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Safeguards Challenges at the Back-end of the Fuel Cycle in Sweden and Finland

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ABSTRACT

Finland followed by Sweden are both expected to be the first countries in the world to construct and operate installations for the final disposal of spent nuclear fuel derived from the respective national nuclear programme. In both countries, the spent nuclear fuel will be deposited in crystalline bedrock in deep repositories. This paper discusses the similarities between the projects, but also describes relevant differences such as installation layout, site location, national legislation and concept for safeguards along with the amount and type of fuel intended for disposal.

For safeguards purposes, the last practical possibility to verify an individual spent fuel assembly is prior to the encapsulation into copper canisters, as there are no plans to open or retrieve the canisters once they have been welded and brought into the geological repository. The repositories are intended to serve as means to safely close the nuclear fuel cycle. After backfilling, the inaccessible nuclear material may be considered as beyond the concept of difficult-to-access, i.e. a repository is not a storage. This is why open-minded, even non-traditional concepts may be required in order to optimise the application of safeguards.

After encapsulation the safeguards system should rely on Continuity of Knowledge (e.g. C/S measures). The chosen measures must be reliable, robust and carefully pre-evaluated in order to avoid potential failures since re-establishing confidence in the integrity of safeguards relevant data, if needed, would likely require comprehensive methods. The back-end of the fuel cycle presents a unique set of challenges for safeguards, especially the geological repository where many conventional safeguards measures cannot be applied. These challenges have been discussed in the SAGOR and ASTOR programme since the late 1980s. Each solution poses challenges added to the practical and safety limitations that need to be taken into consideration, acknowledging the State-level approaches.

INTRODUCTION

Finland and Sweden will be pioneers in the construction of encapsulation plants and geological repositories to dispose of the spent nuclear fuel derived from the respective national nuclear program. In both countries, the concept involves emplacement of the fuel elements in copper canisters with ductile iron inserts. The canisters will then be embedded in bentonite clay (protecting against corrosion and rock movements, preventing water penetration and leakage of radioactive substances) in individual vertical deposition holes at depths of around 450-500 metres in the crystalline bedrock.

One of the motivations behind the construction of a final repository is the so-called generational goal which states that the overall goal of the national environmental policy is to hand over a society to the next generation where the major environmental problems are solved, without causing increased environmental and health problems outside the country's borders. A well-constructed geological repository should ensure a safe and secure solution for the nuclear material and thereby reduce the burden on future generations as the deposited nuclear material will be highly inaccessible once the repository is backfilled. Neither Sweden nor Finland have any plans to retrieve the canisters, unless they are damaged, once they have been deposited and the national legislations prohibit human access to the nuclear material as well as the damaging of the protective barriers like the bedrock properties that isolate the spent fuel from the biosphere. The safety of the repository will be based on a passive system aiming at maintaining technical barriers. There is no need for human involvement once the repository is backfilled, this to ensure the isolation and long-time safety during the period in which the radioactivity of spent nuclear fuel will remain a threat to humans and the environment.

National policy for spent fuel and radioactive waste management is based on the legal requirements contained in the Act on Nuclear Activities, Radiation Protection Act and Environmental Code in Sweden and on the Nuclear Energy Act in Finland. The national policies are also in accordance with the European Union's Council Directive 2011/70/Euratom establishing a Community framework for the responsible and safe management of spent nuclear fuel and radioactive waste. Another basic presumption regarding spent fuel management is the principle of direct disposal, i.e. that no reprocessing will take place even though this is not strictly prohibited by law.

FINAL DISPOSAL IN SWEDEN AND FINLAND

In Sweden the spent nuclear fuel is mainly derived from the twelve electricity-producing power reactors that are located at four sites (Barsebäck, Forsmark, Oskarshamn and Ringhals). Nine of these are BWRs and three PWRs and all were taken into commercial operation between 1972 and 1985. As of today, six of them have been permanently shut down and four units have received a license to start decommission (Barsebäck and Oskarshamn). The remaining six reactors are expected to be in operation until 2045. There are currently no plans to construct new electricity-producing power reactors in Sweden. In addition, smaller amounts of fuel from the old Ågesta reactor (the first prototype nuclear power reactor, PHWR), fuel residues from testing programmes at Studsvik, as well as a small amount of MOX fuel, will be disposed of.

The current estimate is that a total amount of around 12,000 tonnes of spent nuclear fuel, this including the continued operation of the remaining six reactors, will be disposed of at the geological repository in Sweden.

In Finland, most the spent nuclear fuel comes from the four operating power reactors that are located at two sites (Loviisa and Olkiluoto) and were commissioned in 1980s. Two of these are PWRs at Loviisa and two BWRs at Olkiluoto. Additionally, there is a new PWR unit at Olkiluoto to be commissioned soon. The research reactor in Espoo was closed down in 2015 and it is now under decommissioning. The spent fuel was returned to the USA in 2020, so there is no fuel to be disposed of, but waste management and safeguards have to continue as long as there are nuclear materials present. The final disposal installation for spent fuel is under construction in Olkiluoto on land owned by the power company. According to the Government's decisions, the amount of spent nuclear fuel shall be no more than equivalent to 6,500 tonnes of uranium, consisting of the spent nuclear fuel from Teollisuuden Voima Oyj's three nuclear power plant units at Olkiluoto and Fortum Power and Heat Oy's two power plant units at Loviisa.

One fundamental national legal requirement in Sweden and Finland, as in many countries, is that the licensees of the nuclear facilities are responsible for ensuring safe handling and disposal of the spent nuclear fuel and radioactive waste, as well as the safe decommissioning and dismantling of the facilities. The companies operating the nuclear power reactors have joint ownership of SKB in Sweden, and that of Posiva in Finland.

As the competent national authorities, the Swedish Radiation Safety Authority, (SSM) and the Radiation and Nuclear Safety Authority in Finland (STUK) respectively, are mandated to supervise all licensees of nuclear activities at domestic facilities and locations to ensure that they fulfil their responsibilities within nuclear safety, nuclear security, radiation protection, and all obligations as prescribed by the States agreements aimed at preventing the proliferation of nuclear weapons. Both authorities conduct regular inspections and assessments of nuclear and other facilities whose work involves radiation in order to ascertain compliance with regulations and licence conditions.

Even if there are many similarities between the systems for the back-end of the fuel cycle in the two countries there are some differences worth noticing. In the proposed Swedish system, still not approved by the Swedish Government, the encapsulation plant and geological repository will be located at two different sites. This poses additional safeguards challenges compared to Finland where the encapsulation and disposal takes place at the same site, and the C/S measures of the transport cask is therefore expected to be an important part of the system in Sweden. The nuclear fuel to be deposited is more diverse in Sweden than in Finland, which is why SKB plans to conduct a re-characterisation campaign before encapsulation. Their main motivation is the optimisation of the amount of material emplaced in individual copper canisters, but it may give rise to slightly different data values, e.g. for the nuclide content, compared to what has been declared to the IAEA and Euratom. It would then be desirable to make the accountancy for safety and safeguards is consistent [1]. Furthermore, STUK has developed and will carry out its own measurement program on the spent nuclear fuel with the aim to verify all spent fuel before disposal in the geological repository. On the contrary, no measurements for safeguards purposes will be performed directly by SSM. Instead SSM's role will be to oversee that the measurements conducted by SKB cover all important parameters and fulfil the nuclear non-proliferation and safety requirements.

SAFEGUARDS AT THE BACK-END OF THE NUCLEAR FUEL CYCLE

As defined by Article III in the Non-Proliferation Treaty (NPT), Sweden and Finland undertake to accept safeguards concluded by the IAEA in accordance with the IAEA Statute and Agency's safeguards system, for the exclusive purpose of verification of the fulfilment of its obligations under the Treaty with a view to preventing diversion of nuclear energy from peaceful uses to nuclear weapons or other nuclear explosive devices.

Safeguards verification for current nuclear installations in Sweden and Finland, i.e. countries with Comprehensive Safeguards Agreements (INFCIRC/193) and Additional Protocol (INFCIRC/540) in force, builds on traditional safeguards measures. These include verification of accountancy and operating records, repeated physical verification of the nuclear material inventory (e.g. PIV, SNRI, UI, CA), design information verification (DIV), and use of a variety of C/S measures. For installations such as encapsulation plants those measures may still be sufficient, however, a geological repository will pose a more unique challenge due to the fact that the nuclear material will be highly inaccessible once it has been emplaced in the repository. Furthermore, in the event that the Continuity of Knowledge (CoK) is lost, or potential anomalies or any other discrepancies arise, re-verification of the entire nuclear inventory is not practically possible. Therefore, a safeguards approach for a geological repository should be based on a concept that differs from the traditional solutions.

SAGOR and ASTOR

Technical solutions for safeguarding geological repositories have been discussed within the IAEA as well as with State representatives and experts for decades, e.g. the SAGOR and ASTOR programmes[1] which were ongoing from 1988 to 2019 [2] [3]. The background for much of these discussions originates at the inevitable point when it no longer will be possible to physically access or directly survey the copper canisters. What safeguards measures are available, and which would be meaningful to employ, in order to ensure that all nuclear material remain in the geological repository and that no undeclared activity can occur without discovery? Is underground equipment necessary or can the IAEA draw safeguards conclusions in a system where the repository is treated as a containment and monitored to ensure that nothing can be diverted? When discussing these questions it is important to consider what measures would allow for efficient and effective safeguards while providing reliability during the decades-long operational times required.

The SAGOR group developed a generic safeguards concept for geological repositories already in the 1990s. The group concluded that under integrated safeguards the diversion scenarios might be covered by State-level approaches instead of extensive safeguards instrumentation

[1] The topic have also been discussed in several other expert meetings, e.g. the ESARDA working groups C/S and Final Disposal, as well as the Low Level Liaison Committee (LLLC) Encapsulation Plant and Geological Repository working group with representatives from the IAEA, the European commission, Sweden and Finland that have been ongoing since 2013.

against the diversion scenarios that could be excluded when drawing broader conclusions about the States intensions, capabilities etc. [4]. With the implementation of the Additional Protocol in many countries the ASTOR program was aimed at practical aspects of the generic integrated safeguards approach for geological repository sites and the safeguards techniques applicable to specific geological repository sites. However, several participants from the Member State Support Programme to the IAEA attending the ASTOR meetings do not believe that these aims were achieved.

IAEA Safeguards Models

The IAEA has developed Model Integrated Safeguards Approaches for Spent Fuel Encapsulation Plants [5] and Geological Repositories [6]. The latter states that the safeguards objectives for a geological repository should include verifying the design information, maintaining CoK of the nuclear material inventories above ground and in the geological repository, and detecting potential undeclared activities. These approaches were intended to provide guidance when preparing a safeguards approach for a State under integrated safeguards, and included the possible use of geophysical monitoring to ensure integrity of the geological containment. It has, however, at many occasions been pointed out by Member State representatives that the approaches are too generic and that they do not consider the impact of the Additional Protocol and State Level Concept. The confirmed state-wide absence of undeclared activities should render certain proposed monitoring and verification activities unnecessary.

Inaccessibility of the disposed nuclear material

The concept of dual C/S is included in the IAEA Model Approaches to be applied after encapsulation, as the assemblies then cannot be reverified. This concept and the application of dual C/S with a 'difficult-to-access' designation for nuclear material in wet and dry storages were developed in the 1990s. The application of two devices, which are functionally independent and are not subject to a common tampering or failure mode, could provide sufficient confidence in the continued presence of material within a suitable containment so that periodic reverification of the material would be unnecessary. Provision for the use of dual C/S systems, with or without the difficult-to-access designation [7] [8], was made in the IAEA Safeguards Criteria 1991-1995.

It is critical that CoK is maintained throughout the entire period that the nuclear material remains under safeguards, where one efficient way has been through different C/S measures. Traditional C/S measures are useful in an encapsulation plant and may also be applicable in the entrance area of a geological repository, however, at some point in a geological repository the use of traditional C/S measures would not be meaningful or a practical option anymore. The question is when, where and how to apply C/S measures at the repository since reverification of the material is not an option at this stage. We believe that the whole C/S concept for verification underground has to be reconsidered and that non-applicable devices and measures should be avoided. For a geological repository the safeguards measures require a new way of thinking, e.g. to view the bedrock of the repository itself as part of the required C/S measures meant to ensure CoK. Upholding the integrity of the repository is already necessary to fulfil the safety requirements with the backfilling and host rock serving as isolation barriers for nuclear waste [9]. As the expected lifetime of the repository is much longer than that which can be foreseen for institutional control it creates a societal challenge [10]. The assurance of safe and secure land-use will remain a task for future generations, which can partly be assumed to fulfil the obligations as prescribed by the States agreements aimed at preventing the proliferation of nuclear weapons.

During the operational period, the integrity of the geological containment and the underground operations can be inspected and verified by DIV, CA etc. After backfilling the disposal tunnels however, DIV is not applicable for that part of the installation. The practical inaccessibility of the disposed of material might be re-assessed. A proposal by Sandia [11] was to withdraw the disposed material from the verification regime once it becomes inaccessible for measurement, which they argued could be a first step in the ending of traditional safeguards measures during the operational period. This would not be compatible with the current Comprehensive Safeguards Agreement but the foreseen inaccessibly of the nuclear material, especially after backfilling, should be acknowledged while drafting and agreeing the subsidiary arrangements.

POSSIBLE SAFEGUARDS MEASURES AND THEIR CHALLENGES

The implementation of any technical solution needs to be preceded by an evaluation of pros and cons. In this section we discuss some foreseen challenges with certain C/S measures that have been considered for geological repositories, i.e. routine use of equipment underground, noble gas measurement, and monitoring of seismic activity for safeguards purposes.

Equipment underground

The introduction of safeguards equipment underground comes with well-known challenges shared with any type of industrial activity underground; the environment is damp, increased radiation levels combined with ongoing construction and excavation. During the extended operational time, anticipated to be 45 years in Sweden and 100 years in Finland, any type of underground equipment will be vulnerable to technical failures. Apparent risk factors include the operation of heavy machinery, the electric supply, oxygen supply and system to manage underground water levels. These factors along with potential indications of unintended rock movements (seismic indicators, observed fractures or other structural indicators) carries the additional apparent risk of rendering equipment installed underground inaccessible for maintenance for some time duration due to safety concerns.

Geophysical and noble gas monitoring

There are several challenges with propositions involving continuous monitoring of the integrity of a repository or the absence of undeclared activities. Various geophysical methods have successfully been deployed in fields such as mining and hydrocarbon production in order to detect anomalous material properties and/or events. Finding the cause and source of detected events, however, is to this day solely dependent on skilful data interpretation in order to produce a plausible model that can subsequently be tested and verified through other more direct means of investigation (e.g. drilling or other direct sampling). Geophysical methods are therefore at best an unproven technique when it comes to safeguards that may provide a yes or no answer to whether the integrity of a repository is intact, but is unlikely to answer whether the detected signals might indicate some form of undeclared activity. We note that geophysical methods are important and mandatory for the scientific community and public to assure the suitability of the geological formation, but as the methods and results are debatable, these should not be used to collect data to be used as safeguards evidence.

Monitoring of noble gas has been proposed as a possible mean to detect undeclared activities inside a geological repository, but also this technique comes with challenges. Krypton-85 has a half-life of 10.75 years and the operators in both countries plan to store the spent nuclear fuel for a substantial amount of time, often several decades, before disposal. This poses the question just how much of a possible "signal" it is reasonable to expect, where a too low threshold may give rise to an unacceptable high risk for false-positives. The situation is furthermore complicated by the proximity of operational nuclear reactors, combined with the fact that northern Europe already shows relatively high levels of accumulated Kr-85 from the long historical use of nuclear power and the presence of declared reprocessing plants in countries outside Sweden and Finland. It is known that local fluctuations occur due to air movements, e.g. [12], but so far unknown whether these fluctuations can be sufficiently predicted, especially when considering a low threshold for detection.

Concerning both geophysical and noble gas monitoring there are no known acceptance levels for the specific sites regarding what should be classified as safeguards related events. Furthermore, there is no knowledge of the long-time baseline. Before these techniques become reliable and useful for safeguarding the integrity of a repository and/or the absence of undeclared activities, both naturally occurring and man-made events need to be understood in order to avoid false-positive signals with potentially large consequences for the State and the operator.

CONCLUSIONS

Technical solutions for safeguarding geological repositories is not a new topic. Due to the rather unique challenges posed, it has been discussed for decades, e.g. the SAGOR and ASTOR programmes constituted by the Member States Support Programmes to the IAEA. For an installation like a geological repository the traditional facility specific safeguards may not be the best solution.

IAEA safeguards are applied for the purpose of verifying that material is not used for nuclear weapons or explosive devices. It is important to ensure that all mandated activities conducted by the IAEA are carried out in an efficient and effective manner in order to maximise the use of the Agency's resources but it is also important to avoid putting an unnecessary burden on the States and the operation of involved installations. The Agency shall only require the minimum amount of information and data as per INFCIRC/193, Article 8.

After encapsulation of the fuel assemblies, the safeguards concept for geological repositories should rely on ensuring the CoK which before the disposal of the canisters may rely on traditional C/S measures. However, once the canisters are disposed of underground the material becomes highly inaccessible and the verification focus should shift from the canisters to the repository as a whole, to ensure that no disposed nuclear material can be diverted out of the repository and that no undeclared activity can take place in the repository.

The use of indirect methods (e.g. seismic activity and Kr-85 monitoring) at final disposal installations may cause unsolvable safeguards questions instead of serving the purpose of verifying a practically inaccessible inventory of canisters that were designed to contain spent nuclear fuel for longer than our society may exist. A general challenge that is shared by all means of continuous monitoring is the problem that arises in the event that the continuity is lost. There is no proven, practical and clear "plan B" to handle foreseen equipment failure and questionable observations during a repository's decades-long operational lifetime. We believe that the foreseen risk of needing to stop a final disposal process and possibly apply invasive measures, based on signals from indirect methods without a proven reliability for safeguards, is not justified. This issue becomes even more critical after the repository has been backfilled, when any kind of measures that may disturb the repository will counteract the repository's main purpose, i.e. safe disposal of nuclear material.

At the repository, we believe that the use of permanent equipment underground or monitoring of seismic activity and Kr-85 does not constitute efficient and effective safeguards solutions. The concept should rather build on a State Level Approach, focus on credible and relevant diversion risks and scenarios for the country as a whole. A general confirmed state-wide absence of any indication of plausible undeclared activities should play an essential role when developing the concept for each installation. The foreseen inaccessibility of the nuclear material, especially after backfilling, should furthermore be acknowledged while drafting and agreeing the subsidiary arrangements.

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