# REMOTE NEAR REAL-TIME DATA ANALYSIS AND DECISION-MAKING IN EPGR SAFEGUARDS – RISK ANALYSIS

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## Abstract

In less than two years' time, the world's first encapsulation plant and geological repository (EPGR) for long-term storage of spent nuclear fuel will start operations in Finland. The transfer process will run in continuous multi-day campaigns and last for several decades. International safeguards inspectorates, in cooperation with the nuclear operator Posiva Oy and the Finnish national authority STUK, have designed detailed requirements for the safeguards infrastructure and agreed on the main principles of its implementation. These are aimed at meeting the required safeguards goals by the inspectorates at an acceptable cost and inspector workload, while minimizing the impact on the operator's processes.

With the safeguards equipment infrastructure agreed and incorporated into the general design of EPGR facilities, key choices must now be made to determine the best way to apply safeguards along the geological disposal process. A multisensory and multilayer system designed to maintain continuity of knowledge (CoK) on nuclear material flow will monitor all stages of the process; this is expected to generate a large amount of data to be transmitted to EURATOM and IAEA headquarters for real-time processing.

Stages of the disposal process governed by the operator will correlate with the safeguards inspectorates' in-process verification and confirmation points, with near real-time (NRT) analysis performed to match the operator's declarations with the data collected by safeguards equipment along the transfer route. This verification methodology mitigates the impact of losing CoK during the final disposal process.

In-process verification and the inspectorate approvals are time critical as these are needed for uninterrupted process continuation. This paper presents an analysis of the risks of real-time decision support and lists available fallback options in case inspectorate approvals are not possible.

## 1. EVOLUTION OF A SAFEGUARDS CONCEPT AND INFRASTRUCTURE FOR THE EPGR: FROM EARLY CONCEPTS TO THE MODERN TECHNICAL TOOLBOX

The Council of the European Union in its Directive 2011/70/EURATOM [1] pointed out that "*deep geological disposal represents the safest and most sustainable option as the end point of the management of high-level waste and spent fuel considered as waste.*" Two years later, in December 2012, Posiva submitted an application to the Finnish Government for a license to construct a final disposal facility for spent nuclear fuel [2]. The Finnish system for disposal of spent nuclear fuel via an

EPGR is expected to become operational in 2025, making Finland the first country in the world to operate a geological repository of this kind. This year (2023), the operator, Posiva Oy, is incorporating the necessary internal systems, including the agreed safeguards technical infrastructure, into the facility design of the already constructed EP and GR. The EPGR project in Finland is entering the transitional phase between development and implementation, with the duration of the individual (but highly interdependent) process steps still to be tested. The final operational scheme of the EPGR was communicated to the safeguards inspectorates in February 2022, thus providing EURATOM, the IAEA, STUK and the operator with the opportunity to review the envisaged safeguards measures in the context of facility operations.

The history of safeguards for geological disposal systems dates back several decades to when the general principles and concepts were developed for the pilot conditioning plant and for geological spent fuel disposal in Gorleben, Germany [1][4]. The generic guidelines for safeguarding geological repositories were proposed in 1997 based on the work of the IAEA Working Group for the Development of Safeguards for the Final Disposal of Spent Fuel in Geological Repositories (SAGOR) [5]. The work of the SAGOR-I (1994–1998) and SAGOR-II (1998–2005) was continued by the expert group on the Application of Safeguards to Repositories (ASTOR) and resulted in a comprehensive report published in 2016 [6].

During the last decade, in the spirit of safeguards by design, the approach for safeguarding geological disposal sites was further developed by safeguards inspectorates alongside the design and construction of the EPGR in Finland. The process to shape the safeguards measures required an active feedback loop between inspectorates and the operator. The Finnish EPGR facilities can be characterised by the following safeguards-relevant intrinsic features (some of which apply to other EPGRs as well):

- Novelty: Finland to be the first country in the world to operate an EPGR facility for spent nuclear fuel;
- Timescale: Up to one hundred years or more of active operation;
- Multistage implementation: Construction phase, operational phase and the post-closure stage;
- Construction and backfilling of repository tunnels: Continuous for the full operational time;
- High throughput: Up to 60 disposal canisters to be produced and disposed of annually;
- Large capacity: Thousands of canisters to be deposited;
- Re-verification after disposal and backfilling: Feasible, but impractical as access to the deposited nuclear material is possible only after canister retrieval, which would imply safety considerations and be very difficult and extremely costly;
- Natural and engineered barriers' major role in isolation and access restriction [7]: Spent fuel will be deposited in canisters that will become inaccessible for thousands of years at depths of more than 400 metres in a crystalline rock environment that constitutes a geological containment.

The EPGR process adds an additional stage to the nuclear fuel cycle and calls for additional resources for its safeguarding. In fact, a shortage of resources has been identified as an obvious EPGR safeguards implementation risk, albeit one that can be mitigated by advanced planning and capacity building.

At the Finnish EPGR facility, the encapsulation plant and the geological repository are co-located, with the EP constructed directly above the GR and connected to it via a vertical shaft for transport of the disposal canisters. There are two air (inlet and outlet) shafts, one shaft for personnel access and a vehicle access ramp to the GR. In sum, there are five routes leading from ground level down to the GR: one for canisters, two for air, one for personnel and one for vehicles.

The EP has three entry/exit points through which nuclear material could potentially be transported:

- The transport cask (TC) reception hall with connections to the TC corridor and the disposal canister (DC) corridor;
- The entrance to the canister shaft leading to the GR;
- The empty DC reception room connected to the DC corridor.

The general features common to EPGR facilities, together with the novelty first-of-its-kind factor, stimulated the safeguards-by-design (SbD) process with a crucial involvement of the operator's designers [8]. The proposed safeguards measures are designed to meet the safeguards objectives of both EURATOM and the IAEA [9].

Before reaching a final agreement on the safeguards measures for the EPGR, different possible approaches were studied by the inspectorates according to their internal policies and mandates, including:

1) The black box approach: Is it sufficient to know how much nuclear material is entering the GR to be deposited? In this case, containment/surveillance (C/S) at the geological containment would need to monitor the entry points only.
2) Continuous material monitoring: Follow the material through the GR, until it reaches its destined deposition place and verify that the deposition tunnels are gradually backfilled?
3) In-place C/S: Constantly monitor the underground environment after the spent fuel is deposited?

Similarly for the EP, decisions had to be made to what extent the encapsulation process needed to be supervised to meet each inspectorate's safeguards objectives. Only after a decision on the concept is made could the technical solutions be adopted. A key constraint placed on the project in 2012 required that, to meet SbD goals, safeguards equipment infrastructure for the EP and the GR had to be designed with the operator's time schedules in mind. Because the EPGR was not yet finalised at that time, the safeguards approach and the infrastructure necessary to implement it evolved alongside EPGR design for more than a decade in an iterative process, with the aim of being able to draw independent safeguards conclusions without adversely affecting or slowing down facility operations.

An optimum design of the safeguards infrastructure and inspection regime must consider cost/benefit aspects related to equipment investment and an inspector's workload. While highly automated data acquisition and analysis can, to a large extent, reduce inspector presence and, therefore, intrusiveness into the facility operation; it is nonetheless to be expected, especially in the beginning of the operational phase, that a lot of on-site presence and start-up effort will be needed from the national and international safeguards authorities.

The adopted safeguards concept addresses the four consecutive geological disposal process stages by attributing a key objective to each of them [9]:

1) Interim spent fuel storage (before EPGR): Verification of SF to be encapsulated;
2) Transport: Maintain continuity of knowledge (CoK) on verified SF within the TC;
3) Encapsulation plant: Redundant system for maintaining CoK on spent fuel throughout the encapsulation process and for minimizing risk of a CoK interruption, along with the ability to reverify spent fuel in the EP in the case of a loss of CoK;
4) Geological repository:
    a. Material flow monitoring to confirm that the encapsulated SF is deposited in the declared location inside the geological containment;
    b. C/S on all the penetrations leading to the GR;
    c. Confirmation of geological containment integrity.

As the detailed design of the EP and GR changed over the period of 11 years from 2011 to 2022, the safeguards equipment design, and therefore the required infrastructure, had to be continually revised along with it. The original concept was that the final non-destructive assay (NDA) of the spent fuel to be encapsulated was to be performed in the EP itself. This option was ruled out in 2012, as it became clear that the high throughput of the encapsulation process, combined with the lack of the in-process buffering capacity at the EP, would be subject to major operational delays whenever the NDA verification could not be performed as envisaged (e.g., equipment failure) or might be inconclusive. In such cases, the entire encapsulation campaign process would have to be put on hold for a period of up to several days—even with remote data transmission (RDT) from the EP. Therefore, it was decided that the final NDA verification would be performed at the interim wet storage at the reactor sites [10]. While this scheme relaxed the time-constrained NDA verification, it meant that CoK had to be maintained during spent fuel transport to the EP, which would require additional suitable verification equipment.

Ultimately, safeguards inspectorates adopted equipment infrastructure requirements documents describing the safeguards infrastructure to be installed in both facilities (EP and GR). The safeguards infrastructure for the EP has a multi-layer architecture consisting of four main subsystems:

- Video surveillance;
- Laser curtains for containment and tracking (LCCT);
- Radiation monitoring;
- Seals.

The combination of signals from all these systems is designed to provide uninterrupted continuity of knowledge (CoK) on the nuclear material being processed along its path from encapsulation to geological storage. To guard against data loss, all systems can operate on an internal uninterruptable power supply, have a data-acquisition-only, low-power mode, include computers for local data storage, are built with redundancy in all critical subsystems and are connected to the remote data transmission network.

Like other re-batching facilities, the EPGR has a narrow time window for verification during the encapsulation process; therefore, a system capable of providing verification in near real-time allows facility operations to continue unimpeded and prevents delays. The near real-time system (NRTS) to be used for safeguarding the EPGR is being jointly developed by the IAEA and EURATOM; it will be an advanced and more complex evolution of a system already implemented by the IAEA at the Chornobyl nuclear power plant [11], where individual monitoring systems feed their signals to a local, central NRTS system, allowing for prompt, full, remote verification of the operator’s declarations.

Consolidation in an NRTS capable of receiving, storing, sorting and analysing the stream of data of the signals from all the detectors and sensors in a facility enables continuous near real-time data analysis and decision-making. However, deployment of a remotely operated NRTS system in safeguards has several prerequisites and requires the operator to provide safeguards inspectorates with two sets of information:

- Prior to commencement of each process step: Advance information necessary for setting up parameters of the NRTS in preparation for the remote verification;
- As soon as the final parameters of the process are known: Operational declaration containing the time and duration of the envisaged process steps and sequences (e.g., spent fuel loading sequence in the fuel-handling cell), object description (TC, DC, spent fuel data according to the pre-agreed templates) etc.

## 2. THE REMOTE DECISION-MAKING STEPS IN SAFEGUARDING THE EPGR PROCESS – THE CONFIRMATION POINT (“GREEN LIGHT”) CONCEPT

Apart from the non-trivial choice of architecture and software development challenges (not covered in this paper), use of the NRTS for remote inspection and decision-making introduces a number of risks for both the operator and the safeguards inspectorates.

The operator’s goal is to execute all the necessary process steps on the way to the safe and secure geological disposal of spent fuel in a fast, uninterrupted, effective and efficient manner. By reducing the time to detect issues in safeguarding the EPGR process, the NRTS lowers the risk of a process interruption. Nonetheless, the data for verification must be functional, thus selected with great care. Intrinsic redundancy already is assured by the safeguards infrastructure operating inside the EPGR. The NRTS setup must allow signals to be categorized and prioritized according to their criticality for verification of the operator’s declarations and maintenance of CoK.

To reduce the risk of the inspectorates requiring a spent fuel canister to be retrieved from the GR for re-verification, a confirmation point (i.e., “green light”) concept was considered for the Finnish EPGR more than a decade ago. The aim of this concept is to assure the operator that up to those predefined confirmation points: 1) the spent fuel has conclusive positive CoK maintained on it and 2) the inspectorates will not request re-verification. The process and decision steps requiring green-lighting to be passed from the safeguards inspectorates to the operator are shown in Figure 1 for the interim storage and transport stage and in Figure 2 for the encapsulation plant stage.

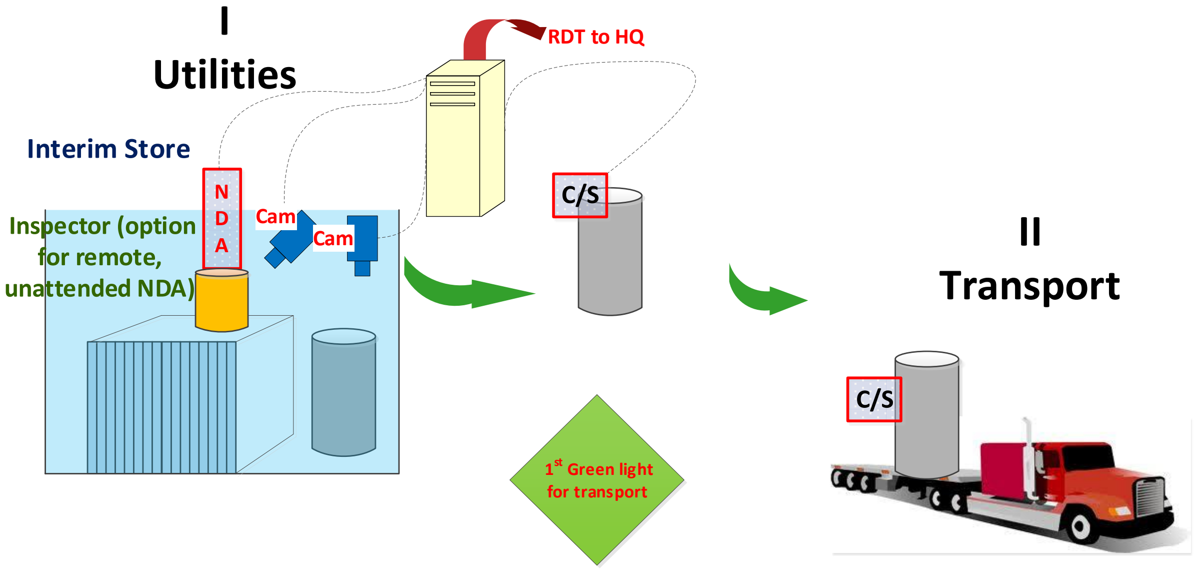

*Figure 1. Simplified diagram showing safeguards infrastructure and the first confirmation step at the interim storage and transport stage.*

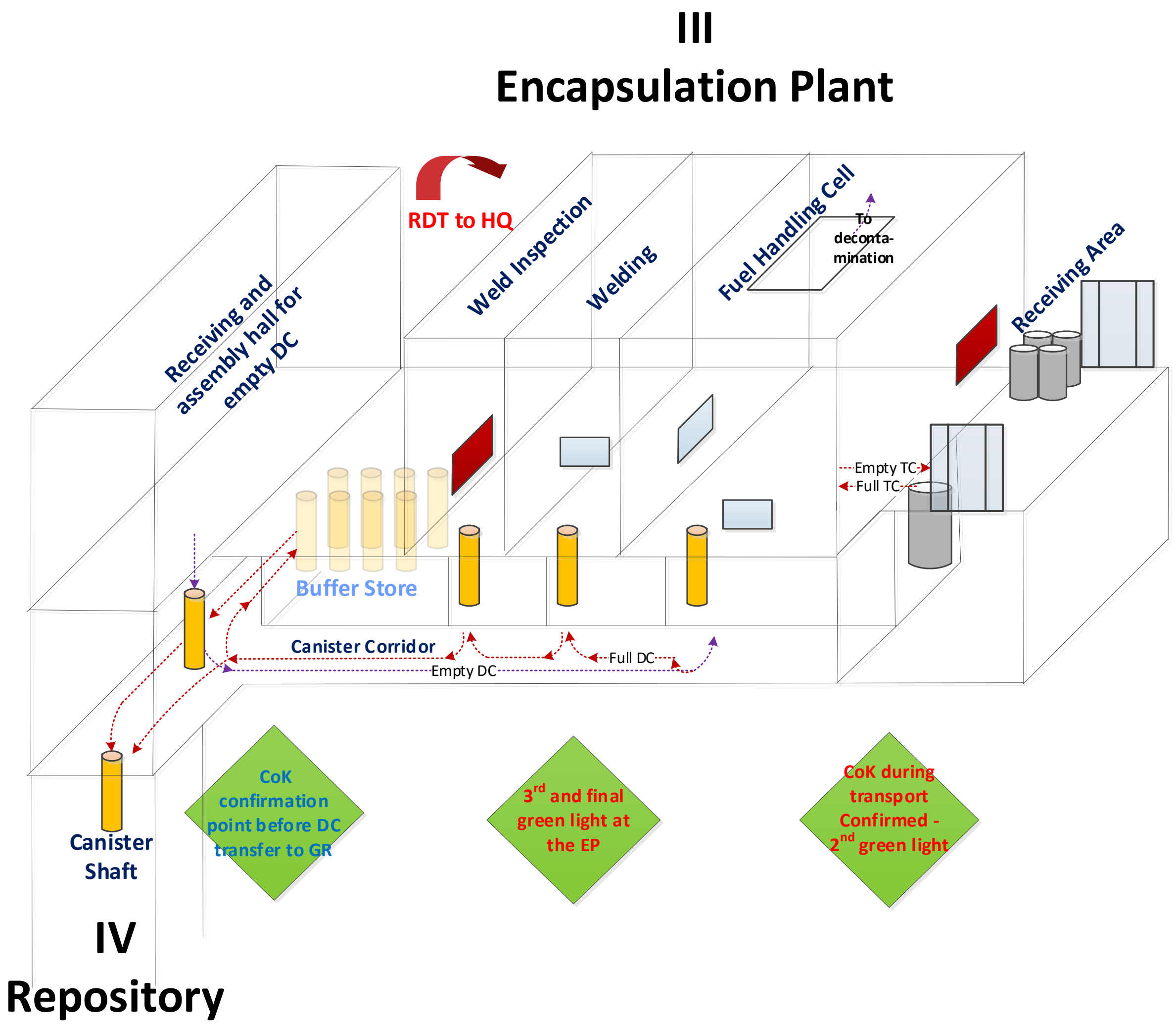

*Figure 2. Simplified diagram of the encapsulation plant showing disposal canister flow and decision points requiring confirmation.*

After transfer to the GR, where they are enclosed by the geological containment, the disposal canisters with spent fuel will no longer be kept under individual containment and surveillance. Rather, C/S measures will be applied to the entire geological containment shown in Figure 3. Additional nuclear material flow monitoring inside the geological containment will be realised using the operator's infrastructure during DC emplacement. The inspectorates will continue using laser technology for independent mapping of the GR's interior, successfully implemented over the last 10 years [12].

## 3. DISCUSSION: RISKS OF REMOTE VERIFICATION AND DECISION-MAKING IN EPGR SAFEGUARDS

The proposed safeguards equipment configuration with NRTS, while expected to facilitate efficient verification and give inspectors several points along the spent fuel path to green-light continued processing, nonetheless has several inherent risks, mainly inconclusive verification results causing delays or even process stoppages or reversals (Figure 4). The known risks and their impact on EPGR operations can be mitigated via the technical and operational arrangements listed in Table 1.

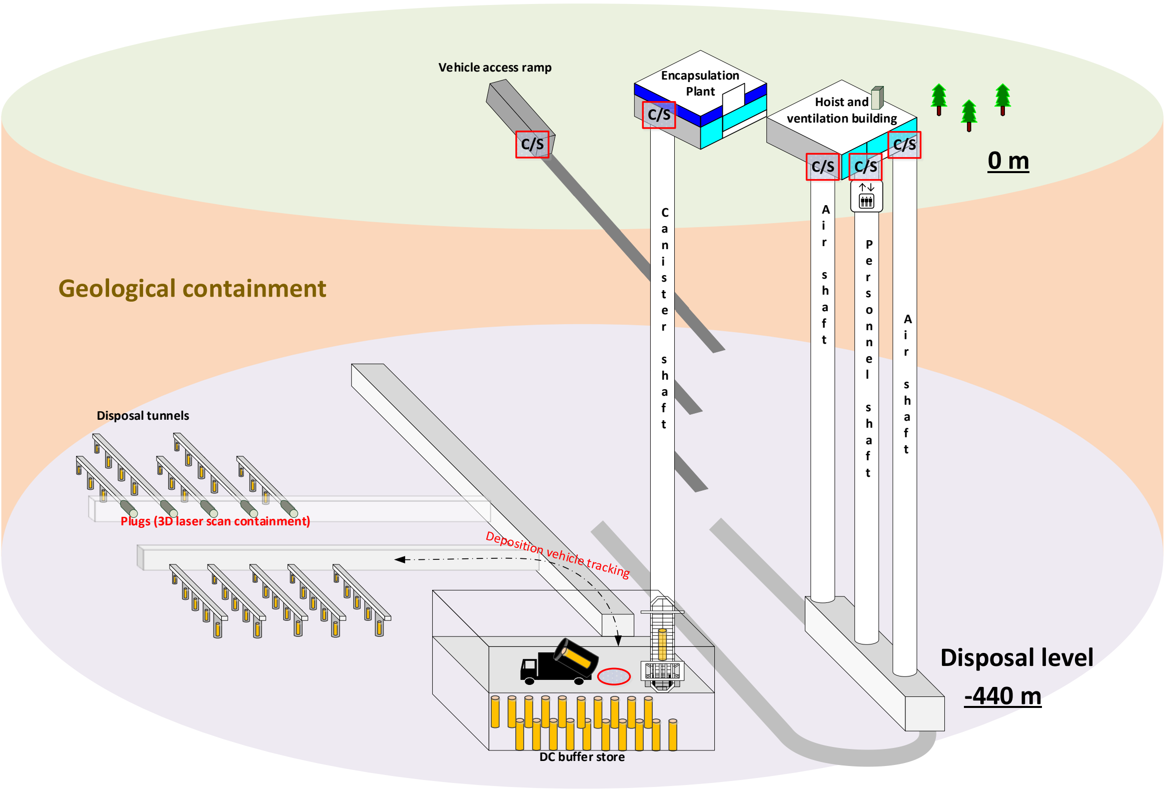

*Figure 3. C/S measures designed for the Finnish GR.*

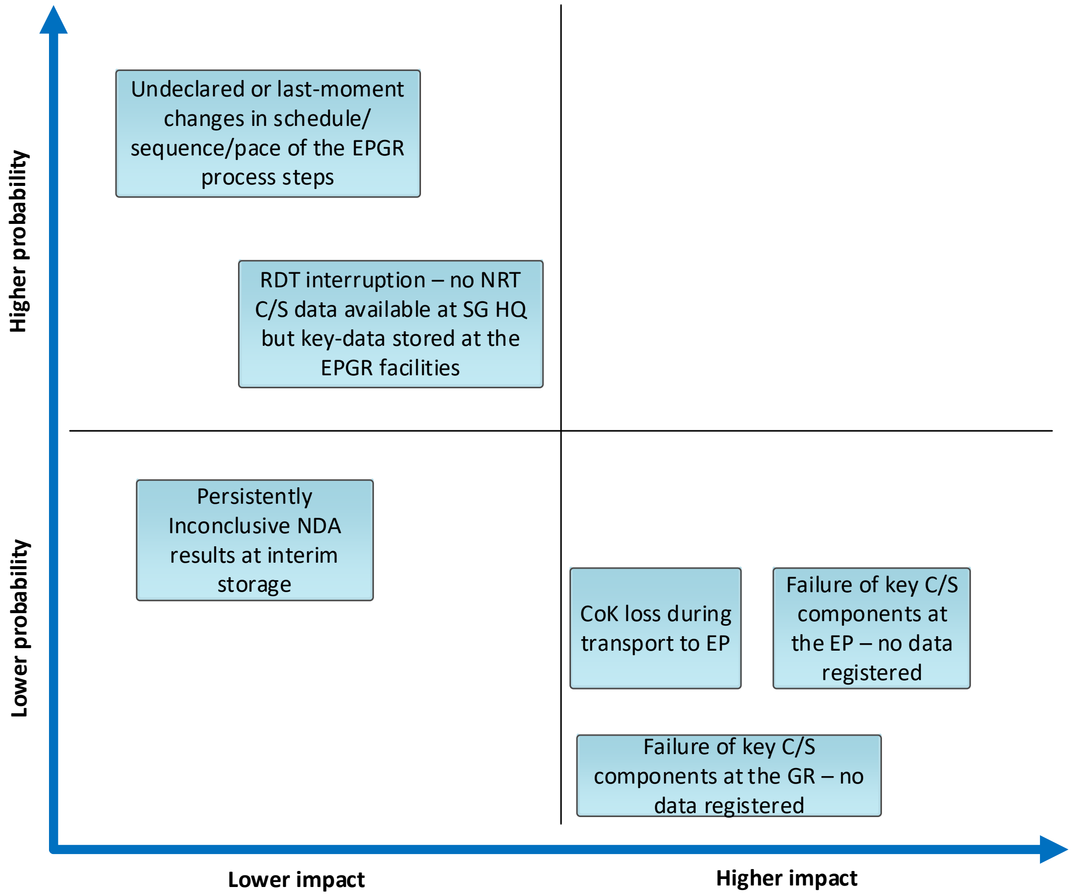

*Figure 4. Main operational risks associated with EPGR safeguards and their consequences.*

Table 1. Risk assessment registry for the implementation of safeguards along the EPGR process.

| Identified Risks | Possible Impact | Mitigation Factors | Possible Further Improvements |
|---|---|---|---|
| Undeclared or last-moment changes in schedule/sequence/pace of the EPGR process steps | Process stopped for several hours until discrepancy clarified and green light given | – Advance information and declaration submission time, content and format agreed with the operator<br>– NRTS capable of providing instant warnings and information on discrepancies | – Provisions for fast-track emergency contacts (operator and inspectorates) to be established |
| Inconclusive NDA results at the interim storage /<br>NDA equipment failure | No green light – process delay | – Agreed detailed provisions for advance information and spent fuel data declarations<br>– Spare NDA equipment readily available on site<br>– NDA performed in campaigns, unrelated to TC loading<br>– Inspectors' presence on site at the initial mutual learning stage<br>– Realistic acceptance criteria | – Operator empowered to replace inconclusively verified assemblies |
| RDT interruption – no NRT data available at SG HQ | No green light – process delay | – Inspectors' presence on site at the initial mutual learning stage<br>– RDT architecture designed to avoid single points of failure<br>– State-of-the-art industrial components with redundancy<br>– Fast response capability maintained by safeguards inspectorates | – Full authentication of signals from the operator's instruments (e.g., cameras, radiation monitors) |
| CoK loss during transport to the EP | Process delayed due to 1) possible verification in the EP or 2) cask shipped back to wet storage for re-verification | – Redundant measure for CoK<br>– Readiness of NDA station in the EP | – Further development of containment tools |
| Failure of all CoK components at the EP – no data registered | Stop the process; re-establish CoK | – Redundant multi-system/sensor CoK infrastructure<br>– Constant state-of-health monitoring by the NRTS provides early warnings and triggers immediate corrective actions<br>– Inspectors' presence at the initial learning stage | – Sealing of the emptied TC before it leaves the EP<br>– Authentication of the operator's equipment |
| Failure of all C/S components at the GR – no data registered | Additional measures implemented by inspectorates: detailed investigation of the case, increased inspection effort, holistic assessment of the GR system state | – Multi-layer C/S applied to the geological containment<br>– Material flow monitoring inside the GR and monitoring of geological containment integrity<br>– Thorough knowledge, verification and periodic re-verification of the underground installations by the inspectorates | – Continuous improvement of C/S system reliability<br>– Development of new techniques such as muon tomography that can verify the integrity of the geological containment |

Confirmation of the operator's declarations and maintenance CoK is sequential. The key decision-making steps and associated confirmation points are identified in Figure 1 and Figure 2. The first of the envisaged green lights is linked to the results of the NDA performed at interim storage before fuel shipment. It is expected that safeguards inspectors will be present on site during NDA in the initial (at least one year long) learning stage of EPGR operation, after which the NDA measurement could be performed unattended. An option to perform an advance NDA measurement campaign prior to a large population of spent fuel assemblies (SFAs) being encapsulated would guard against last-minute discrepancies causing delays in scheduled TC loading and transport to the EP. In this case, C/S measures must be applied over a segregated area storing the pre-verified SFAs. Discussions with interim storage operators are ongoing to ensure an adequate safeguards infrastructure for this scenario.

The second confirmation point is upon arrival of every TC at the EP. The operator must obtain this green light before unloading the SFAs from the TC. The proposed redundancy measures along the path from interim storage to the EP are designed to mitigate the risk of loss of CoK during TC transport.

The third confirmation point is for the IAEA to verify and clear every loaded DC produced at the EP prior to its lid being affixed and welded shut. This is an important step in the process, as from the moment a loaded DC is welded closed, any re-verification of its contents would be very costly. Issuing this time-constrained green light in a timely manner is a challenge for the safeguards inspectors. The risk of a slowdown in the encapsulation workflow is mitigated by the NRTS feeding the required data to the inspectorates’ headquarters in a timely manner, such that the outcome can be communicated to the operator within a pre-agreed timeframe. An additional measure that could mitigate the potential risk of inconclusive C/S inside the EP is to apply a seal on each empty TC. The operator could open this seal only after the third green light is given, but the encapsulation process could continue.

Together with the C/S measures, including monitoring of the entrances and the exits, applied along the entire EP process, the adopted stepwise green-lighting process reduces the possibility of losing CoK on the encapsulated spent fuel. These measures also fulfil EURATOM’s requirement to confirm CoK for the entire on-surface part of the geological disposal process. After the third green light is given, an additional confirmation step is not foreseen, as the NRTS will be used to conclude that CoK on each DC is maintained until shipment to the GR. This last confirmation point plays an important role in EURATOM’s approach.

The envisaged use of the NRTS together with the proposed green-lighting steps to confirm the operator’s declarations aims at the least invasive method of confirming CoK. This approach is to be tested in the initial period and may be adjusted in the future.

## 4. CONCLUSION

Safeguarding the high-throughput EPGR differs from safeguarding any other facility hosting a continuous, moderate-throughput process to handle itemized nuclear material. The challenge posed by the EPGR is the in-process NRT safeguards application and the maintenance of confidence in the integrity of the geological containment. The envisaged NRTS will be central to the performance of the remote verification activities, especially during the on-surface part of the EPGR process, which requires a highly functional and reliable system. The selection of the measures planned for the GR was based on thorough knowledge of GR design and the disposal process, and vastly benefited from the cooperation with the operator, Posiva Oy and the Finnish regulator STUK. A geological containment consisting of more than 400 meters of rock, through which safeguards inspectorates cannot perform classical physical verification activities of the nuclear material, led to the adoption of multi-layered safeguards measures, along with the intention to use new techniques for monitoring the integrity of the geological containment. The complete EPGR safeguards system proposed by EURATOM and the IAEA is designed to minimize the risk of a loss of CoK, with minimum impact on the operator.

Any NRTS, whether for EPGR or other safeguards applications, must be evaluated with regard to its efficiency vs. effectiveness ratio. While it may provide tighter safeguards and potentially be less invasive to the operator, an NRTS nonetheless requires considerable investment from the safeguards inspectorates. With its time-constrained signal analysis and decision-making, NRTS operation relies on elaborated IT solutions, with interfaces that enable efficient work, especially in terms of minimizing the risk of errors and omissions which may yield inconclusive results and require rapid on-site deployment of inspectors. Setup of an NRTS is not trivial and entails defining which signals are indispensable to confirm an operator’s declarations and maintain CoK along the EPGR process, and which signals can be used as a backup. Overall reliability of the NRTS system and the quality of its user interface are a prerequisite for efficient NRT safeguards applications. Given the novelty of the EPGR and NRTS implementations, it is expected that safeguards inspectors will have to be on site to supervise the process from the initial stage of the EPGR operation until all NRTS functionalities have been tested and proven stable and reliable.

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