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Geophysical Methods To Exclude Undeclared Activities At A Geological Repository

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ABSTRACT

Disposal of spent nuclear fuel is expected to be carried out according the IAEA safety standards. The site investigations are needed to demonstrate the suitability of the site to be selected for the geological repository. Results from investigations are also used for the design of the repository layout. The hydraulic impermeability of the hosting geological formation surrounding the repository is essential for the safety case. Therefore, performance of rock mass and engineered systems as containment and isolation barriers are considered during planning, design, construction, operating and closing of the repository. At a geological repository the new challenge is to verify the spent fuel accountancy using indirect methods by excluding undeclared activities.

The designers and rock engineering of a repository need site characterisation data from different geophysical surveys, pilot drillholes ahead of tunnel front with related geophysical, geological, and hydrogeological investigations, and monitoring. Geophysical methods have developed and focused on the site-specific scientific and technical needs. Their role in safeguards have been under discussion during the development of IAEA safeguards approaches for geological disposal to detect undeclared activities. Geophysical methods have been proposed for Design Information Verification as the rock engineering needs the understanding of the host geology. The exploratory works can provide sets of safeguards-relevant information, but in practice only the engineered underground constructions can be accessed to be verified; and, only until backfilling of the drifts and tunnels in the repository. The other application is related to Containment and Surveillance, i.e. detection of human intrusion. In particular, the monitoring of the site conditions give assurance about the natural responses of the formation and should detect and localize any unknown and unwanted phenomena. The Additional Protocol was introduced for this purpose to exclude undeclared activities, but it does not include the application of geophysical techniques. However, the public research for safety case supports the same safeguards mission at a geological repository. In this presentation, the current understanding the applicability of geophysical techniques for safeguards purposes is analysed.

INTRODUCTION

Waste management has always been at the centre of many debates about nuclear energy and the sustainability of nuclear activity around the world. The disposal of nuclear waste; in particular spent nuclear fuel, is a political, economic and scientific challenge. The acceptance of a selected repository site needs scientific statements and proven passive safety for hundreds of thousands of years. The performance of the engineered and natural isolation barriers including the possible transport routes of radionuclides in the host geology at the selected site have to carefully explored beforehand, but the disturbance of site should be minimal. Therefore, the exploration geophysical methods are vital non-destructive methods to locate impermeable and stable hosting geological formations for a repository.

The very long-term nature of radioactive waste disposal is also not easily compatible with the economic lifetimes of the original liability holders. This requires that all elements of the system – accrued funds, expected future returns, the lifetimes of nuclear power plants, the expected costs of politically sustainable technical solutions and the liabilities for residual risks – are reviewed and realigned at regular intervals. The OECD/NEA has reviewed the current economic guarantees and risks in assessing the long-term economics (OECD 2021). The financial resources for the decommissioning of nuclear installations and the handling of spent nuclear fuel and radioactive waste is guided the Council Directive 2011/70/Euratom that is a legally binding framework for the responsible and safe management of spent fuel and radioactive waste within the European Union.
Also, the IAEA Joint Convention on Safety of Spent Fuel Management and Safety of Radioactive Waste Management (1997) encourages Member States to take the appropriate steps to ensure that adequate financial resources are available to enable the appropriate institutional controls and monitoring arrangements to be continued for the period deemed necessary following the closure of a facility. The principle of "polluter pays" is here extended to the period when there is no foreseen nuclear industry.

The Joint Convention contains separate articles on spent fuel and radioactive waste management including general safety requirements, siting of proposed facilities, design, and construction of facilities. The binding framework requires the assessment of the geological formation for the siting of proposed facilities. The assessment of a suitable geological formation and design of disposal facility needs geoscientific expertise among other issues. The guidelines to develop the waste management facility are given in the IAEA Specific Safety Requirements, SSR-5.

In the IAEA SSR-5 the Requirement 15, in particular Chapter 4.27, gives the framework for site characterisation "Characterization of the geological aspects has to include activities such as the investigation of: long term stability, faulting and the extent of fracturing in the host geological formation; the volume of rock suitable for the construction of disposal zones; geotechnical parameters relevant to the design; groundwater flow regimes; geochemical conditions; and mineralogy." One of the paradigms for nuclear waste management is not to unnecessarily disturb the site conditions. Therefore, the necessary geological sampling, i.e., drilling and coring should be at much lower that typically needed in mining or even rock construction. Regarding the spent nuclear fuel disposal, the asset, volume of good quality rock, cannot be certified or proved with dense drilling programme, as compared to mining. Therefore, non-intrusive geophysical methods or borehole methods have been developed for the site-specific purposes. As the geophysical methods are used applied for the purpose to explore the most stable and impermeable part of the site under investigations the results can serve to the safety and safeguards missions.

Monitoring is also needed to confirm the safety case under Requirement 21 of the SSR-5: A programme of monitoring shall be carried out prior to, and during, the construction and operation of a disposal facility and after its closure, if this is part of the safety case. This programme shall be designed to collect and update information necessary for the purposes of protection and safety. Information shall be obtained to confirm the conditions necessary for the safety of workers and members of the public and protection of the environment during the period of operation of the facility. Monitoring shall also be carried out to confirm the absence of any conditions that could affect the safety of the facility after closure.

This international guidance makes the framework to collect and document site investigation data very precisely. The national building codes are usually not that strict for mining or civil engineering, but nuclear authorities regulate according the IAEA guidance – and for understanding the site geology, the designers and rock engineering of a repository need site characterisation data from different geophysical surveys, pilot drillholes ahead of tunnel front with related geophysical, geological, and hydrogeological investigations, and monitoring. Geophysical methods have developed and focused on the site-specific scientific and technical needs.

NOMENCLATURE DIFFERENCES BETWEEN ENGINEERING, SAFETY AND SAFEGUARDS

The second paradigm is the fact that traditional safeguards with timely inventory verifications cannot be applied to the disposed of nuclear materials after emplacement. Therefore, the application of geophysical methods has been discussed within the IAEA and the Expert Groups SAGOR and ASTOR that have involved in the development IAEA safeguards to geological repositories since late 1980s. The disposed canisters might be detected by remote techniques, depending on the capabilities of the selected methods, their distance to target, target size and contracts to the material properties and differences between to target and the geological media. In favourable circumstances some indications on the disposed materials might be observed. Therefore, geophysical methods have proposed mainly for verification of the host rock properties and access control. Methods are difficult to standardise for exploration and even more challenging is the proven use in nuclear safeguards. Also, the terminology and nomenclature between the different disciplines does deviate.

Geophysical methods have been proposed for Design Information Verification as the exploratory works can provide sets of safeguards-relevant design information, but in practice only the engineered underground constructions can be accessed to be verified. The geological formation itself cannot be verified even by repeating the different surveys. It is obvious the person-depended features in selecting instruments, survey design and data collection parameters, processing and visualisation will give different interpretations of the rock formations. The coverage, range and resolution of an individual survey is likely to remain incomplete. However, the rock engineering needs the understanding of the host geology and geophysical information is needed for design. The Design Information Questionnaire (DIQ) for geological repositories includes question about geological characterisation activities and even the rock reinforcement methods. Thus, the definition of design information may be understood in different ways. During the SAGOR and ASTOR projects several case histories and proposal were presented to support the use of geophysical techniques for IAEA safeguards. These are recently reviewed by Heikkinen (2021).

Geophysical monitoring has been proposed for the long-term safeguards of the repository to detect undeclared activities as a Containment and Surveillance (C/S) measure. In particular, the monitoring of the site conditions give assurance about the natural responses of the formation and should detect unknown and unwanted phenomena. The monitoring may give indications about unknown features in the host rock, but its role to create safeguards-relevant evidence is not obvious - although monitoring serves for the purpose to confirm the integrity of the geological formation. There will be the practical question about the selection sensors and methods, that of the size of the object to be “sealed” and monitored, and also the long-term maintenance of equipment. The current monitoring provides information about the stability and impermeability of the host rock and has been reviewed by Pentti and Heikkinen for the Olkiluoto repository (2017).

As pointed out above, the role of safeguards at a geological repository is not obvious. Traditionally, material accountancy is the safeguards measure of fundamental importance and timely statements of verifications are to be provided (INFCIRC/153). In a repository this can cannot not be performed due the inaccessibility of the material. The IAEA has indicated (2018) that the primary safeguards objective in geological repositories is the detection of diversion. The IAEA (2018) proposes even the sharing of monitoring data from access control to have common benefits between safeguards, safety and security. However, it is commonly understood that nuclear safety and security are national responsibilities. One of the safeguards interests is the construction of additional drifts and tunnels. Geophysical surveying and monitoring methods have capability to exclude these undeclared activities with reasonable credibility, but the detection of undeclared drifts or tunnels is challenging.

The third paradigm is that the Additional Protocol was introduced for this purpose to detect undeclared activities, but it does not include the application of geophysical techniques. On the other hand, the AP extents the verification task to the whole state in concern instead of the specific nuclear facilities or repository installations. However, the public research for safety case supports the same safeguards mission at a geological repository. Thus, the IAEA has the full possibility to use the geophysical research in the state-level approach and assess how the state is following the IAEA safety standards. The advance is that the acceptance of the waste management and the geological repository need public acceptance and thus all geophysical information is made public unlike that at many other commercial construction projects. The IAEA perform the IRRS, IPPAS and ARTEMIS missions to assist the Member States to follow their nuclear safety, security and waste management obligations. These IAEA findings are essential also when ascertaining the safety and security of disposal for safeguards conclusions. This kind of 3 S might facilitate safeguards implementation at the state-level.

TUNNEL DETECTION CHALLENGE

The detection of unknown tunnels has been one the targets for geophysics for years. The tunnels dug e.g., for trafficking routes under fences or borders have been in the interests of military or civil guards from the ancient times (e.g. Won et al. 2004, Sabatier and Matalkah 2008). It rather common that the tunnel itself is difficult to detect, but the intension, technology, new infrastructure, and consequences reveal the existence or even location of the tunnel. However, the distance-to-target exercises for cylinders, buried pipe etc. and modelling have been carried out are also typical in textbook among more demanding geometries or material properties to give estimates about the detectability of a tunnel. More recently environmental and geohazard issues at old, abandoned mines have created a need to re-establish knowledge about old tunnels and shafts, their subsidence risks, and possible groundwater and contamination flow paths. In these investigations, the geophysical indications are proven with drilling or sampling that gives the evidence. At the geological repository of high-radioactive material this is not acceptable. The site may be visited, but the isolation barriers shall not be disturbed. Regarding the deep geological repository concept, also the deep location exceeding credible and accurate range of investigation for most of survey techniques, is setting further challenge to detection of undeclared activity. The safeguards and security challenge is to exclude the undeclared activities by confirming the intactness of the host rock and that is has been built for its purpose.

Isaksson et. al. (2010) analysed the possibility to detect and locate an abandoned repository from the ground level. Analysis was using the known contrasts of surrounding rock mass and engineered structures within the rock, from down to depth of 500 m. Without prior information of existence of a repository, only seismic reflection method might provide adequate resolution and range to detect related tunnel network. However, the possible indications give no information about the nuclear material content. Neither can the indications describe in detail the layout of the repository. In case the layout of the repository is not known beforehand, accurate description of tunnel locations and purposes may not be obtained by remote sensing. Even if an adequate description of the layout survives, it is unlikely to verify the details from distance.

The geophysical toolbox is strong and multifold when adjusted for a given purpose and target. Under the non-proliferation framework, the UN Special Commission's missions to Iraq in 1990s showed that the extensive toolbox of magnetic, gravity, electrical, electromagnetic, GPR, radiometric, seismic refraction and reflection, and underwater sonars can be brought to the remote sites in order to detect and verify buried metallic objects (Won et al. 2004). The reasoning was lack of transparency and cooperation of the State. The field studies were carried out in exploratory mode to locate targets for possible verification under the inspection framework at a given day. The working practices deviated from typical exploration tasks since the inspection framework is based on the safeguards agreements and agreed procedures. At a geological repository, the transparency and cooperation are the basic assumptions to get permission and licence to dispose of hazardous material. Therefore, the IAEA can easily assess the field investigations instead of making its own. The controversy is also due to the fact that "no additional disturbance" is allowed at a repository site. Moreover, a special geophysical mission to detect and verify deep seated activities in bedrock is unlikely to become productive. In the depth, random inspections to verify the declared usage of the underground premises might implemented to exclude undeclared activities. Success may be gained if a suspected activity would be located near or at surface close to the repository. The remote sensing techniques might the primary means to detect undeclared activities.

Tunnels, wells and boreholes are relatively small sized objects viewed from greater distance, so both their detection, separation from near-by other objects, and reliable description of layout from the distance become a challenge. The distance to target and differences in material properties are essential to study beforehand. A clandestine penetration might be collapsed of water filled in the in case there is no supporting infrastructure for ventilation or drainage. It is apparent that a number of misleading observations, called false positive alarms would easily be produced with a survey, requiring lots of checking and confirmation; and, there would always remain a possibility for a relevant event to remain unnoticed.

Despite of these challenges, there exist several potential methods to detect anomalous features in the host rock at an engineered geological repository, e.g., iron containing support structures or tools can be observed using magnetic and electromagnetic methods and tunnel spaces can be detected using gravimetric measurement. Moreover, tunnel related voids or electrically conductive structures can be detected with electric tomography surveys. Any of these methods is limited in its functionality to a range of 10–60 m in maximum from the survey position in a tunnel or borehole. The ground penetrating radar (GPR) and seismic survey provide possibilities to detect tunnel surfaces as reflecting objects. The GPR will not operate through metal containing support structures or within electrically conductive bedrock, and highest range is delimited also by interference by tunnel walls and installations. Range is even in favourable conditions (from borehole at best) some tens of metres. Seismic reflection method is the most capable in producing imaging data from the bedrock behind the tunnel wall or from boreholes, up to distances of several hundreds of metres. Tunnel geometry is setting limitations to reasonable survey design. The method also requires contact to rock surface, considerable number of sensors and tools to be installed and moved in tunnel, time to implement and process, and requires highly expertized personnel to carry out. Any of the listed methods would also be prone in producing number of false positive anomalies of natural origin. Best possibility to avoid confusion in application of the results would be carrying a baseline and repeat type of survey, where only changes to initial survey results would be paid further attention.

Imaging in higher detail would often require closer distances to the target that what is acceptable at a regulated repository. This could be enabled by using tunnels or boreholes placed in the near volume of repository, which however cannot be allowed as these would be risking the long-term safety of the disposal. Boreholes could be used for active survey from closer distance, or for monitoring, which would require permanent instrumentation that would have a limited operational lifetime and would require frequent maintenance or replacement.

A combination of surveys including accumulating data from seismic monitoring, and timely repeated seismic surveying using either passive (natural and cultural noise related) signals or selectively implemented active source using surveys, provide a likely technology to exclude existence of an undeclared activity within the repository perimeter. In case of an attempt to intrusion into the repository, an approach from distance through the rock mass would let several months of early warning time to react in observations, as tunnel construction is fairly slow process, requiring also plenty of logistics and for example energy resources. Therefore, the tunnel detection at a repository might be less laborious by concentration in motivation, available infrastructure, assessment of safety case compared to the challenged applying potential exploration methods.

REFLECTIONS FROM TUNNELS AT REPOSITORY SITES

Site investigations are needed to demonstrate the suitability of the site to be selected for the geological repository. The hydraulic impermeability of the hosting geological formation surrounding the repository is essential for the safety case at repositories built in hard, but brittle crystalline bedrock. In the pre-nuclear phase of a repository or in underground research laboratory there are tunnels and underground premises that serve also for site specific “tunnel detection exercises”; although, the main interest is to locate water bearing fractures in the rock mass. One of challenges is to distinguish between the two kinds in indications since both types of discontinuous features in the host rock may introduce similar anomalies, i.e., reflections in geophysical soundings. During the develop of site investigations at potential repository sites some indications were obtain from near-by drifts and shaft. The first observations were from Stripa project in Sweden using borehole radar, and later from Grimsel site in Switzerland, and from Äspö underground laboratory in Sweden, using seismic tunnel reflection surveys.

At the Olkiluoto site characterisation has been based on borehole investigations using several methods including borehole-to-borehole or to surface tomography electric, electromagnetic and seismic surveying, in the site investigation phase, and 3-4 main logging methods in the pilot hole cored before tunnelling. The access tunnel to the repository level can also be dealt with like a person-size borehole itself. Some geophysical soundings have been carried out at the tunnel surface to e.g., to estimate excavation damaged zone, follow fractures that are met at the tunnel wall etc. Heikkinen (2021) analysed the resolution and detection capabilities of the reported active electromagnetic, electric, and seismic sounding and corresponding passive monitoring at several site in different geological circumstances.

Micro seismic monitoring has been used for the detection of seismic events at Olkiluoto, either natural tectonic and stress-field originated, or events induced by ongoing excavation and stress-field redistribution (as required in the SSR-5). It has adequate operational history starting before the excavation of the repository proving detection and localisation capability of excavation blasts to distances of several kilometres and within the repository construction area using semi-automated seismic event localisation. Both drill and blast excavation and tunnel boring machine (TBM) operated tunnelling creates mechanic noise which can be detected and localised using seismic monitoring by experienced specialists. Therefore, seismic monitoring is been considered safeguards-relevant and the localisation have been published in the annual reports to give confidence about the declared excavations works. The challenge is that tectonic earthquakes may cluster in fracture plane that is difficult differentiate from man-made clusters. The analysis needs expertise and tailored software.

The safeguards-by-design guide (IAEA 2018) indicates the challenges and indicates that the IAEA verification is not expected to duplicate all of site characterisation. However, there are proposals to carry out research for e.g., seismic monitoring for human activities and ground penetrating radar for hidden rooms. The experience from Olkiluoto indicates that traffic in tunnel, construction and building, e.g., drilling and hammering at underground rooms creates vibration and seismic noise in such an amount that the monitoring can focus only on excavation blasts. The penetration of the GPR in Olkiluoto is so limited, that hidden rooms should be search for using more suitable methods. Great distance and small size of objects would not allow any detection of hidden rooms from ground surface, nor credible separation from declared, existing rooms. This kind of work has to be carried out from tunnels anyway and is possible only before backfilling of the repository space. The site understanding is essential to define the practical methods. In our understanding the IAEA should not duplicate any of the site characterisation for safeguards purposes but ascertain the research and development work for repository safety and security for cost-effectively safeguards conclusions.

CONCLUSIONS

Non-destructive and indirect geophysical methods are essential to locate stable and impermeable rock formations for geological disposal of nuclear waste. The disposal is well regulated according to IAEA safety standards that on the other hand limit the acceptance to disturb the natural conditions of a potential site (Paradigm 1). This increases the need for to non-destructive geophysical methods during the repository development.

Geophysical methods are not capable for nuclear materials verification (Paradigm 2), but they can be interpreted as tools to exclude safeguards-relevant undeclared activities like clandestine tunnelling into a repository. However, the methods are laborious to be applied as security measures to launch realistic alarms. Similarly, for safeguards the methods may give indications on changes in rock properties, but the detection of undeclared activities in the deep the host rock e.g. that of human access to the disposed of materials is difficult to be justified by these indirect indications without verifiable evidence. The detection must be carried out using other means than geophysics.

Long-term monitoring of a repository site can be applied by the IAEA to create deterrence against undeclared activities, but on the other hand, the safety and security are obligations of the state party to the joint convention to nuclear waste management to be assessed by the IAEA. However, the potential misuse of the disposal facility must be excluded by regular or short-noticed IAEA inspections as a routine safeguards procedure, but the long-term disposal should be assessed by analysing continuously the intentions and policies in the country (Paradigm 3). The additional protocol measures are defined for this purpose at the state-level instead of site-depended geophysics.

The costs of geophysical surveys or monitoring are difficult to estimate. The individual surveys have to be defined according to site-specific needs. Present cost estimates can be found in Heikkinen (2021). The basic principle is that the “polluter pays” requires that the cost estimate for the nuclear industry is transparent and predictable. Therefore, the unforeseen costs should be avoided, and the public geoscientific information available and review missions should be used as appropriate by the safeguards authorities instead of independently repeat the exploratory or monitoring works. This needed change in safeguards culture towards the cost-effectively state-level assessment remains as one of the main near-future challenges.

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