SAFEGUARDS VERIFICATION CONCEPT FOR DISPOSAL OF SPENT NUCLEAR FUEL

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ABSTRACT

Finland is developing a national safeguards concept for disposal of spent nuclear fuel in a geological repository, taking into account inputs from EC and IAEA SG inspectorates. The disposal is planned to start around 2025. It is imperative that the fuel will be verified before disposal, since after disposal the fuel will be inaccessible forever. An NDA verification system with two simultaneous methods, PGET (Passive Gamma Emission Tomography) and PNAR (Passive Neutron Albedo Reactivity), has been built and tested. The measurement time needed is about 5 minutes. The selected methods may complement each other which greatly enhances the verification performance of the system as a whole. The measurements will initially be conducted at the shipping facility in the intermediate storage pools, before transfer of the fuel to the encapsulation plant. The verification process aims to be unattended by the inspectorates and automated, so it needs to be under continuous remote surveillance. The measurements shall create credible assurance that the declaration of the fuel is correct and complete. To ensure that the preservation of knowledge is maintained, the collected data will be stored for future generations who will not have access to the fuel itself. The data analysis shall be concluded before the transfer of the fuel from the wet storage to the encapsulation plant, so the verification process shall be designed to consider operational requirements of the nuclear operators as well as of the inspectorates. This paper describes the verification process envisaged and identifies the processes which need to be developed.

INTRODUCTION

Disposal of spent nuclear fuel to the geological repository in Olkiluoto, Finland is expected to start in mid 2020’s. It has been agreed that all fuel items will be verified before final disposal. Selected verification method is Passive Gamma Emission Tomography (PGET) whose priority is to confirm the integrity of the spent fuel items. In addition, Passive Neutron Albedo Reactivity (PNAR) developed by STUK for possible joint use with IAEA and EC will be used. Combination of PGET and PNAR can verify integrity of the spent fuel and confirm its operational history. Additionally, the FORK detector (FDET) may be used as a measurement instrument in case of unforeseen difficulties.

FDET is old and well-known method, but the analysis and understanding of the method has been further developed in recent years [10, 11, 12]. The PNAR method had been initially proposed in the 1980's [5], but was developed only recently in STUK [6], [7], [8]. PNAR is an evolution of FDET, providing not only more accurate verification of fuel history but also an additional parameter, the PNAR ratio, which is proportional to neutron multiplication and fissile mass inside the fuel item. PGET was authorized by the IAEA for safeguards use in attended mode in 2017 [2],[3],[4]. A pool of PGET devices has been sourced from an industrial supplier by the IAEA and the EC. PGET is able to confirm integrity of the spent fuel items and to detect a single missing pin. It also supports confirmation of the irradiation history by neutron counting and gamma spectrometry.

This paper does not describe the methods, their detailed capacities or recent tests and developments of the analysis's methods. Updated information of PGET and PNAR methods will be available in Virta et al and Tupasela et al [14], [15]. The focus in this paper is to describe the concept and verification process itself.

DISPOSAL PROCESS AT THE ENCAPSULATION PLANT

Finland has currently 2 operating Nuclear Power Plants (NPPs), Olkiluoto and Loviisa. Olkiluoto NPP resides on the same 5 km long island with the encapsulation plant and final repository. Currently it is expected that the disposal process will start with Olkiluoto 1-2 BWR fuel. Disposal of Loviisa fuel is expected to start 20 years from now. Therefore, we do not discuss in this paper the concept regarding Loviisa NPP fuel.

Spent Olkiluoto fuel is currently residing in an intermediate storage at the NPP site. The fuel is transferred from the storage to the Encapsulation Plant (EP). The whole transport sequence will occur inside a fenced area. The transfer cask will also be the same, as the one used by the NPP operator for internal transfers from the reactors to the internal storage. The cask has a capacity of 41 assemblies, but it is expected that only 36 assemblies are moved at a time to the EP, since it is convenient that the amount of transferred assemblies at a given time is divisible by the disposal canister capacity (12).

The capacity of the EP is 1-2 canisters/week. Encapsulation is a conveyor-line type process, where the fuel is moved from the transfer cask to a disposal canister inside a fuel handling cell. The disposal canister is a 5cm thick copper canister with nodular cast iron insert, which has 12 positions for BWR-type fuel. After filling the canister, its iron insert lid will be bolted, and the copper lid welded. After welding, opening of the canister is possible, but it destroys the canister, which makes it a very expensive and disruptive operation. If the canister remains intact, verification of individual fuel items after welding is not possible. The EP has no positions to store individual fuel assemblies outside of the cask and canisters; the buffer storage of EP is intended for filled and welded canisters only.

REASONING FOR COMPREHENSIVE VERIFICATION

Verification of fuel going to the final repository has been discussed extensively during the past 25 years. The need for comprehensive verification was deemed very important by the inspectorates (STUK, EC and the IAEA). When the fuel within the welded canisters is emplaced in the geological repository, it is designated as ‘difficult-to-access,’ as it is not possible to verify it within the repository. All stakeholders prefer not to ever retrieve the fuel. Therefore, prior disposal verification shall be done with a technology able to provide credible assurance, which satisfies not only the contemporary safeguards actors but also future generations that the fuel disposed of has been verified with sufficient accuracy. Since we do not know the exact needs of future generations, we should use the most sensitive methodology to verify all fuel items. Creating as good as possible verification information before disposal minimizes the risk of a future generation facing the situation of failing to make necessary conclusions about the disposed fuel.

A large part of spent fuel items in Finnish intermediate has been in storage pools for decades and verified by item counting and by instruments qualitatively observing Cerenkov light. Prior to its designation as ‘difficult-to-access,’ the spent fuel items require the use of a more accurate verification technology, to confirm their operational history and ensure their completeness. Continuity of knowledge (CoK) will then be maintained until disposal in the geological repository. Although the selected applicable verification methods and instruments result from recent technological breakthroughs, they could however be improved and changed during the disposal project, which is expected to last 100 years.

Comprehensive verification was also seen useful from the point of view of the implementing company Posiva Ltd. If the fuel is measured before the ownership change from the NPP operator, Posiva as a recipient obtains the confirmation that all fuel declarations are verified to be correct and complete.

REASONING FOR METHODS SELECTED

A measurement performed for safeguards verification purposes may potentially provide useful information for nuclear safety. For instance, data may be used to verify the fuel history, which can provide additional information for residual heat calculations. However, the verification methods for the Finnish disposal are selected based on safeguards needs. If the data can be additionally used for safety purposes is only a plus.

IAEA's expert group ASTOR recommended in its final report [1] that the following attributes should be satisfied by the NDA verification system:

1. Capable of pin level detection.
2. Capable of verifying that the declared assembly is consistent with measured signals.
3. Capable of measuring assembly neutron multiplication.
4. Capable of measuring fuel assemblies at the measurement location and in the medium of interest.
5. System should be robust, low maintenance, and have a low false alarm rate.
6. System should be difficult to trick with pin substitution.
7. System should measure the weight of the assembly.

The PNAR-PGET combination fulfills the list, except the last one, which requires a scale, or load cell. FDET is a reliable and affordable instrument that is useful for verification of fuel history. PNAR can provide the same information added with multiplication data.

PGET reliability assessment was part of the authorization process for SG use by the IAEA and at present, no failures of commercial PGET leading to the system failure in the field have been observed. Operating experience is constantly increasing.

Low false alarm rate can be reached with the PNAR instrument. Research show that the PNAR Ratio evaluation provides measurement dynamic range, which is more than 50 standard deviations [9]. PGET is a much more challenging case in this regard. Since testing goes to single pin level, ensuring acceptable false positive alarm rate require advanced data evaluation methods which have been thoroughly tested and are still improved.

Table 1. ASTOR Expert Group recommendations for the NDA system prior disposal.

ASTOR NDA Group Recommendation	PGET	PNAR
Capable of pin level detection	Yes	No
Capable of verifying that the declared assembly is consistent with measured signatures	System feature	
Capable of measuring assembly neutron multiplication	No	Yes
Capable of measuring all fuel assemblies at the measurement location and in the medium of interest	Yes	Yes
Robust, low maintenance and low false alarm rate	?	Yes
Difficult to trick with pin substitution	System feature	
Measure the weight of the assembly	Load cell attribute	

The verification method developed is fast enough so all fuel can be measured without disturbing the process excessively. In the proposed system the time needed for the verification measurement is about 5 minutes and it can be done for the fuel hanging from the gripper of the fuel transfer machine. With the needs for fuel handling, the complete measurement process will add about 10 minutes to the time required for loading a fuel element from the storage pool into the transfer container, if measurements are made as a part of the transfer process.

A load cell does not provide meaningful results for underwater measurements because of buoyancy. The encapsulation plant fuel handling cell is equipped with a load cell in its fuel crane and the weight will be recorded for every assembly by Posiva and reported to STUK.

VERIFICATION LOCATIONS

There are in principle two possible options for verification location where the “final” verification can be conducted:

1. At the shipping facility - intermediate wet storage
2. At the Encapsulation Plant (EP) hot cell

Table 2 summarizes pros and cons of these options.

Table 2. Pros and cons of measurement location options

Measurement location option	Pros	Cons
1. Shipping facility	Provides more time for conclusions	C/S required during transport to EP
	Proven methods available	Requires an additional verification system at the EP, For the case that C/S fails during transport,
2. Encapsulation Plant	Comprehensive verification just before encapsulation.	Safeguards conclusions are on the critical path of the encapsulation process. Non-conclusive results would seriously disturb the process
	Risk of losing C/S during transport avoided	More NDA method development required due to dry environment

The drawbacks of Option 1 - verification at the shipping facility - can be mitigated. The requirement of C/S over the transport can be arranged and solutions have been proposed and are under investigation. The EP will also be equipped with a verification system(s) in case C/S fails.

On the other hand, the downside of Option 2 is difficult to mitigate. It is important to note that the encapsulation plant has no buffers or storing areas for assemblies. Therefore, only fuel accepted and verified for encapsulation should be introduced into the process, unless the reliance for conclusive verification result is very high and the risk of occurrence of mistakes in operational records attached to the spent fuel items can be demonstrated negligible . Inconclusive verification results would seriously disturb the process. This kind of pressure to provide only conclusive safeguards results is not at all desirable when reliable results are required.

Rautjärvi et al [13] concludes that "The final accountancy verification of spent fuel assemblies should take place at the shipping facilities, and no measurements are planned to take place at the Encapsulation Plant. However, a structural provision for the NDA measurements in the hot cell will be prepared." We align ourselves with this conclusion and start systematic verification measurements only at the shipping facility. Measurements at the Encapsulation Plant will be conducted when continuity of knowledge is compromised.

However, we leave the option open for systematic NDA measurements in the hot cell in the future. After a few years of operation, when more experience is gathered and in air measurements are thoroughly tested, the option to measure in the EP may be re-considered.

The ownership of all instruments is yet to be negotiated, but in any case, the data will be used by all inspectorates STUK (national), EC (regional) and the IAEA (international), who will use the verification results as a basis for their independent conclusions. Practicalities for data sharing will be discussed between the inspectorates. Also data storing over extended periods of time shall be discussed.

THE CONCEPT FOR VERIFICATION AT THE INTERMEDIATE STORAGE

An illustration of the PGET+PNAR combined verifier is shown in Figure 1. It is a modular system comprising a quadropod, which has separate positions for the PGET and PNAR instruments. The system will be positioned at the bottom of the fuel pool. The intermediate storage of Olkiluoto NPP has multiple pools with installed racks. Some areas are not filled and equipped with racks, so those areas can be used to accommodate the verification instrument.

The capabilities to undertake the verification in attended mode are in existence. It is planned to enable unattended mode under surveillance. After successful collection of the verification data, the transfer machine driver will receive a signal that the fuel assembly can be transferred to the cask. The inspectorates and the operator need to agree upon the clearance procedures in detail. The conclusion that all 36 fuel items are as declared, is needed before the transport cask lid is closed.

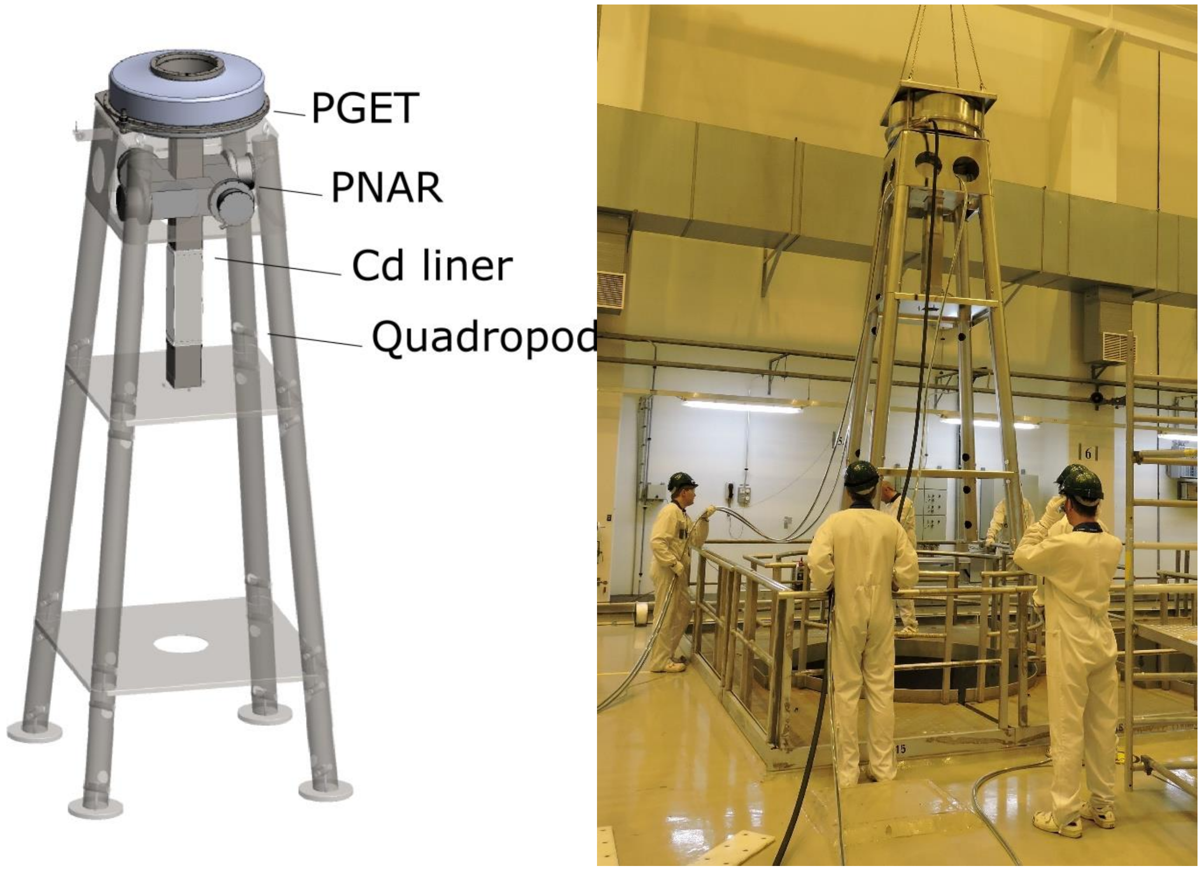

Figure 1. PGET+PNAR instrument.

STUK plans to arrange jointly with the IAEA and EC multiple measurement campaigns in TVO in 2021 – 2024 with a PGET+PNAR instrument. These campaigns will provide more data to refine analyses, will further improve the capability of the system and enhance the system's reliability. The campaigns will also be used to improve the system for full deployment and conceptual testing.

OPTION FOR ADDITIONAL VERIFICATION AT THE ENCAPSULATION PLANT

The encapsulation plant handling cell has a verification station underneath the handling cell. It can accommodate PGET, PNAR and/or FDET instruments. PGET installed in encapsulation facility may also be used as a reserve instrument to implement PGET verifications in interim storage would the need arise.

If CoK after successful verification at the encapsulation plant is maintained, there is no need to re-verify the fuel at the encapsulation plant. Some level of measurement activity is needed to develop and maintain the capability and to test that all process components are operational. Successful evaluation of PGET measurement in air has not been yet demonstrated. Additional radiation shielding may be needed, which requires modeling and testing. Method development and validation require a set of measurements to be conducted. PNAR instrument needs to be redesigned for dry environment, since the method involves a large volume of moderating material around the detectors.

In a very serious and exceptional case a closed and welded canister can be opened and connected to the handling cell and re-verification performed. However, the safeguards concept of the EP and geological repository shall be such that this is extremely unlikely to ever happen.

RESEARCH NEEDS

Separate from the consolidation of NDA methods and development of their capacity to be operated in unattended mode, there are still quite a few capabilities to be developed, tested, and implemented to support the concept described.

1. Fuel declaration arrangement is needed. The declaration shall include information required for verification measurement analysis. PGET analysis needs information of fuel type and irregularities. PNAR analysis also requires information of fuel history.

2. It is envisaged that the measurement systems at the intermediate storage and at the encapsulation plant may both be fully remote controllable by the inspectorates. This also requires automatization of the PGET and PNAR instruments. It is planned that the instrument shall be monitored and operated remotely.

3. Automatic preliminary analysis and signaling system for the operator shall be developed. The system should be developed to the level where it can automatically provide an easily interpretable signal to the operator about the success of the verification data collection. After analysis a traffic lights signal should tell the operator how to proceed, a proposal is shown in Figure 2.

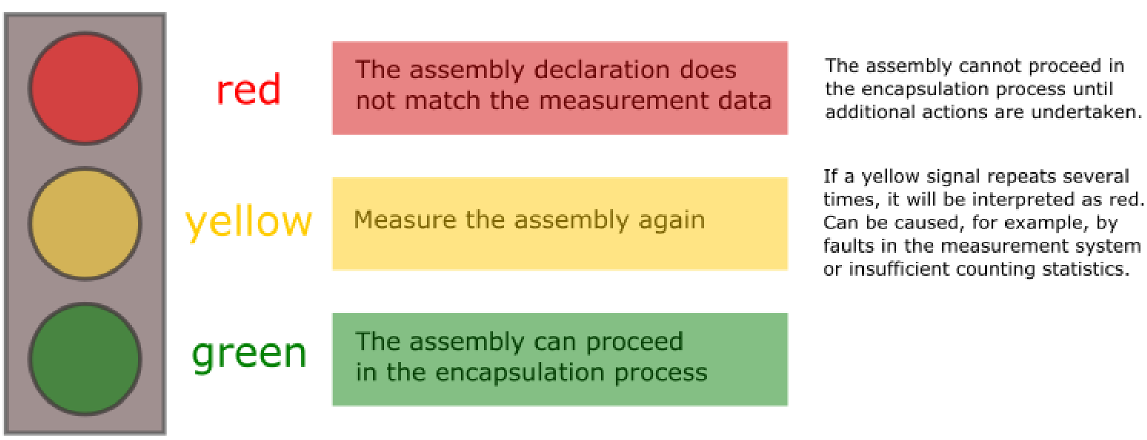

Figure 2 Traffic light signal for indicating the status of the verification data collection.

The methods shall be robust enough to guarantee high, preferably >99%, success rate in the first measurement. If the success rate is around 97%, verification of one assembly out of 36 in the cask fails on average. This can be too disruptive for the operator.

4. Development of efficient tools for the inspectorates. The inspectorates should relatively quickly provide clearance to the operator that the fuel item can proceed to the encapsulation process. Since automatic analysis can not be fully relied upon, the inspectorates need to have analysis tools for advanced analysis. PGET measurement analysis require special expertise and there is a need to carefully compare the data with the operator’s declaration.

5. Development and parallel implementation of different PGET data evaluation tools could be a solution to increase the confidence level of the result and overall ensure acceptable levels of false alarms.

6. To use selected NDA methods in dry environment requires some research to be done.

7. Development of measurement databases where fuel and measurement data will be stored and archived. All inspectorates should maintain their own archives as they see necessary. If the database is combined it should be arranged so that all parties can rely on the immutability of the data.

These development tasks are taken together and in cooperation with the international inspectorates, EC and the IAEA. This requires intense development effort.

CONCLUSION

The NDA concept of the Finnish disposal process is planned to combine PGET and PNAR methods. Supplemented by weighing performed by the operator it satisfies all the spent fuel NDA recommendations of the ASTOR Group of experts. Intensive method development and testing is ongoing as a joint effort of the IAEA, EC and STUK.

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