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Non-destructive assay sampling of nuclear fuel before encapsulation

C. Hellesen and S. Grape

Division of Applied Nuclear Physics, Department of Physics and Astronomy, Uppsala University, Box 516, 751 20 Uppsala, Sweden
E-mail: carl.hellesen@physics.uu.se, sophie.grape@physics.uu.se

Abstract:

Swedish spent nuclear fuel is planned to be verified before being encapsulated and placed in a geological repository 500 meters below ground in the bedrock. Verification before encapsulation is intended to ensure both the safe storage of the spent fuel, and that Sweden is honoring its international obligations according to the NPT, international treaties and bilateral agreements on the topic of nuclear safeguards.

The measurements will mark the last chance of verifying the spent fuel, as there are no plans to retrieve them once they enter the geological repository. With respect to nuclear safeguards, fuel assemblies will likely be verified for both gross defects and partial defects, whereby a fraction of the fuel content has been removed or replaced. A conclusion also needs to be made on the correctness of the fuel assembly declarations, translating into a verification (or determination) of the fuel parameters such as initial enrichment, burnup and cooling time.

Keywords: non-destructive assay; spent nuclear fuel; sampling; encapsulation

1. Introduction

Sweden is a country with a substantial fraction of electricity being produced by nuclear power. The spent nuclear fuel is currently stored in the Swedish Interim Storage Facility for Spent Nuclear Fuel (Clab) in Oskarshamn. The proposed future encapsulation facility Clink will be built next to Clab, and it is planned that the fuel will be measured here before being encapsulated and shipped to the geological repository in Forsmark. This repository will be a so-called “difficult-to-access storage” since the fuels are not easily retrievable. This means that spent fuel assemblies that can be dismantled should be verified with a partial defect test or, if not available, the best available method approved for inspection use; spent fuel assemblies that are difficult to dismantle (e.g., welded fuel assemblies) should be verified with at least a gross defect test. The reason is that spent nuclear fuel contains up to 1% of plutonium, which is a nuclear-weapons usable material.

There is a need to develop a sampling plan for the spent nuclear fuels. This sampling plan needs to include sufficiently many fuels in the fuel inventory in a partial defect test to ensure that the probability to discover a missing specified quantity is at least 90% or greater [1]. Often, a specified quantity is equal to a significant quantity (SQ), which for plutonium is 8 kg [2]. This means that in total, the false-negative rate of a diversion of 1 SQ should be below 10%.

The measurements will be non-destructive, possibly including several measurement techniques in one location. According to the IAEA, the measurements will take place in “the assembly handling cell” [3] before placing the fuels in the copper canister. It is not clear at this stage what this location corresponds to; possibly it could mean the fuel handling pool at the upcoming Clink facility, but not necessarily. If we assume that the measurements will take place under wet conditions, measurements could be performed on the pool side, in a dedicated measurement room next to the pool via collimators, inside the pool or at fuel racks or integrated into the fuel handling equipment [4].

Although this context is inspired by Sweden, the situation is similar to that of many other countries. The IAEA requirements are the same everywhere, and it is likely that the implementation of nuclear safeguards verification in a pioneering country becomes the standard, or at least a guide, for other countries.

2. Experimental verification challenges before encapsulation

There are several open questions remaining with respect to the nuclear safeguards verification, and specifically with relevance to the sampling plan. Having said that, we here consider that not all fuels will be measured with the same accuracy (given that instrument accuracies are expected to improve over time), and that some kind of random sampling will be performed. Examples of relevant questions in this context are:

- What exactly needs to be measured?
- What level of defects need to be verified with which confidence?
- What accuracies and uncertainties are associated with the considered measurement techniques or instruments?

A spent nuclear fuel typically contains up to 1% plutonium, which is particularly sensitive as it can be used as raw material in a nuclear explosive device (NED). It is classified by IAEA as a direct use material [2]. This is in contrast to the

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uranium in the fuel, which is low enriched (LEU) and cannot be used in a NED without subsequent enrichment. LEU, like irradiated nuclear fuel, is classified by IAEA as indirect use nuclear material. Since plutonium can be chemically separated from other elements in the fuel it is vital that the spent fuel is accounted for.

For all weapons usable materials, a significant quantity (SQ) is defined as the approximate mass for which the construction of a NED cannot be excluded. For plutonium this is 8 kg [2]. This means that a PWR assembly, with a weight of about 600 kg, contains up to 6 kg plutonium. If a larger fraction than ⅔ of the fuel rods in two separate assemblies are diverted and replaced with dummy rods of equal mass, it could make up one SQ of plutonium. Furthermore, if smaller fractions are diverted from a, potentially large, number of fuel assemblies, one significant quantity of plutonium can be accumulated over time, a scenario known as roll-up [5]. To exclude the risk of a roll-up scenario in an encapsulation plant, where on the order of 100 000 assemblies will be encapsulated, will obviously be a challenge. It is important that the fuel assemblies are tested for defects at different levels prior to encapsulation. In this paper we consider diversions from 50% of an assembly down to single pin level.

Within nuclear safeguards, it is important to assure that a significant quantity of weapons usable material is not diverted. The diversion can take many shapes. If we consider 17 by 17 PWR assemblies, each rod contains about 20 grams of plutonium. Acquiring a total of one SQ would require the removal of one single pin from 400 PWR different assemblies. It can be argued that it is sufficient for nuclear safeguards inspectors to detect one single diversion attempt *before* the series of diversions have accumulated to a total of one SQ, rather than necessarily detecting 400 cases of partial defects on the single rod level. A positive outcome in a random sample could then initiate sampling on a more detailed level of a larger number of assemblies to investigate the possibility of an actual diversion attempt (as opposed to a mistake, such as a wrongly declared assembly).

A sampling protocol would have to be established. Course measurement techniques, capable of detecting diversions involving a large fraction of missing fuel pins, would need to be used more frequently. Very accurate techniques, capable of detecting diversions of small fractions of missing pins, could be used less frequently.

There are a limited number of instruments currently authorized for partial defect testing on the 50% level by the IAEA: the Digital Cherenkov Viewing Device (DCVD) [6] and the Fork detector (FDET). In addition, the passive gamma emission tomography (PGET) system [7] has also recently been authorized for genuine partial defect verification, meaning verification on the single pin level. Work on improving these techniques, as well as the development of new ones, is ongoing. See for example [8].

3. Methodology

In this work we have studied the defect verification of a fuel inventory intended for encapsulation with a Monte Carlo based sampling approach. Two types of simulations have been used.

In the first type, the sampling is tested at three levels of defects, 50%, 10% and single pin. The defect level is here referred to as f_{defect}. In the first case, 50% of the rods, in a randomly selected small subset of the assemblies, have been substituted with dummy rods of the same mass. In the second case, 10% of the rods have been substituted, and in the third case, single rods are substituted.

The 50% defect corresponds roughly to the detection capability of the digital Cherenkov viewing device (DCVD) [6] and the single pin defects correspond to the detection capability of the passive gamma emission tomography (PGET) [7]. Currently, there is no authorized technique for detecting defects at the 10% level. However, one objective of this study is to evaluate the role for such a technique, and we refer to it here as the 10%-technique.

The diversion scenario considered in this study is a continuous accumulation of smaller quantities of fissile material, also referred to as roll-up. To our knowledge this is the first technical study that investigates detection level as a function of diversion scenario and instrument capability in connection to verification of a large inventory of spent nuclear fuel.

When evaluating the effectiveness of different fuel verification techniques, two parameters are of central importance: the true positive rate as well as the false positive rate; these are denoted here as p_{detect} and p_{false}. The value of p_{detect} is the probability that a fuel assembly with a partial defect is correctly identified as such. On the other hand, p_{false} is the probability that an untampered fuel assembly is mistaken for a partial defect assembly. The two parameters play different roles, which is further discussed in section 6. These probabilities are connected to the measurement techniques used and are given as input to the Monte Carlo sampling. The probability of a successful cumulative diversion of, in total, one SQ without detection is denoted as P_{divert} and is a result of the simulation.

In the simulation, a random sampling of the fuel inventory is made.

- First, a number of assemblies in the inventory are selected randomly for diversion, in total adding up to SQ of plutonium.
- Second, a number of assemblies in the inventory are selected randomly for verification. The fraction of verified assemblies is referred to as F_{sample}.

- Third, for each verification, randomized defect tests are generated based on the probability p_{detect}. If a test scores a true positive, the diversion attempt is considered to have failed.

In the first simulation type, F_{sample} is varied from 10^{-3} to 1.0, and different levels of p_{detect} are tested. With this procedure we evaluate the required sampling frequency at different levels of p_{detect} for diversions at fixed defect levels (50%, 10% and pin level).

However, the detection probability of an instrument is typically not a constant but will vary with the defect level. For this reason, we also perform a second type of simulation with diversion attempts at different levels of defects, starting from single pins and up to 50% detects. Further, in the second simulation p_{detect} is not kept constant. For the DCVD and the 10%-technique, we assume that p_{detect} is a function that increases with the size of the defects; while for the PGET we assume that p_{detect} is close to 1.0 for all defect sizes.

In [9] the efficiency of a DCVD for partial defect detection was investigated. It was concluded that the measured light intensity from spent fuel assemblies agreed with the modeled intensity within ±30%. If the level of p_{false} should be kept acceptably low, a threshold for defect detection can be used that corresponds to p_{detect} = 1.0 around a 50% defect level. For defects at a 25% level, p_{detect} will drop to 0.5, and for defects close to the single pin level p_{detect} will be 0. In the modeling we therefore assume that p_{detect} follows a soft step function through these points. Similarly, we assume that p_{detect} for the 10%-technique follows a similar soft step function but reaches 1.0 for 10% defects.

The procedure in the second simulation type is similar to what is described above for the first type, with the difference that all three techniques are used together, but with different sampling frequencies. Further, if a positive result is found, the same assembly is always tested again with a more accurate technique. For example, if the DCVD makes a positive measurement, it is re-verified with the 10%-technique, and if the 10%-technique makes a positive measurement it is re-verified with the PGET. Once the PGET makes a true positive measurement, the diversion attempt is considered to have failed.

In the Monte Carlo simulation of the sampling we have here assumed that all assemblies sent for encapsulation are 17 by 17 PWR type with 264 fuel pins and contain 1% plutonium. This is a simplification, but these assumptions are trivial to change to the exact conditions for the SNF inventory under consideration. For example, the Swedish inventory consists of a mix of PWR and BWR fuels with burn up levels varying from about 10 to 60.

4. Results

The results from the first simulation type are presented in figures 1 through 3. In figure 1 we show the probability for diversion success of one SQ plutonium (P_{divert}) as a function of sampling frequency. In this case the partial defects are on the level of 50% in 17x17 PWR assemblies. The results show that, given a 95% detection probability of diversion attempts (P_{divert}=0.05) and p_{detect}=0.5-0.75, every fuel assembly needs to be verified in order to ensure that one SQ of plutonium has not been diverted. Should the sampling be made less frequently, or with a less accurate method, it cannot be ruled out that a diversion of one SQ has been made at some place in the fuel inventory.

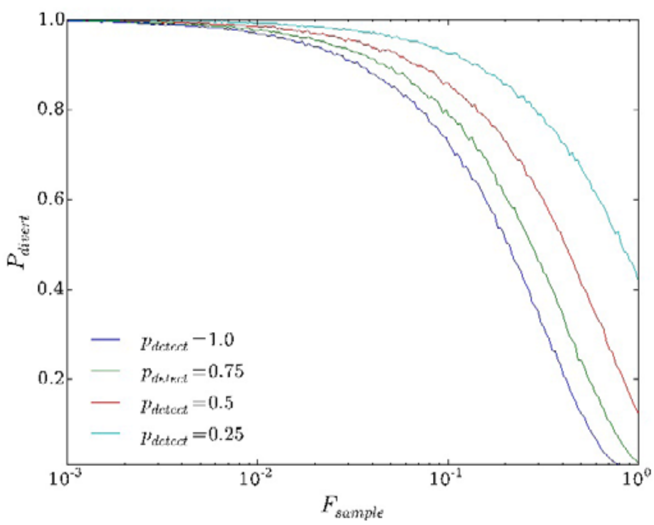

Figure 1. Probability for diversion success of in total one SQ if fuels suffer from a 50% partial defect level. The different curves correspond to different values of p_{detect}, indicating the level of accuracy of the selected instrument at this level of partial defects.

Continuing with figure 2, we show the results of the sampling for the case of defects at a 10% level. Here, the sampling frequency and accuracy needed to detect a total diversion of one SQ are inversely related. If the accuracy (p_{detect}) is close to 1.0, i.e. the risk of false negatives is small; it suffices to test for diversions at this level with a sampling frequency of around 1/4. However, if the accuracy of the chosen method is lower, the sampling must be done more frequently (approaching every assembly) in order to achieve a reasonably low risk for a successful diversion at some place in the inventory.

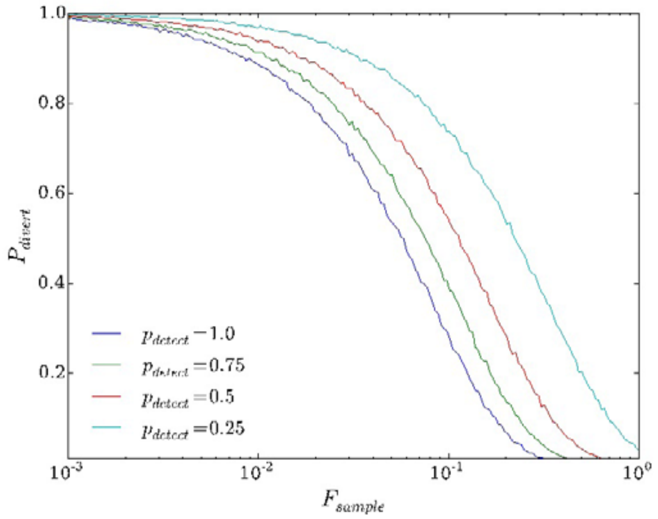

Figure 2. Probability for diversion success of in total 1 SQ if fuels suffer from a 10% partial defect level. The different curves correspond to different values of p_{detect}, indicating the level of accuracy of the selected instrument at this level of partial defects.

In figure 3 the situation for partial defects at the single pin level is shown. Qualitatively it is similar to the situation described above, although the required sampling frequencies are more than one order of magnitude lower.

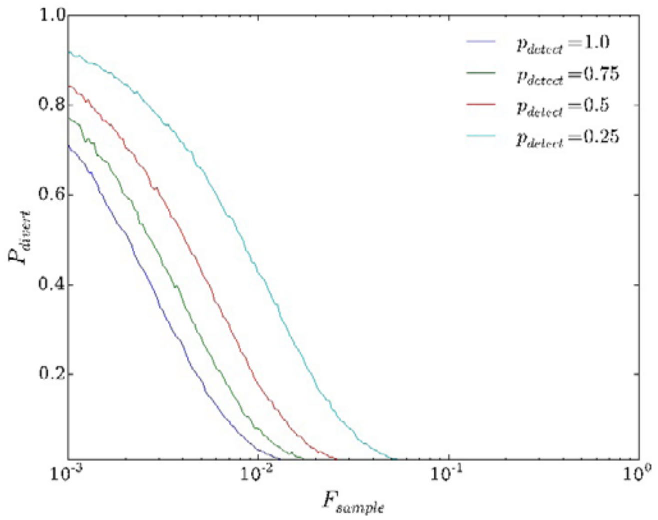

Figure 3. Probability for diversion success of in total 1 SQ if fuels suffer from a single rod partial defect level. The different curves correspond to different values of p_{detect}, indicating the level of accuracy of the selected instrument at this level of partial defects.

Finally, in figure 4 we show the results of the second simulation type with all three instruments operating in parallel. The different sampling rates used are based on the results presented above, from the first simulation type. For the DCVD and the 10%-technique, we sample every assembly and every ¼ assembly, respectively. However, for the PGET we test two sample rates. The two curves in figure 4 correspond to sampling every 1/100 assembly with the PGET, while the dashed red curve corresponds to sampling every 1/20 assembly.

While a sampling of every 1/100 assembly with the PGET is adequate to detect a diversion of 1 SQ from multiple single pin defects, there is a blind spot for diversions around 2%, which corresponds to about 5 pins per assembly. For such diversions, 1 SQ is acquired too quickly, and the 10%-technique is not yet sensitive enough to detect the defects. However, with a sampling of every 1/20 assembly with the PGET (dashed red curve) the blind spot is reduced significantly.

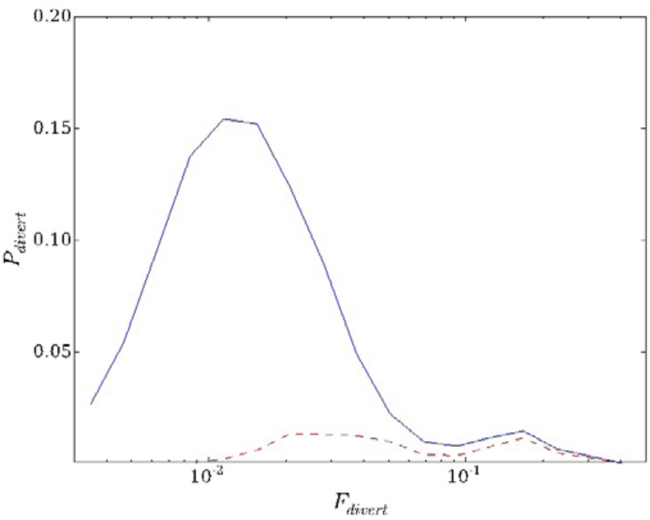

Figure 4. Probability for successive diversion of in total 1 SQ at varying levels of defects, from single pin to 50%. The solid blue and dashed red curves correspond to sampling 1/100 and 1/20, respectively, of all fuel assemblies with the PGET instrument

Some implications can be noted from the results in this paper. Diversions can take place with varying levels of defects, and the sampling procedure must take this into account. If a diversion scenario considers large defects from a few assemblies, one SQ can be acquired relatively fast. Consequently, a sampling of every assembly has to be made with a quick and robust method that can reliably detect large defect levels. Here we used a maximum of 50% of the rods missing, and the probability for true positive detections, p_{detect}, must be kept around 75% or higher. On the other hand, if a diversion is made from small quantities over long times, it is only necessary to sample a (small) subset of the assemblies to detect one manipulated fuel assembly. However, the measurement technique must be capable of detecting small defects. We used an example of partial defects on the single rod level, and depending on the level of p_{detect}, somewhere between 1/500 and 1/100 of all assemblies must be assayed. However, this number increases to about 1/20 of all assemblies when

5. Discussion

The nuclear safeguards verification needs to be non-intrusive and interfere with regular operations of the facility to a minimum extent. Currently, the DCVD [6] is authorized to be used for verification of defects on a level of 50%. The operation of a DCVD is straightforward, quick and in many aspect non-intrusive, and sampling every assembly should not pose a serious interference with the routine operations of the facility.

At the other end of the spectrum, passive gamma emission tomography (PGET) of the fuel assemblies has the potential to detect single missing rods from fuel assemblies. In comparison to the DCVD, it is more time consuming and requires the fuel to be moved to a dedicated measurement station. Sampling every assembly would likely result in a serious interference with the operations of the facility. However, individual diversions at the level of a few pins are small enough to allow for a sampling frequency at 1/20 or lower, which could be more easily incorporated into the facility operations. Under the assumption that one copper canister consisting of four PWR assemblies is filled each day, it would only be necessary to use the PGET a few times every week.

However, with the currently available measurement techniques, detecting possible diversions at a defect level of about 10% poses a considerable challenge. Actually, this concerns any partial defect level between 50% and a few pins. Such defects cannot be reliably detected with the DCVD technique and there is no other technique existing today for partial defect verification at that level today. While a PGET device could in principle be used to detect defects at about 10% with very high accuracy (p_{detect}≈1.0), the required sampling frequency would still be comparably high. In the case of a facility for encapsulation of PWR assemblies, around 1/4 of the assemblies would have to be sampled. This would mean that the PGET would have to be operated several times per day.

Instead, adding a third measurement technique capable of reliably detecting defects at the 10% level, but with a measurement time significantly shorter than the PGET, is preferable. With three systems running in parallel, a robust verification of defects at all levels can be made with little interference with the routine operations of the facility. The DCVD could be used for all assemblies, the 10%-technique a few times per day, and the PGET a few times per week.

Finally, the importance of p_{false}, i.e. the probability for a false positive result, must also be considered. A likely sampling procedure would be that a positive result using a course technique, e.g. a DCVD scanning for 50% defects, is followed by an examination using a more accurate technique designed for defects at the 10% level in order to verify if the positive result is an actual defect or a measurement error. Likewise, a positive assay with a technique designed to detect defects at the 10% level would be followed by an examination using the most precise instrument, the PGET.

However, if p_{false} is too high, the use of the more accurate measurement technique would be dominated by verifying false positive assemblies identified by less accurate techniques. Optimizing the sampling procedure requires detailed knowledge of p_{detect} and p_{false}, which is beyond the scope of the paper. But we do note that the two probabilities are likely related. Setting a low threshold for a positive result, can increase the value of p_{detect}, which would result in a lower required sampling frequency. But at the same time, a lower threshold is also likely to result in a higher false positive rate, which would increase the usage of more precise instruments. Likewise, while longer measurement times interfere more with the operations of the facility, they can also potentially reduce noise and increase p_{detect} as well as decrease p_{false}, and therefore lessen the interference with the facility operations.

6. Conclusion

This simulation study aims at investigating how spent nuclear fuel can be sampled for the purpose of verifying defects, for instance before encapsulation and placement in a difficult-to-access storage. The fuel assemblies are expected to be measured in order to draw conclusions on gross and partial defect verification. The nuclear safeguards verification needs to be non-intrusive and to interfere with regular operations of the facility to a minimum extent.

The results show the importance of having an available selection of partial instruments capable of detecting varying levels of partial defects. Instruments that can quickly survey a large fuel inventory and give results on whether or not a large fraction of the fuel material has been diverted, are valuable in excluding a diversion scenario where large amounts of nuclear material are removed from a few items. On the other hand, instruments that are able to perform partial defect verification on a low level, e.g. single rods missing, are very valuable for excluding a roll-up scenario.

Currently, there are authorized instruments that can be used to verify partial defects on a level of 50% as well as single missing rods. The results here show that, assuming an interest for keeping the sampling frequency with the PGET low, there is a motivation for developing instruments capable of verifying defects at a level around 10%. Without such instruments, one is referred to an extensive use of the PGET. If a 10%-technique can be found that is quick and robust, its extensive use may not be a problem.

Further, one should keep in mind that partial defect tests might not be the only verification that needs to be made. There could also be an interest to perform additional assays to verify the fuel parameters (cooling time, burnup and initial enrichment). If such a measurement can provide a defect test at a 10% level as well, it can be used as a complement to a PGET.

Finally, it can also be pointed out that the PGET does not directly probe the fissile content in the assembly, but infers it indirectly from measurements of the gamma emission from fission products. In a diversion scenario where dummy replacement rods have been loaded with Cs-137 a PGET would not detect the diversion.

Consequently, there could also be an interest to employ other methods that directly probe the fissile content of the assemblies, even if such methods have a lower sensitivity than the PGET. Examples are neutron-based techniques such as the differential die away self interrogation (DDSI) [10].

7. Acknowledgements

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