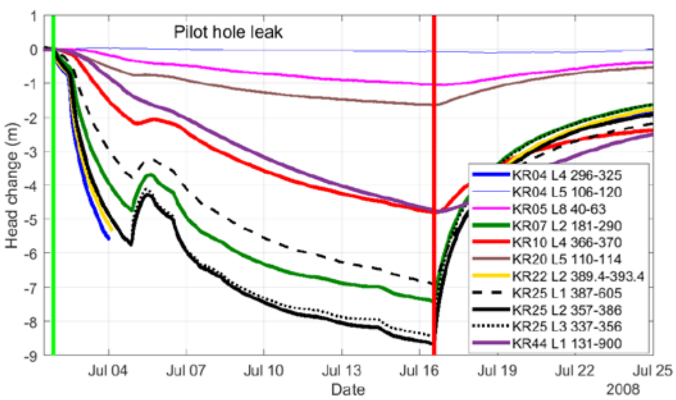

Figure 5. Change of hydraulic head in some monitored drillhole sections during a leak from a pilot hole intersecting the HZ20 structure. The vertical green and red lines mark the beginning and end of the leak, respectively. Drillhole section labels consist of a drillhole code (KR+number), section code (L+number), and range of drillhole length in metres.

The second example is also related to the HZ20 system. In July 2009, as a preparation for the raise boring of one of the vertical shafts, grouting holes were drilled at the level of zone HZ20. During a leak from one of the holes, head changes graphed in Figure 6 occurred. In about 12 hours, head decreased by almost 20 m in drillhole sections L3 of OL-KR4, L2 of OL-KR25, and L1 of OL-KR22. The response was much smaller or zero in other sections of the same drillholes, demonstrating how hydraulic effects propagate significantly better along the hydrogeological zones than in other directions.

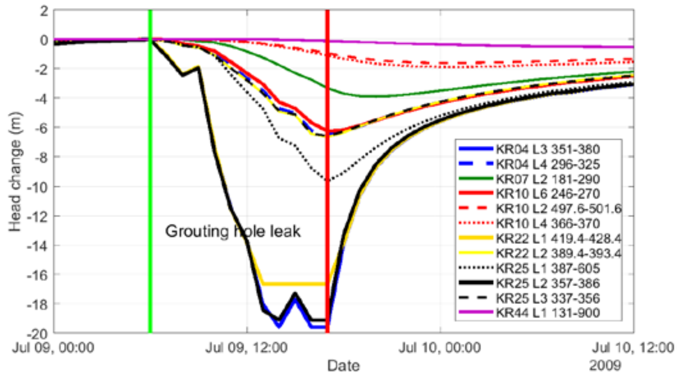

Figure 6. Change of hydraulic head in some monitored drillhole sections during a leak from a shaft grouting hole intersecting the HZ20 structure. The vertical green and red lines mark the beginning and end of the leak, respectively. Drillhole section labels consist of drillhole code (KR+number), section code (L+number), and range of drillhole length in metres.

During the excavation of the ramp, dozens of responses to temporary groundwater leaks, similar to the two examples presented here, have been observed. Most of them have been mediated by zones HZ19 and HZ20. Moreover, in a number of monitored drillhole sections, a long-term drawdown (decrease of head) has developed due to hydraulic connections to the underground premises. On the basis of this experience, hydraulic head monitoring data is sensitive to tunnelling in the repository site. When excavation or drilling intersects a major hydrogeological zone or a local hydraulically conductive feature, groundwater pressure is inevitably affected, and the effect propagates to distances of hundreds of meters in a matter of hours. Advantages in comparison with microseismic monitoring are, firstly, that continuous monitoring data is automatically stored from all operational sensors and, secondly, that the effect of excavation is not instantaneous but usually lasts for at least a couple of days even if the leak itself is quickly stopped. Therefore, missing a signal because of failed triggering of the measurement system is not possible. On the other hand, there are the evident limitations that, firstly, a response can usually only be observed if the tunnel or drillhole penetrates a hydrogeological zone that also intersects monitored drillhole sections, and secondly, the exact location of the leak causing the head decrease cannot be determined from the data because of the heterogeneity of

<table>
<tr><th>Motivation</th><th>Subject</th><th>Target/method</th><th>Frequency</th><th>Relevance to safeguards</th></tr>
<tr><td rowspan="3">Interaction between surface environment and groundwater in bedrock</td><td rowspan="3">Land use</td><td>Aerial photographs</td><td>Every other year</td><td>Can supplement present satellite imaging</td></tr>
<tr><td>Records of changes in infrastructure and other land use</td><td>Continuous</td><td rowspan="2">Can supplement present accounting of surface facilities</td></tr>
<tr><td>Update of land use grid</td><td>Next 2018</td></tr>
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Table 3. Targets of monitoring of surface environment assessed relevant for safeguards.

the structures mediating the effect. However, a rough estimate of the location can be deduced if the same effect is observed in more than one monitoring section.

2.3 Hydrogeochemical monitoring

Hydrogeochemical monitoring studies the evolution of groundwater properties and salinity distribution both in the overburden and deep in the bedrock. The principal method is taking and analysing groundwater samples from various targets. Some simple chemical parameters are also monitored continuously in situ, for example pH and conductivity of groundwater leaking into the tunnel. Issues of interest range from the natural chemical and microbiological properties of groundwater in the repository site to human influence due to foreign materials used underground. For the most recent annual monitoring report on hydrogeochemistry, see Lamminmäki et al. [23].

It is, in principle, conceivable that undeclared tunnel excavation or construction on the surface would give rise to detectable changes in groundwater chemistry by disturbing groundwater flow and introducing foreign substances. However, such effects are likely to be slow, limited in range, and ambiguous to interpret. The relevance of all geochemical monitoring to the implementation of safeguards is thus hypothetical at best.

2.4 Monitoring of the surface environment

Monitoring of the surface environment includes long-term investigations to acquire site-specific input data for biosphere modelling, research of the interaction between surface environment and groundwater, and studies of the environmental impact of the final disposal project. Moreover, radiological studies aimed at establishing a baseline for the future monitoring of radioactive releases from the disposal facility have been part of the programme, but in the 2016 update, they were organized into a separate project. For the most recent annual monitoring report on surface environment, see Pere et al. [24].

Among the studies of surface environment, the monitoring of land use is assessed relevant to the implementation of safeguards (see Table 3). It involves aerial photographs taken every other year, keeping record of changes in infrastructure and other land use, and maintaining a land use grid describing the principal use of every 50 m × 50 m square of Olkiluoto. All these data are useful for supplementing the present material used to verify Posiva's design information and site declaration.

Some targets of the monitoring of surface environment have hypothetical but no practical relevance to safeguards: noise measurements or the chemical monitoring of a sedimentation pool containing process water pumped from the underground premises and of ditches that lead waters from the construction site and rock spoil piling area to the sea could, in principle, reveal undeclared activity, but similarly with the hydrogeochemical monitoring discussed above, with high uncertainty and in an ambiguous way. The rest of the targets, like studies on the quality of sea and drainage water, recording forest and aquatic management activities, monitoring surface hydrology and meteorology, and evaluating the impact on exploitable natural resources, have no relevance to safeguards.

2.5 Monitoring of the engineered barriers

In the KBS-3V [25] final deposition concept that Posiva plans to implement, the spent nuclear fuel is encapsulated in the original fuel elements into cylindrical canisters with a copper casing surrounding a cast iron interior. After emplacement into vertical deposition holes, the canisters are surrounded with a buffer of bentonite clay blocks, and finally the tunnels are backfilled with bentonite, and tunnel openings and drillholes are closed with various plugs and seals. The canister, bentonite buffer, and tunnel backfill constitute the "engineered barrier system" (EBS) that together with the natural barrier of bedrock is intended to ensure containment of the deposited radioactive material, protection against external disturbances, and retention and retardation of any releases. Posiva's monitoring programme includes a separate discipline for EBS monitoring, which is still in the development stage. Therefore, EBS monitoring does not currently produce results relevant for the implementation of nuclear safeguards.

3. Summary and conclusions

This article discusses the Olkiluoto Monitoring Programme and its potential in implementing nuclear safeguards on the disposal facility for spent nuclear fuel that Posiva Oy is constructing in Olkiluoto, Finland. A systematic assessment of each monitoring method leads to the conclusion that three of them produce safeguards-relevant results: microseismic monitoring, automatic hydraulic head monitoring in deep drillholes, and land use monitoring. In addition, some methods can, in principle, indicate surface excavation or tunnelling, but only at a short distance (if at all) and after the activity would already have been detected visually.

Results of microseismic monitoring, i.e. the detected and located seismic events in Olkiluoto and the surrounding region are reported to the Finnish Radiation and Nuclear Safety Authority (STUK) for safeguards assessment since the early stages of the excavation of the repository. This method of monitoring has proven to accurately detect blasts from underground excavation as well as on the surface.

Automatic hydraulic head (groundwater pressure) monitoring acquires hourly data from over 200 packer sections of deep drillholes in Olkiluoto. A significant share of the monitored sections have been positioned in sub-horizontal hydrogeological zones, where pressure variations, caused by groundwater leaking from the zone into drilled holes or excavated spaces, have been observed to spread over long distances. Therefore, hydraulic head monitoring, has potential to reveal clandestine tunnelling or drilling from the ground surface towards the depth of the disposal facility.

The advantages of the hydraulic head monitoring include sensitivity to all methods of excavation in contrast to microseismic monitoring that can reliably only detect blasting. Moreover, the effects on head that can reveal underground activity are long-lasting or even irreversible, so the probability of missing a significant signal is low. The most obvious disadvantages are that the source of the signal cannot be located with the same accuracy as in microseismic monitoring, and that the method is sensitive only to activities within the hydraulically conductive zones. Posiva already reports interpreted results of hydraulic head monitoring regularly for the supervision of the construction and long-term safety of the disposal facility. Thus, this information could with relative ease be taken into account in the implementation of nuclear safeguards.

The monitoring of land use in Olkiluoto involves aerial photography and updating a land use grid every second year. These results, if reported to STUK for safeguards purposes, can be used to supplement other aerial or satellite imagery of the Olkiluoto site in verifying the declared surface constructions and activities. The monitoring reports are published and thus these can be used by the IAEA as open source information when analysing the nuclear fuel cycle-related activities in Finland.

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