Strål
säkerhets
myndigheten
Swedish Radiation Safety Authority

Author: Sophie Grape, Erik Branger,
Li Caldeira Balkeståhl, Zsolt Elter, Carl Hellesen,
Staffan Jacobsson Svärd and Peter Jansson.
Division of Applied Nuclear Physics, Uppsala university, Uppsala

Research

2019:01

# Research within technical safeguard at Uppsala university during 2016-2018

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## SSM perspective

### Bakgrund

Kompetens inom området nukleär icke-spridning och kärnämneskontroll är en förutsättning för att ett land ska kunna leva upp till de internationella krav som följer av fredlig användning av kärnenergi. Det är därför viktigt att det finns långsiktiga forskningsprogram på flera universitet för att upprätthålla kompetensnivån i landet. Eftersom det finns begränsade satsningar från andra aktörer, såsom Vetenskapsrådet, bidrar SSM till finansieringen av forskning vid bl.a. Uppsala universitet inom kärnämneskontroll. SSM bidrar både i form av en bredare satsning på en forskningsgrupp, men även med mer riktade satsningar.

Kärnämneskontrollen är till sin natur ett internationellt område och SSM sätter stor vikt vid att de forskningsgrupper vi stöder aktivt deltar för att bidra till utvecklingen av internationella krav och riktlinjer, likväl som i det internationella vetenskapssamhället. Gruppen vid Uppsala universitet har lång tradition av att arbeta i nära samarbete med operatörer och kontrollmyndigheter, vilket ger dem en unik möjlighet att sätta sin forskning i ett sammanhang.

### Resultat

Gruppen vid Uppsala universitet för fissionsdiagnostik och kärnämneskontroll har under perioden bedrivit forskning inom en rad olika projekt med fokus på metoder för att verifiera använt kärnbränsle: Utveckling av metodologier inom kärnämneskontroll med fokus på verifiering av använt kärnbränsle och instrumentet Digital Cherenkov Viewing Device; Multivariatanalys på gammaspektroskopidata från använt kärnbränsle; Neutronanalys av använt kärnbränsle med hjälp av tekniken Differential Die-Away Self Interrogation; Kärnämneskontroll för Generation IV system; Gammatomografi för verifiering av partiella defekter hos använt kärnbränsle; Uppskattning av osäkerheter hos mätningar av använt kärnbränsle inför inkapsling.

Forskningen har resulterat i en rad vetenskapliga artiklar och resultaten från de olika projekten har även presenterats i samband med olika internationella möten och konferenser.

### Relevans

För SSM finns dubbla syften med satsningen på forskning inom området för nukleär icke-spridning vid Uppsala universitet. Forskningen i sig bygger upp långsiktig nationell kompetens både vid universitetet och hos SSM:s egen personal. Den bidrar också till utvecklingen av mättekniska metoder och analyser främst mot tillämpningar för verifiering av använt kärnbränsle, där delar av resultaten från gruppen använts för framtagande av nya verifieringsmetoder inom det internationella atomenergiorganet (IAEA). SSM anser att det är viktigt att kompetens och forskning finns kvar och kan utvecklas bl.a. inför kommande utmaningar med verifiering av använt kärnbränsle och atypiska bränslebehållare inför ett framtida slutförvar.

**Behov av vidare forskning**

SSM anser att den forskning som bedrivs inom gruppen för fissionsdiagnostik och kärnämneskontroll vid Uppsala universitet är viktig. Gruppen har god specialkunskap för vidareutvecklingen av vissa verifieringsmetoder som är viktiga inom internationellt kärnämneskontroll, och SSM:s satsningar på grupp vid Uppsala universitet kommer att fortsätta.

**Projektinformation**

Kontaktperson SSM: Lars Hildingsson
Referens: SSM 2016-661 / 7030086-00

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# Sammanfattning

Uppsala universitet bedriver forskning inom teknisk kärnämneskontroll, med stöd av Strålsäkerhetsmyndigheten (SSM). Perioden januari 2016 till juni 2018 har omfattats av avtal SSM2016-661 och forskningens verksamhet har inkluderat insatser från tre doktorander och sju seniora forskare. Den här rapporten sammanfattar den forskning som har möjliggjorts med hjälp av det avtalet.

Den utförda forskningen berör en rad olika forskningsprojekt: (1) Utveckling av metodologier inom kärnämneskontroll med fokus på verifiering av använt kärnbränsle och instrumentet Digital Cherenkov Viewing Device (2) Multivariatanalys på gammaspektroskopidata från använt kärnbränsle (3) Neutronanalys av använt kärnbränsle m.h.a. tekniken Differential Die-Away Self Interrogation (4) Kärnämneskontroll för Generation IV system (5) Gammatomografi för verifiering av partiella defekter hos använt kärnbränsle, och (6) Uppskattning av osäkerheter hos mätningar av använt kärnbränsle inför inkapsling.

Flera av dessa projekt har finansiering också från andra avtal med SSM, eller via andra källor, men det är avtal SSM2016-661 som möjliggör samordning och koordinering av projekten och ger en stabil grund för verksamheten som i sin tur möjliggör att andra medel kan sökas.

Under avtalsperioden januari 2016-juni 2018 har en doktorand disputerat och två försvarat sina licentiatavhandlingar. En av dessa två studenter kommer att disputera under oktober 2018. Åtta vetenskapliga artiklar har publicerats i granskade tidskrifter, och ytterligare två är under granskning. Utöver det har sex artiklar publicerats eller blivit accepterade för publikation i s.k. ”conference proceedings” i samband med internationella konferenser och möten.

Utöver ren forskningsverksamhet har också andra aktiviteter bedrivits under avtalsperioden. Flera forskare vid Tillämpad kärnfysik vid Uppsala universitet har varit aktivt engagerade i organisationen ESARDA och flera av organisationen arbetsgrupper, samt i nationella och internationella utbildningsinsatser som rör både grundutbildningsstudenter, doktorander och yrkesverksamma inom fältet.

# Summary

Uppsala University has since January 2016 undertaken an extensive research programme in technical nuclear safeguards within the framework of contract SSM2016-661, including in total 3 PhD students and 7 senior researchers. This report marks the final reporting covered by this contract.

The executed research covers the following projects; (1) Methodologies for safeguards assessment of irradiated nuclear fuel assemblies using the Digital Cherenkov Viewing Device; (2) Multivariate analysis of gamma spectroscopy data from irradiated nuclear fuel; (3) Neutron assessment of irradiated fuel using the Differential Die-Away Self Interrogation technique; (4) Nuclear safeguards for future Generation IV systems; (5) Gamma tomography for partial-defect verification of irradiated nuclear fuel assemblies, and; (6) Estimation of uncertainties involved in measurements of spent fuel before encapsulation. Several of the projects are co-funded also from other contracts with SSM and with other funding parties, whereas the current contract (SSM2016-661) forms the foundation for the coordination and execution of all projects.

During the funding period (January 2016-June 2018), one doctoral student has achieved the PhD degree and yet two have achieved the PhLic degree, of which one student is scheduled for the PhD dissertation in October 2018. Eight scientific papers have been published in peer-reviewed scientific journals, and two more is currently under review. In addition, six scientific papers have been published or accepted for publication in proceedings from international conferences and meetings.

Related to the research programme are also other engagements in national and international nuclear safeguards; Several of UU's researchers are strongly involved in the European Safeguards Research and Development Association (ESARDA), as well as in national and international education efforts for both undergraduate students, PhD students and experts in the field.

# Chapter I: Introduction

Uppsala University (UU) has a long record in research within technical nuclear safeguards and the UU researchers in this field are internationally recognised, having a range of collaborations with researchers in other countries, being active in international working groups and being frequent participants in international conferences and meetings, and publishing new research findings regularly in established scientific journals covering this field. The research programme in technical nuclear safeguards at UU is maintained by a combination of base funding and project funding, where one may note that the latter is enabled by the base funding. Consequently, the activities are concentrated to a set of research projects with different time spans and contents, for which funding is applied for and resources are allocated separately, whereas the basis for all activities is formed by the individual scientists involved in the research programme and the base support enabling the full range of activities.

The current report accounts for the full range of activities within the research program on technical nuclear safeguards at UU, constituting the final report for contract SSM2016-661, which forms the base funding for the research program. Several of the research projects that are accounted for in this report are co-funded by separate contracts with SSM and other funding parties, for which this report may form an intermediate status report. However, the scope of this report is to present all activities covered by funding from SSM2016-661, independently of whether the activities are ending with this contract of continued under other contracts.

In the reference section, publications to peer-reviewed journals are listed with a “j” prefix, conference contributions are listed with a “c”-prefix, and theses are listed with a “t”-prefix. Publications by Uppsala University researchers before this contract entered into force, as well as references by researchers outside of our group are listed without a prefix.

# Chapter II: Researchers in technical nuclear safeguards at Uppsala University

Employees involved in nuclear safeguards research in the Nuclear fission and safeguards group at Uppsala University during January 2016-June 2018 are listed in Table 1. Research funding by SSM is marked in bold and is described in more detail in Table 2.

**Table 1.** Researchers active in the nuclear safeguards research programme at Uppsala University during the period January 2016-June 2018.

| **Nuclear safeguards researchers funded by SSM** | **Main tasks in the nuclear safeguards research programme** | **Funding** |
|---|---|---|
| Sophie Grape | Group leader and coordinator for the technical nuclear safeguards research programme at UU. Main supervisor for Matilda Åberg Lindell, Tomas Martinik and Erik Branger. *On parental leave April 2016-March 2017* | **SSM**, UU |
| Erik Branger | PhD student in nuclear safeguards | UU, **SSM**, **SSM-DCVD** |
| Li Caldeira Balkeståhl | Postdoc working ~90% with the MVA project in collaboration with Los Alamos National Laboratory (LANL) | UU, **SSM**, **SSM-MVA** |
| Zsolt Elter | Postdoc working on the MVA project. *On ~50% parental leave during February-May 2018.* | UU, **SSM**, **SSM-MVA** |
| Carl Hellesen | Researcher in GenIV and nuclear safeguards. *On parental leave April 2017-November 2017.* | VR, UU, **SSM**, **SSM-uncertainty** |
| Staffan Jacobsson Svärd | Senior Lecturer in nuclear safeguards. Active in UGET and co-supervisor for Erik Branger | KSU, SKC, VR, FKA, **SSM-UGET** |
| Peter Jansson | Researcher in UGET and co-supervisor for Tomas Martinik and Erik Branger. | KSU, SKB, UU, **SSM-UGET** |
| Tomas Martinik | PhD student in nuclear safeguards. Finished with PhLic in April 2016. | UU, LANL, **SSM** |
| Matilda Åberg Lindell | PhD student in nuclear safeguards. Finished with PhD in March 2018. | VR; UU, **SSM** |
| **Researchers without funding from SSM:** | | |
| Peter Andersson | Researcher, co-supervisor for Matilda Åberg Lindell until Feb 2018. | SKC, UU |
| Ane Håkansson | Professor, co-supervisor for Matilda Åberg Lindell and Tomas | UU, SKC, FKA |

| | | |
|---|---|---|
| | Martinik. Active in the ANNETTE project. | |

As can be seen in the Table 1, a number of different SSM-contracts support the nuclear safeguards research at UU. However, it should be noted that there is one main contract that facilitates additional research activities, and that is the Competence support contract SSM2016-661. Without this, it would not be possible to “quarantine” nuclear safeguards researchers from industry funding, and it would not be possible for the researchers to take on new tasks and projects as they arise. For completeness, all SSM contracts mentioned in Table 1 are further specified in Table 2.

**Table 2.** Funding from SSM, used for research in technical nuclear safeguards during the period January 2016 – June 2018.

| Funding notation | Title of contract | Period |
|---|---|---|
| SSM | ”Kompetensstöd inom nukleär icke-spridning vid Uppsala universitet” (SSM2016-661) | January 2016-June 2018 |
| SSM-MVA | ”Multivariat analys för kärnämneskontroll” (SSM2015-4125) | November 2015-October 2018 |
| SSM-DCVD | ”Kärnämneskontroll – doktorandtjänst vid Uppsala universitet” (SSM2012-2750) | October 2013-December 2018 |
| SSM-Uncertainty | ”Mätnoggrannhet vid verifiering av använt kärnbränsle före slutförvaring” (SSM2016-4600) | January 2016-April 2018 |
| SSM-UGET | ”Stöd till Sveriges stödprogram till IAEA avseende gammatomografi” (SSM2016-130 / SSM2017-951-1) | 2016 / 2017 |

Researchers who are (or have been) full-time working within nuclear safeguards are: Sophie Grape, Li Caldeira Balkeståhl, Zsolt Elter, Erik Branger, Tomas Martinik and Matilda Åberg Lindell. Carl Hellesen is part-time active in nuclear safeguards, while Staffan Jacobsson Svärd and Peter Jansson have worked with nuclear safeguards within the support programme of IAEA. They are, together with Ane Håkansson and Peter Andersson also co-supervising PhD students in nuclear safeguards.

# Chapter III: Research Projects

This section of the report describes research that is facilitated by the contract SSM2016-661, which enables the researchers in the group to take on different research project over time. Many of the research projects described here have additional funding as well, either from separate SSM contracts or from other sources.

## 1. Research related to the Digital Cherenkov Viewing Device (DCVD)

Since January 2016, Erik has been working on characterizing the Cherenkov light emissions from irradiated nuclear fuel assemblies in wet storage. Through simulations, the parameters affecting the Cherenkov light production were identified and quantified, and the results of the simulations were presented in paper [j1]. Building on this work, the Cherenkov light production from complete fuel assemblies were simulated, and systematic differences between assemblies of different designs were identified. The results were presented in paper [j2]. The magnitude of the systematic differences on the Cherenkov light production are described, and the loss of accuracy introduced by making simplifying assumptions in the simulations are quantified.

Based on the work of [j1], [j2] and the ESARDA 2015 conference paper [1], an improved prediction model has been developed with increased capability to make predictions of the total Cherenkov light intensity of an assembly. This method improves upon the previously used one by considering the assembly design, the irradiation history of the assembly and the complete fission product inventory of the assembly. The method requires a comprehensive computation to be performed once per fuel design, and parameterizes the Cherenkov light production as a function of gamma and beta emission spectra and assembly designs. Once this pre-computation has been done, it is relatively fast to make a prediction of a fuel assembly from operator declared irradiation history, making the method useful to inspectors in the field.

In December 2016, Erik defended his licentiate thesis [t1], which was based on papers [j1], [j2] and [1]. The scrutinizer of the work was PhD Anders Hjalmarsson (UU).

During the 2017 ESARDA conference, Erik presented work on simulating and investigating the so-called near-neighbour effect, where radiation from one assembly enters a neighbouring assembly and creates Cherenkov light there [c1]. Through simulations, the near-neighbour effect was investigated and quantified, and a method to predict its intensity was developed. The method was validated using already existing measurement data from a measurement campaign dedicated to quantifying the near-neighbour effect, with good results. The paper [c1] was selected for publication in the ESARDA Bulletin.

Erik has been given access to DCVD measurements from an IAEA measurement campaign on 9 months cooled spent PWR nuclear fuel. The measurements have been analysed, and the research has recently been accepted for publication in the Journal of Instrumentation [j3]. The article investigates three prediction models for total Cherenkov light intensity from spent nuclear fuel: i) the conventional prediction model, ii) the prediction model developed within this PhD project, and iii) the near-neighbour prediction model that was presented at the ESARDA conference in 2017 [c1].

Research is also ongoing with respect to analysis of data taken during the DCVD measurement campaign in the summer of 2017. An important result that was discovered is that the background subtraction model implemented in DCView does not fully manage to subtract the background. Investigations have therefore been performed with the goal of analysing different background components in the signal. The results were summarized in a manuscript that has been submitted to the Journal of Instrumentation [j4].

During the spring of 2018, Erik has also participated in a measurement campaign at Clab. The goal was to evaluate the new DCVD software, which includes the new prediction model for single assemblies developed within this PhD project. The near-neighbour predictions are however not included in this version. The new software update and the new prediction model will be available to inspector shortly.

The project is now approaching its end and we are concluding and summarizing the research.

Work is also proceeding with investigating the light transport from the spent nuclear fuel to the DCVD. A paper is being written on the topic, with the purpose of investigating the relation between emitted and detected Cherenkov light intensity. The article compares the two quantities and investigated simplifications made in the light transport model in order to see if it is possible to make the computations less heavy. The article also investigates the effect of different top plate designs, and different ways how to include them in the modelling.

Erik is now also writing on the thesis itself, and this work is anticipated to proceed during the coming months.

# 2. Multivariate analysis on gamma spectroscopy for nuclear safeguards

Since January 2016, there has been extensive work and progress on investigating the application of multivariate analysis to nuclear safeguards. The research was initiated by the interest to investigate whether development of new analysis approaches could complement the development of new instrumentation to strengthen nuclear safeguards. A first attempt was made to investigate the application of multivariate analysis algorithms to passive gamma spectroscopy data, and specifically to study whether it is possible to determine fuel parameters of interest without relying on operator declarations.

## 2.1. Initial MVA studies

Principal Component Analysis (PCA) was applied to the data for the purpose of vitalizing whether there exist structures in the data that motivate more complex algorithms to be used. In PCA, so-called principal components, which capture the largest variance in the data, are identified and used to reduce the dimensionality of the data. A modified version of Partial

Least Square (PLS) regression was then used to find the relation between the activity of each gamma-emitting fission product and the fuel parameters of interest. It was found that CT could be determined rather accurately from the first principal component of PCA, and that PLS regression could be used to determine IE and BU with a fixed CT, at least for cooling times shorter than 20 years when multiple gamma energies remain in the fuel to be measured. For longer cooling times it seems that more information is necessary, and our intention is to include neutron data as this is sensitive to fissile content and relatively independent of cooling time. The results were published in the Annals of Nuclear Energy [6].

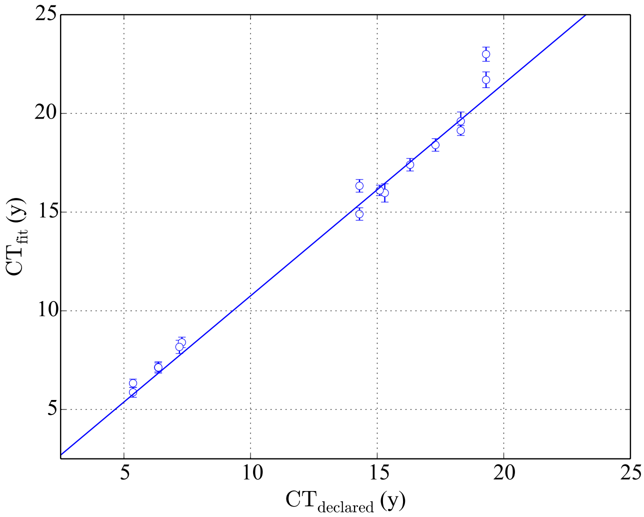



**Figure 1:** Fitted CT versus declared CT for 16 PWR fuel assemblies using MVA of fission product gamma spectroscopy.

Since then, work has continued along the path of application of MVA for nuclear safeguards analysis. The MVA work on fission product gamma spectroscopy has been continued by examining a previously recorded data set from 25 PWR fuel assemblies from SKB. It was found that 16 assemblies were measured with adequate statistics to perform the analysis. The results on fitted CT versus declared CT are shown in Figure 1. Overall there is a good agreement with differences typically smaller than 1 year. However, there are a few outliers. Most notably one assembly with fitted CT = 23 y and declared CT = 19.3 y. Interestingly, this assembly has a very atypical burn up history, being first loaded in July 1980 and finally discharged in June 1995. The model data used in the MVA is based on a 4 year irradiation time as described in [6], and an explanation of the discrepancy in fitted and declared CT could be the difference between the actual and modelled irradiation history. A sensitivity analysis using an error propagation also shows that the main source of uncertainty in the analysis originates from the assumptions used in the model data, such as power density and irradiation time. Uncertainty in fitted CT due to statistics in the data is small in comparison.

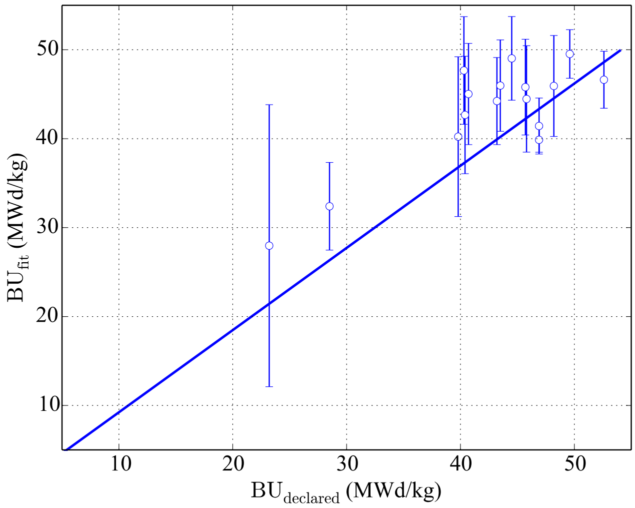



**Figure 2:** Fitted BU versus declared BU for 16 PWR fuel assemblies using MVA of fission product gamma spectroscopy.

Further, in Figure 2 we show the results on fitted and declared BU from the same 16 PWR assemblies used in the CT analysis. Overall, the agreement is typically within 5 MWd/kg. In this case, the uncertainty in the fitted values is dominated by the statistics in the data. For this reason, measuring the fuels with longer data acquisition times to allow for better statistics is likely to reduce the errors. This is in contrast to the analysis of CT discussed above, where the errors are dominated by the model assumptions. In principle, the model errors could be reduced by using more accurate assumptions on burnup history. However, this would negate one of the main benefits of the multi variate analysis presented here, namely that no prior information on the fuel assemblies is used in the analysis. Neither the burnup history of the assemblies, nor the detector geometry and setup. The analysis is therefore completely independent from operator declarations.

In addition, two more projects are ongoing with respect to the topic of MVA; one focusing on further development of the analysis based on gamma spectroscopy data, and one on modelling the neutron detection capability of the Differential Die-Away Self Interrogation instrument for inclusion in the MVA analysis. The latter project is taking place in collaboration with researchers from Los Alamos National Laboratory.

## 2.2. Ongoing MVA gamma spectroscopy studies

On the gamma spectroscopy side, studies have been performed to investigate the possibility to determine partial defects based on multivariate analysis of passive gamma spectroscopy using a HPGe detector [c2]. Namely, we investigate through simulations whether the diversion of certain parts of a spent fuel assembly can be detected from the change in the modelled gamma spectra. Since fuel pins made of UO2 are strong attenuators of gamma rays, mainly the outer rods of the assembly contribute to the passive gamma spectroscopy signal. However, as shown in Figure 3, the pin-wise relative contribution to the detector signal strongly depends on the gamma energy: a higher gamma energy is associated with a larger contribution by the central fuel pins. Therefore, upon substituting fuel pins with non-radioactive, strongly attenuating materials, one may observe a different change in the passive gamma spectra for lower and higher energy gamma peaks as compared to the spectra of an unperturbed assembly with the same BU, IE and CT values.

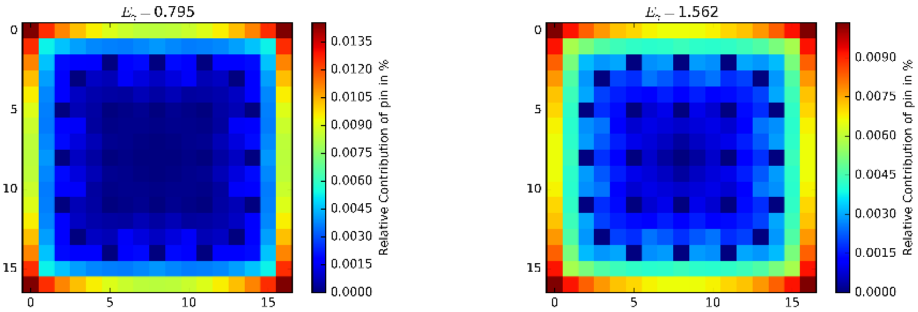



**Figure 3.** Relative pin-wise contribution to a gamma detector in a 17x17 PWR assembly, when the detector is facing the corner pins (the plot is an average over the four corners). Left: Gamma energy of 0.795 MeV Right: Gamma energy of 1.562 MeV

MVA techniques are applied to investigate the ability to detect partial defects from changes in the spectra. The training of MVA methods (e.g. classifiers) is based on synthetic data, and accordingly a vast amount of simulations of passive gamma spectra (i.e. observations or samples) are needed, thus the computational time of these samples is crucial.

## 2.3. Computational methodology

At the beginning of the project, the general Monte-Carlo code MCNPX was used to simulate the gamma particle transport between the fuel and the detector. However, using Monte-Carlo based methods in a heavily shielded and collimated geometry is time consuming. In [c3] the disadvantages of using MCNP(X) for the current task are discussed and a way overcoming the disadvantages using an in-house code is described.

In order to produce synthetic data in a fast and reliable way, a 2-dimensional point-kernel method which can evaluate the energy dependent geometric efficiency of rectangular fuel assemblies has been developed. The user defines the geometry of the gamma source (a rectangular lattice) and the positions in the lattice can be filled with fuel (coaxial cylinder elements corresponding to fuel pins with cladding). The user also defines the material compositions of these cells, and the detector points where the efficiency needs to be evaluated. The program, named FEIGN, iterates through each source pin, calculates the distances travelled by the photons in various materials by evaluating the intersections of the lines and the circles (e.g. pins and cladding). An example of the working principle is illustrated in Figure 4 for a simplified, 4x4 fuel assembly, which contains only fuel pins in water.

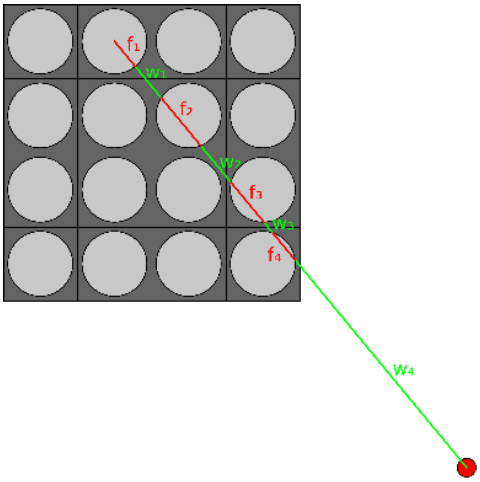



**Figure 4.** Working principle of FEIGN: example of a 4x4 assembly, where only fuel pins surrounded by water are present. The gamma ray emitted from the pin travels $f_1+f_2+f_3+f_4$ distance in fuel and $w_1+w_2+w_3+w_4$ distance in water before reaching the detector point.

The attenuation of gamma rays is applied to determine the proportion of photons reaching the detector point from the assembly. The total attenuation coefficients are taken from the XCOM database.

## 2.4. Calculated geometric efficiency

To demonstrate the output of the software, four different fuel assembly configurations were selected. The selected configurations are shown in Figure 5 and referred later as "Orig" (an intact, 17x17 fuel), "Exter", "Inter" and "Random", the three latter being assemblies with partial defects on the level of 30%. The different partial defect cases describe scenarios where 80 rods are replaced with steel dummies in the periphery, in the central region or in random positions, respectively.

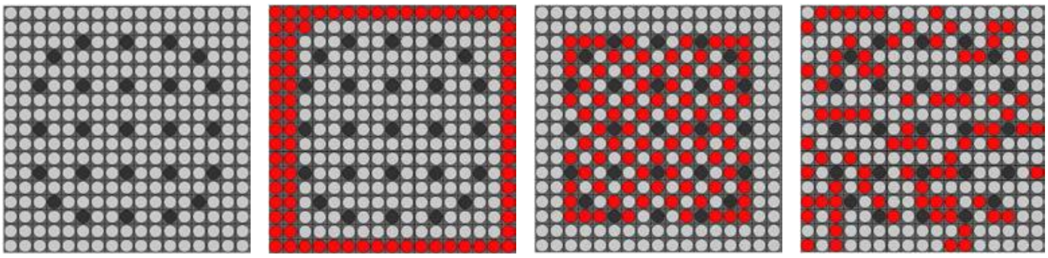


**Figure 5.** Examples of fuel configurations (grey: fuel rod, black: guide tube, red: steel dummy replacement rod). From left to right: "Orig" - intact fuel, "Exter" - 80 peripheral rods replaced, "Inter" - 80 central rods replaced, "Random" - 80 randomly selected rods replaced.

In all cases, four detector points were placed 55 cm away from the centre of the fuel assemblies, facing each corner. Figure 6 shows the calculated geometric efficiency curves for the four configurations as an average over the four detector positions. The results show that if peripheral parts are substituted, the contribution to the spectrum by high energy photons is drastically reduced. The opposite result is found if fuels are substituted in the central region, this results in a higher contribution to the spectrum by high-energy photons as compared to the intact "Orig" configuration. Although, physically there is no point of normalizing the curve, normalization highlights how replacement of different parts affects the low and the high energy parts differently as shown in Figure 6 (right). It can be seen that in the "Exter" case, the low energy photons which tend to contribute to the detector mostly from the peripheral pins, are relatively speaking mire shielded than in the other cases. The evaluation of these geometric efficiencies may be useful in other works, determining the BU of spent fuel, to perform calibration such as the one mentioned in [j5].

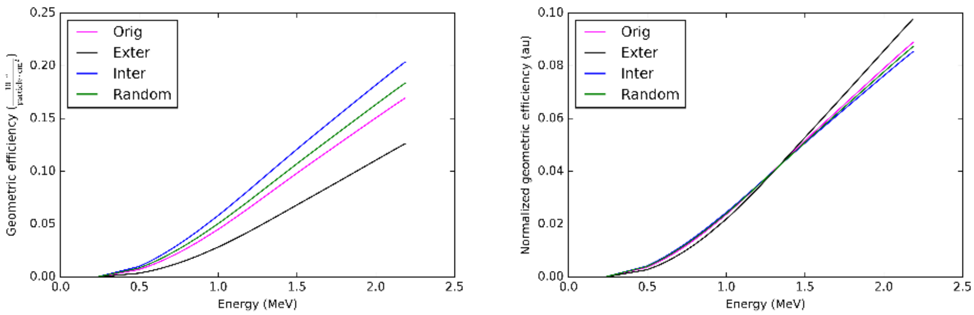



**Figure 6.** Left: The calculated geometric efficiency curves Right: Normalized geometric efficiency curves.

The code also allows for the quick evaluation of the pin-wise detector contributions as shown in Figure 3, which may be useful for tomography studies to calculate pin-wise weights for reconstructing the tomographic images.

## 2.5. Building and analysing the dataset

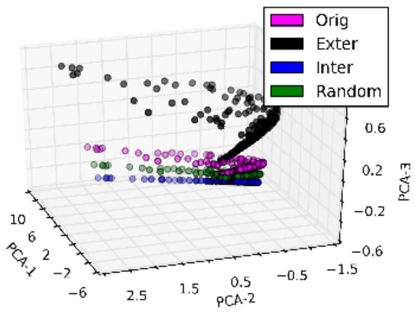
In order to do MVA based on gamma spectroscopy data, we need to create an inventory of gamma signatures from different fuels. The gamma emission spectrum, determined from Serpent2 inventory calculations, is multiplied with the geometric efficiency calculated by the point-kernel model, and with an intrinsic efficiency curve of the detector, as determined by a separate Monte Carlo simulation.

In [j5] 36 gamma energy lines are listed as possible candidates for MVA. We have implemented a recursive feature selection algorithm in order to select 10 gamma energies, which have the highest correlation to the response variable (i.e. the ten gamma energies which are the most important for classifying intact and partial defect fuels). The selected lines are listed in Table 3.

**Table 3.** The 10 selected gamma energy lines (in MeV) that have the highest contributions to the response variable.

| Isotope | Gamma energy [MeV] |
|---|---|
| Ru-106 | 2.112 |
| Cs-134 | 1.365 |
| Cs-137 | 0.662 |
| Eu-154 | 0.873, 0.996, 1.004, 1.246, 1.274, 1.494, 1.596 |

For each of the four fuel configuration shown in Figure 5, 200 fuel assemblies (samples) were simulated with a BU of 20-50 MWd/kgU, CT of 5-30 years and an IE of 3.5 %. Thus the dataset can be arranged in a 800 by 10 matrix, in which each row gives the feature vector of the given sample and each column corresponds to one feature. In order to visualize the data, the Principal Component Analysis (PCA) dimension reduction method was applied. The first three principal components are shown in Figure 7 (left). Using three principle components, it seems possible to classify the samples into the four classes defined in Figure 5. However, at long cooling times the classification becomes less trivial, because less data remains to be analysed (gamma energy peaks disappear from the spectrum). The selected energy lines listed in Table 3 imply that the Eu-154 lines dominate the feature selection, and based on the correlation scores in the analysis the four most important energy lines are in fact Eu-154 gamma energies. It may then be possible to determine fuel configuration based on only Eu-154 information, without loss of accuracy due to limiting the isotopes under consideration. In Figure 7 (right), the first two principal components for a dataset including only Eu-154 energies are shown. We observe only four separate dots, because the principal components are only sensitive to the fuel configuration, and the variability due to BU and CT is eliminated from the dataset. This result is promising. Currently we are investigating which classification methods are best suited for the problem, and how the classification is affected when counting errors are included in the dataset.



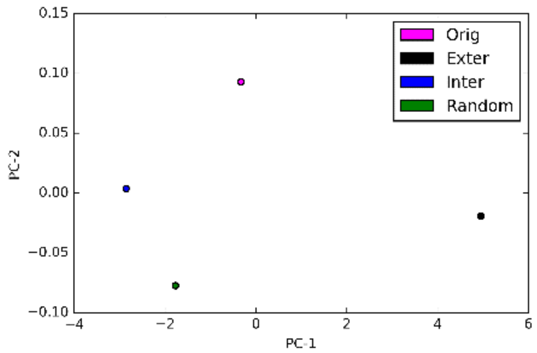




**Figure 7.** Scores for the three first principal components with lines from Table 1 (left). Scores for the first two principal components when only Eu-154 lines are included (right).

# 3. Research on DDA and DDSI under NGSI

Since several years, Uppsala University has a collaboration with Los Alamos National Laboratory (LANL) related to the Next Generation Safeguards Initiative [2]. This research contains the development of instrumentation to meet challenges in nuclear safeguards in the coming 25 years. Of specific interest to Uppsala University is work related to two different measurement techniques called Differential Die-Away (DDA) [3] and Differential Die-Away Self Interrogation (DDSI) [4]. These are neutron detection techniques, whereby a spent nuclear fuel assembly is assayed either using an external neutron source, or using the fuel itself to initiate fission processes.

## 3.1. Research on DDA

From Uppsala University's side, work has earlier been focused on the DDA measurement technique, with a licentiate thesis being produced as a result of the collaboration between UU and LANL [t2]. The thesis comprises three publications, which all deal with modelling of the DDA instrument response. In [5], the instrument response to asymmetrically burned spent nuclear fuel was investigated. This research is one step in the direction of considering more realistically burned nuclear fuel, which do not necessarily have a flat burnup profile as a result of the varying neutron flux in the reactor. In [6], more realistic DDA prototype instrument designs were investigated. This research was prompted by questions related to how changes in the design, such as neutron source position, shielding and detectors, would influence the expected overall instrument response. In [7], the development of the DDA instrument for deployment at the Central Interim Storage Facility for Spent Nuclear Fuel (Clab) was studied. Specifically, the selection and design of individual components as well as operational aspects of the DDA instrument developed for its specific use in Clab was described. In [8], research on how the instrument can be customized for dedicated purposes was presented. Of specific interest was to develop a light-weight instrument for portable applications, and one for improved partial defect detection capability.

## 3.2. Research on DDSI

Since 2016 however, the collaboration concerns primarily the DDSI measurement technique. From UU's perspective, the purpose of the collaboration is both to be active in instrument development relevant to the future verification before encapsulation of spent nuclear fuel, and to further develop the MVA approach described earlier by including neutron signature in addition to the gamma spectroscopy data already considered. With respect to the MVA work, this collaboration facilitates a unique opportunity to access data from the same set of spent nuclear fuel assemblies assayed with different measurement techniques.

The principle of the DDSI-instrument is to detect neutrons, emitted from spontaneous fission in the spent nuclear fuel, in coincidence in the detectors surrounding the fuel assembly. In [9], extensive modelling work performed on DDSI within a PhD project is described. The studies show that the multiplication of the spent nuclear fuel, which depends on the specific isotopic composition, affects the lifetime of a fission chain in the fuel. Using neutron coincidence techniques, it is possible to assay the evolution of the neutron population and obtain information that can be used to determine the fuel parameters. The so-called Rossi-alpha distribution, which enables a determination of the sought-after die-away time, can be determined by measuring the time distribution of the number of neutrons that are detected in coincidence with a first neutron. This die-away time is typically described by an exponential function that described the mean neutron lifetime $\tau$, when in reality the correlation between detected neutrons in in fact either considered as a fast correlation (neutrons from the same fission) or a slow one (neutrons from different fissions, but in the same fission chain). The relative magnitude of the two die-away times reflect assembly multiplication and hence fissile content. Although the primary focus of the DDSI methodology has been on determination of fissile content and Plutonium mass, efforts have also been directed towards verification of partial defects and determination of IE and BU using integration with different NDA techniques.

Since 2016, the focus of the research collaboration between LANL and Uppsala University has been on the DDSI methodology, as it has been the one of the two neutron techniques that has been most actively researched. The multivariate analysis based on gamma spectroscopy data described earlier falls short with respect to spent nuclear fuel with cooling times longer than 20 years, and this is where we believe that including neutron detection data will be most valuable. For that reason we started up a new project, aimed at doing just this. The DDSI instrument has since then been modelled in the MCNP6 code, Figure 8 shows a schematic layout.

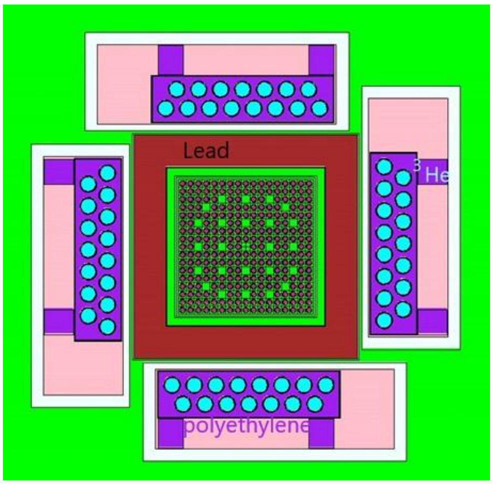



**Figure 8.** Schematic cross-section of the DDSI instrument as modelled in MCNP.

After implementation of the instrument in the software, the instrument response to the PWR 17x17 spent nuclear fuel assemblies in a Serpent fuel library was modelled with IE=2-5% (in steps of 0,5%), BU= 15-50 MWd/kgU and CT=5-70 years. More details about the simulation choices made were presented in [c4]. Rossi-Alpha Distributions were created, and the early die-away time was estimated using an exponential fit in the time window of 4-52 microsecond for all fuels. Work is now ongoing with respect to merging the analysis of the gamma spectroscopy data and the DDSI data to encompass a MVA that includes both passive gamma and passive neutron data.

The primary objective is to evaluate the importance of the neutron data as a complement to gamma spectroscopy data in the MVA, with an initial focus on the determination of the fuel parameters of intact nuclear fuel. Analysis was therefore performed in a similar manner as described in [j5]. Here, CT was assumed to be known, and PLS regression was used to determine BU and IE. Given the neutron signal that is available also for long-cooled fuels (where the results in [j5] were shown to fail), the new analysis focused on simulated fuel assemblies with CT>20 y. The features used in the analysis were the activity of Cs-137 and Eu-154 (normalized to sum to 1 for each fuel assembly), and the early die-away time from the DDSI. First results show that BU and IE can be determined with similar RMSE as in [j5], namely 2.4 MWd/kgU for BU and 0.4% for IE. Figure 9 shows the results of the PLS analysis plotted against the true values of BU and IE, and the nearly linear relation shows that the method is working. These results will be presented in [c5] and further work is ongoing to develop the algorithm further.

In parallel with the MVA efforts, measurements with the DDSI instrument on spent nuclear fuel has taken place at Clab in February 2018. The focus of those measurements was to make a first measurement campaign on spent nuclear fuel with the prototype device that has been built by LANL, and to compare the measurement response with the modelled one.

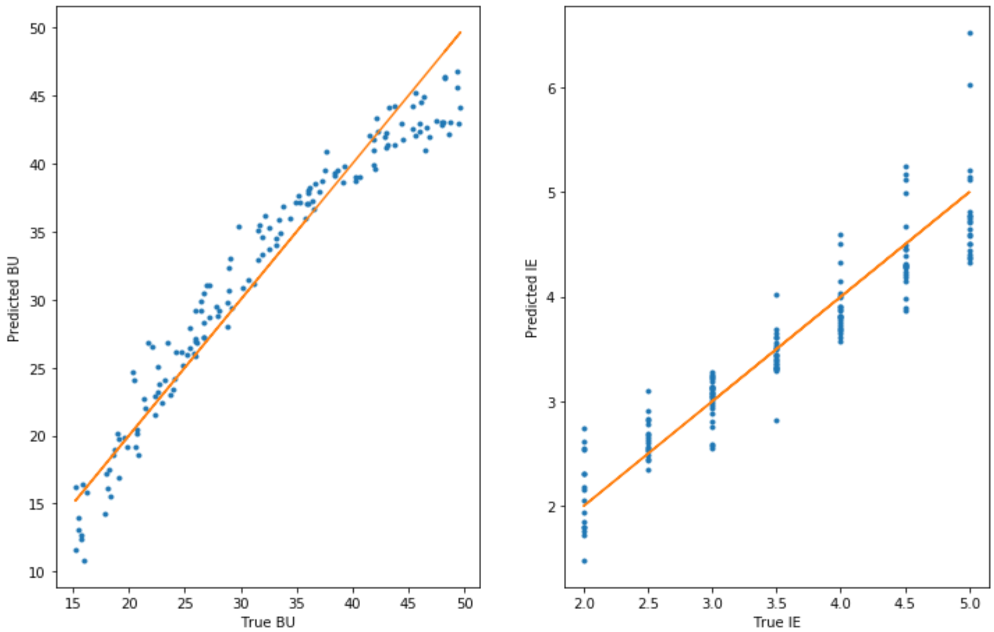



**Figure 9.** Predicted vs. true values from the PLS algorithm for known CT, for BU (left) and IE (right).

# 4. Nuclear safeguards for Generation IV systems

## 4.1. Nuclear safeguards evaluation and analysis techniques

Matilda Åberg Lindell defended her PhD thesis on February 23, 2018 [t3]. The thesis was entitled ”Nuclear safeguards evaluation and analysis techniques for application to nuclear fuel material in Generation IV nuclear energy systems”. The faculty opponent was Professor Juhani Hyvärinen from Lappenranta University of Technology, and the committee consisted Professor Thomas Jonter (SU), Associate Professor Teodora Retegan (Chalmers), Associate Professor Anders Nordlund (Chalmers), Docent Katarina Wilhelmsen (FOI) and Klaas van der Meer (SCK CEN).

The thesis consisted of two sections; the first one on research related to methodologies for estimating the resistance to proliferation in Generation IV nuclear energy systems and this part of the thesis has been described earlier in e.g. [10]. The second one focused on the use of multivariate analysis techniques for nuclear safeguards purposes in the fuel recycling part of the fuel cycle.

During 2017 and 2018, the research has had a strong focus on the use of multivariate analysis (MVA) approaches to Gen IV nuclear energy systems. Considering the fuel recycling part of a Gen IV fuel cycle, the research task has been to investigate the applicability of MVA to the verification of spent nuclear fuel, using only data from passive gamma spectroscopy. This has been researched using simulation tools.

Initially, the purpose was to investigate the possibility to discriminate UOX fuels from MOX fuels, considering that both types of fuels can be expected in the reception area of a fuel recycling facility [j6]. Training and evaluation data of spent nuclear fuel were modelled in the code Serpent, and nine gamma-emitting isotopes that can be expected to be measured using a HPGe-detector were selected for analysis. Principal Component Analysis (PCA) was used for visualization and exploration of data, and the analysis revealed promising structures in the data. This enabled further analysis, and in a second step seven different MVA algorithms were chosen for the purpose of discriminating between UOX and MOX fuels. The results revealed that classification between UOX and MOX was successful for several different MVA algorithms up to cooling times of around 20 years, when only two isotopes remain to be measured.

MVA algorithms were also used for regression analysis, whereby the sought after fuel parameters were determined [j7]. Five linear and non-linear MVA algorithms were evaluated in the determination of initial enrichment, burnup, cooling time and initial fissile content. The analysis showed that the best fuel parameter determination was obtained using regression decision tree for cooling time determination, and the support vector machine regression for burnup and initial fissile content determination. Initial fissile content was however more poorly estimated than both cooling time and burnup. Plutonium mass in UOX fuels could also be well predicted in the analysis.

### 4.2. New doctoral student project on MVA and Gen IV

As a continuation of the research, and with the financial aid from SSM, we have been able to announce a new PhD position at Uppsala University. The focus of the new position is on the application of multivariate analysis algorithms to existing and future nuclear energy systems. The announcements are called ”Doktorand-tjänst i kärnämneskontroll med fokus på multivariata analysmetoder” (”PhD student position in nuclear safeguards directed to the application of multivariate analysis techniques to existing and future nuclear fuel cycles”) and the last day for application is on May 30th. 29 candidates submitted their applications. We are hoping to have a candidate starting with us in the fall of 2018.

# 5. Gamma tomography within the Swedish support programme to IAEA

Work with tomography at Uppsala University is done under the Swedish support programme to the IAEA and it is therefore not part of the work under contract SSM2016-661. Gamma tomography work will hence be reported separately.

However, one piece of work on tomography was funded from this contract, namely the writing of a scientific article for the ESARDA Bulletin. This contribution was selected from the ESARDA symposium contributions [j8] to be published in the Bulletin. The article has now been published, and it summarizes the main scientific results from the IAEA support program task JNT A 1955 (Unattended Gamma Emission Tomography – UGET – Phase I) during 2013-2016 [c6].

One may also note that an additional journal publication was produced by UU within the UGET project during the period covered in this report, describing the use of image analysis to deduce information from tomographic data used for partial-defect verification of nuclear fuel assemblies [j9].

# 6. Measurement uncertainty before encapsulation

Verification of spent nuclear fuel before encapsulation poses unique challenges since the fuel assemblies will be put in a difficult-to-access storage which, in practice, makes re-verification impossible. Therefore, before encapsulation, one must be able to, with high confidence, conclude that all fissile material is correctly accounted for and that all fuels have been operated in accordance with their intended use. An accurate verification of the fuel parameters IE, BU, CT and possibly Pu content can be expected, as well as a verification of assembly defects, i.e., when one or many complete rods are missing from a fuel assembly.

There are however practical limitations that restrict measurements. The limitation to non-destructive assay is one example, as is the time available for measurement and data analysis since a minimum interference with operations is requested.

Within this project, the question to be answered relates to how sampling of the inventory of spent nuclear fuel should be done, in order to draw conclusions on the non-diversion of significant quantities of Pu. For example, the Swedish interim repository for spent nuclear fuel (CLAB) contains several thousand fuel assemblies to be placed in a final, geological, repository. Considering that each assembly weighs between 200 and 600 kg and has a plutonium concentration of about 1%, it just takes a small fraction of the inventory to reach a significant quantity of plutonium (8 kg). This is defined as the smallest amount of plutonium for which the assembly of a working nuclear explosive cannot be excluded. One way to divert plutonium from the spent fuel is to remove individual rods from the assemblies before encapsulation and replace with dummy rods.

For this purpose, several model fuel inventories were created with partial defect levels of 50%, 10% and single pin level were modelled by substituting 50% of the fuel material, 10% of the fuel material or a single pin in a fuel assembly with non-fuel material. The sampling frequency was then varied between very low values to every fuel assembly, and the probabilities for true positives (partial defect fuel assembly is correctly identified as such) and false positive (intact fuel assembly is by mistake identified as a partial defect fuel assembly) were studied.

The results show that with a 50% partial defect level in fuel assemblies, in principle every fuel assembly needs to be verified with an instrument that has a detection probability for this partial defect level of 50-75% (i.e. the sampling frequency needs to be close to 1), see Figure 10 (left). Otherwise one cannot rule out that diversion of one significant quantity of Pu has taken place somewhere in the handling process.

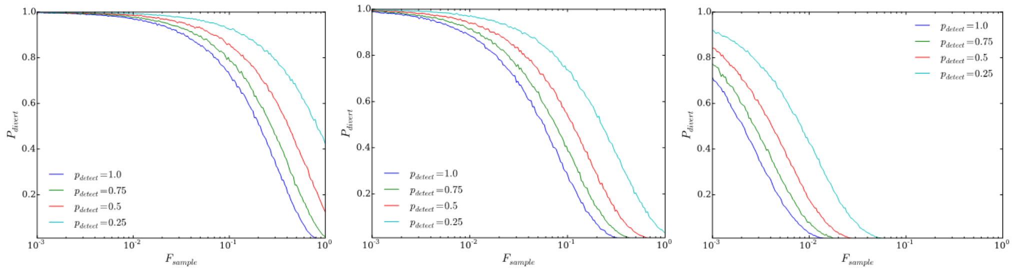



**Figure 10.** Results of probability of diversion as a function of instrument detection level (different colour coding on the solid lines) and sampling frequency, for partial defect levels in spent nuclear fuels on the level of 50% (left), 10% (centre) and single pin level (right).

For partial defects on the 10% level (Figure 10 (centre)), detection levels of 50-75% require sampling of around every third fuel and a detection level of 100% requires sampling of every fifth fuel. For diversion of single rods (Figure 10, (right)), the sampling frequencies are reduced by more than an order of magnitude. For a detection probability of 50-100% it is sufficient to sample around one fuel assembly in a hundred.

Preparing for a detection of partial defects on the level of single pin to 50%, it is clear that sampling frequencies will vary from assaying one fuel assembly in around a hundred, down to every single fuel assembly. We also note that there is a lack of instruments able to detect partial defects in the interval of single pin level up to 50%, which means that the instrument able to detect diversions of single pins would also need to be operated for detecting partial defects up to 50%. The sampling frequency can be expected to increase when considering BWR fuels, as there are more of them going to be encapsulated per day as compared to PWR fuels.

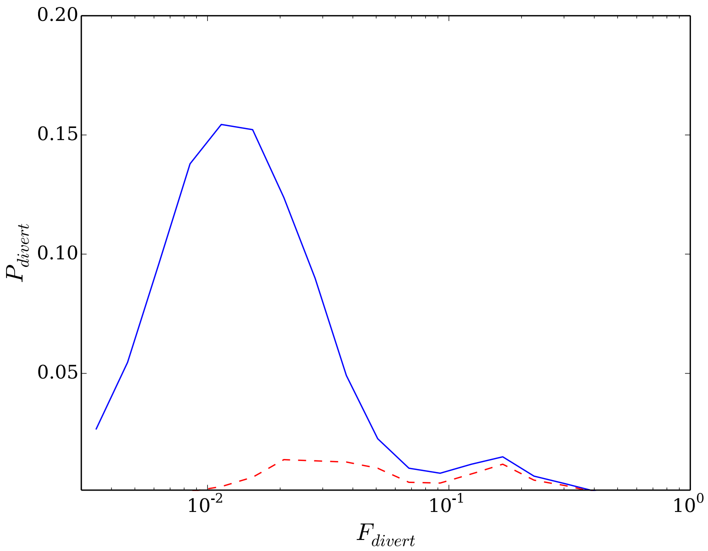



**Figure 11:** Probability for successive diversion of in total 1 significant quantity at varying levels of defects, from single pin to 50%. The solid blue and dashed red curves correspond to sampling 1/100 and 1/20, respectively, of all fuel assemblies with the PGET instrument

In addition, in Figure 11 we also show the results from a second simulation type where the fraction of diverted rods is varied and all three instruments are used in parallel. Two cases are shown where the most sensitive instrument, capable of detecting single missing rods, is used for every 1/100 assembly and every 1/20 assembly. It is clear that even if a sampling of only 1/100 assemblies is enough to detect a diversion constituting of single missing rods it is not enough to reliably detect a diversion of about 5 rods per assembly ($F_{divert}$ = 2% for PWR assemblies) since 1 significant quantity (8 kg Pu) is obtained too quickly. Instead, using the most sensitive instrument for every 1/20 assemblies, a reliable detection of a diversion is seen for all levels, from single rods to 50% of the rods. A manuscript detailing this work has been submitted and is now under review with the journal [j10].

# Chapter IV: Other engagements

## 1. ESARDA – The European Safeguards Research and Development Association

Uppsala University is a member of the ESARDA organization, and we are heavily involved in two working groups.

### 1.1. Training and Knowledge Management (TKM)

Sophie Grape has been chairing the Training and Knowledge Management working group from May 2015 to December 2017. During this period, the ESARDA course has been continuously given by JRC Ispra, and the suggested improvements regarding a new strategy for education, training and knowledge management have taken on a new form. Since the approval of the European project ANNETTE, dedicated to the development of a master education in nuclear engineering, efforts have been directed along this new line. Four ESARDA members (UU, SCK CEN, FZ Jülich and JRC Ispra), represented in the TKM working group are dedicated to the development of a new nuclear safeguards course, targeting the need of vocational education of experts in the field.

According to the agreement, UU (Sophie Grape) is responsible for developing three educational modules in the nuclear safeguards course: “The history of nuclear safeguards”, “The nuclear fuel cycle” and “Non-destructive assay”. The modules should contain course material, case studies and exercises, and the use of e-learning tools is encouraged. For this reason, video material will be recorded, covering parts of the lecture. UU is also involved in the Nuclear safety module, with Ane Håkansson being one of the coordinators.

It is planned that the ESARDA partners offer the ANNETTE nuclear safeguards course in February 2019, and the ANNETTE project will be evaluated by the end of 2019.

### 1.2. Non-Destructive Assay (NDA)

Peter Jansson has been vice chair in the working group Techniques and Standards for Non-Destructive Analysis (NDA) since May 2015, and took on the chair position in May 2017. Regular meetings with the working group has been held twice per year, once in conjunction with the annual meeting of ESARDA and once during autumns. In conjunction to the last annual meeting in Luxembourg, in May 2018, the working group arranged an international workshop on Numerical Modelling of NDA Instrumentation and Methods for Nuclear Safeguards which attracted 21 presentations and about 50 participants plus 54 participants that attended the live video stream from the workshop.

### 1.3. The ESARDA Reflection group

Peter Jansson, being the chair of the NDA working group, participates actively in the reflection group set up to reflect about the strategic future of ESARDA.

# 2. Interaction with the general public and the surrounding society

Uppsala University has an obligation to contribute with information to the general public and give expert opinions when asked for. Research in nuclear safeguards is an example of a topic that is important for the surrounding society, and as an expert, Sophie Grape is a member of the Swedish National Council for Nuclear Waste. The council reports on research and other topics of relevance to the final repository for spent nuclear fuel, arranges seminars, and engages in discussions and meetings with politicians and environmental organizations.

Members of the safeguards group initiated a dialogue with the Ministry of Research and Education regarding funding of national nuclear technology research and education. This dialogue prompted a discussion with the Swedish Research Council, VR, in the same matter and together with input from SSM, relevant (although not sufficient) research funding within new nuclear technology is now regularly issued by the VR.

# 3. Education

Parallel with the work covered by this contract, members of the safeguards group at Uppsala University also involved themselves in various commitments. Just to mention a few:

- In 2010 the Bachelors Engineering programme KKI at Uppsala University was started based on an initiative by the Division of Applied Nuclear Physics. The programme implies that students from all over Sweden are offered to take their last year of studies in Uppsala studying nuclear power technology. Regrettably, as an aftermath of the Fukushima incident and the following public debate, the student's interest for this programme ceased. Therefore, the programme was put on hold 2016, waiting for better times. The safeguards group was heavily involved in this programme, which covered the whole range of subjects connected to nuclear power utilisation making the finished engineers highly attractive to the nuclear sector. Some courses within the programme covered nuclear safeguards. For example, in the course "nuclear power operation", experts from the industry participated as teachers where in-depth knowledge of the practical implementation of safeguards in Swedish nuclear installations was transferred. For us, it is highly satisfactory to conclude that, as a consequence of the new political interest for building nuclear power competence in Sweden, we now have reason to restart the programme next year.

- A nuclear safeguards course will be offered in the ANNETTE project, as described earlier in section 5.1.

- Members of the safeguards group, together with colleagues from Chalmers technical University, initiated in 2017 SAINT (the Swedish Academic Initiative on Nuclear and radiation Technology research and education) as a formal collaborative platform based on the nuclear related activities going on at Uppsala University and Chalmers. The aim with SAINT is to provide a forum where strategic decisions and consolidations can be made regarding research and education within radiation sciences in general. Although SAINT currently comprises only two universities, the plan is to invite several more during this year. Currently SAINT is aiming for a workshop late autumn were colleagues from disciplines such as radiation protection, radiation biology and oncology will be invited. Another project operated by SAINT is the so-called e-learning project. Here the two universities have gathered all their expertise, including members of the safeguards group, to create a series of courses directed to first-year students on the university level all over the country. The material covers all important aspects of nuclear power utilisation and we hope that this material shall function as an eye opener for many students who seldom meet nuclear power in their early stages of education. The course material is based on video recordings and will be conducted in Swedish.

- Members of the safeguards group are involved in the SSM reference group addressing future nuclear technology competence. This work is completely in line with Uppsala university’s general idea to be part of the work in order to create a global welfare society and constructively work for the phase-out of fossil fuel in the world.

- The Nordic Academy for Nuclear Safety and Security; NANSS, function currently as Uppsala University’s portal to our extensive contract education directed to Swedish professionals and to some extent, our students.

# Chapter VI: Publications and references

The first three sections summarise the scientific publications that have been published by the Nuclear fission and safeguards group at UU during the contract period January 2016-June 2018. The last section lists other references to the presented work.

## 4. Scientific publications in peer-reviewed journals, published as part of the research programme


[j1] E. Branger, S. Grape, P. Jansson, S. Jacobsson Svärd, E. Andersson Sundén "On Cherenkov light production by irradiated nuclear fuel rods", Journal of Instrumentation, volume 12, June 2017

[j2] E. Branger, S. Grape, P. Jansson, S. Jacobsson Svärd, E. Andersson Sundén "Comparison of prediction models for Cherenkov light emissions from nuclear fuel assemblies", Journal of Instrumentation, volume 12, June 2017

[j3] E. Branger, S. Grape, P. Jansson, S. Jacobsson Svärd "Experimental evaluation of models for predicting Cherenkov light intensities from short-cooled nuclear fuel assemblies", Journal of Instrumentation, volume 13, February 2018

[j4] E. Branger, S. Grape, P. Jansson, S. Jacobsson Svärd, "Experimental study of background subtraction in Digital Cherenkov Viewing Device measurements". Submitted to Journal of Instrumentation in May 2018.

[j5] C. Hellesen, S. Grape. P. Jansson, S. Jacobsson Svärd, M. Åberg Lindell, P. Andersson, "Nuclear spent fuel parameter determination using multivariate analysis of fission product gamma spectra", Annals of Nuclear Energy, vol 110, pp. 886-895, December 2017

[j6] Matilda Åberg Lindell, Peter Andersson, Sophie Grape, Carl Hellesen; Ane Håkansson, Måns Thulin, "Discrimination of irradiated MOX fuel from UOX fuel by multivariate statistical analysis of simulated activities of gamma-emitting isotopes", Volume 885, 21 March 2018, Pages 67-78

[j7] Matilda Åberg Lindell, Peter Andersson, Sophie Grape, Ane Håkansson, Måns Thulin, "Estimating irradiated nuclear fuel characteristics by nonlinear multivariate regression of simulated gamma-ray emissions", Nuclear Instruments and Methods in Physics Research A, Volume 897, 21 July 2018, Pages 85-91

[j8] S. Jacobsson Svärd et al., "Outcomes of the JNT 1955 Phase I Viability Study of Gamma Emission Tomography for Spent Fuel Verification", The ESARDA Bulletin No 55, December 2017

[j9] A. Davour, S. Jacobsson Svärd, P. Andersson, S. Grape, S. Holcombe, P. Jansson, M. Troeng, "Applying image analysis techniques to tomographic images of irradiated nuclear fuel assemblies", Annals of Nuclear Energy, pp. 223-229. (2016).

[j10] C. Hellesen, S. Grape, "Non-destructive assay sampling of nuclear fuel before encapsulation", Submitted to the ESARDA Bulletin in 2018.

# 5. Conference contributions and meeting presentations, published as part of the research programme

[c1] E. Branger, S. Grape, P. Jansson, E. Andersson Sundén, S. Jacobsson Svärd ,“ Investigating the Cherenkov light production due to cross-talk in closely stored nuclear fuel assemblies in wet storage”, Presented at the 2017 ESARDA safeguards symposium, Düsseldorf, Germany.

[c2] Z. Elter, L. Caldeira Balkeståhl, S. Grape, C. Hellesen: Partial defect identification in PWR spent fuel using Passive Gamma Spectroscopy, Will be part of the Conference proceedings from PHYSOR 2018, Cancun, Mexico.

[c3] Z. Elter et al. “Geometry-based Variance Reduction in simulations of Passive Gamma Spectroscopy from Spent Nuclear Fuel”, Proceedings of the ESARDA NM-NDA-IMNS’18 workshop

[c4] L. Caldeira Balkeståhl, Zs. Elter, S. Grape, C. Hellesen: MCNP simulations of prototype DDSI detector, Proceedings of the ESARDA NM-NDA-IMNS’18 workshop

[c5] L. Caldeira Balkeståhl, Zs. Elter, S. Grape, C. Hellesen: Application of Multivariate Analysis to Gamma and Neutron Signatures from Spent Nuclear Fuel, Will be part of the Proceedings of the Institute of Nuclear Materials Management Annual Meeting, July 22-26, Baltimore, Maryland, 2018

[c6] S. Jacobsson Svärd, L. E. Smith, T. A. White, V. Mozin, P. Jansson, P. Andersson, A. Davour, S. Grape, H. Trellue, N. Deshmukh, E. A. Miller, R. S. Wittman, T. Honkamaa, S. Vaccaro and J. Ely, “Outcomes of the JNT 1955 Phase I Viability Study of Gamma Emission Tomography for Spent Fuel Verification”, Presented at the 2017 ESARDA safeguards symposium, Düsseldorf, Germany.

# 6. Theses presented as part of the research program

[t1] E. Branger, “Studies of Cherenkov light production in irradiated nuclear fuel assemblies”, Licentiate thesis, Uppsala University, 2016.

[t2] T. Martinik, “Development of Differential Die-Away Instrument for Characterization of Swedish Spent Nuclear Fuel””, Licentiate thesis, Uppsala University, 2016.

[t3] M. Åberg Lindell, “Nuclear safeguards evaluation and analysis techniques for application to nuclear fuel material in Generation IV nuclear energy systems”, PhD thesis, Uppsala: Acta Universitatis Upsaliensis, 2018.

# 7. References


[1] E. Branger, S. Grape, P. Jansson, S. Jacobsson Svärd, “Improving the prediction model for Cherenkov light generation by irradiated nuclear fuel assemblies in wet

storage for enhanced partial-defect verification capability", The ESARDA Bulletin No 53, December 2015
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[3] A. C. Kaplan et al., Determination of Spent Nuclear Fuel Assembly Multiplication with the Differential Die-Away Self-Interrogation Instrument, Nuclear Instruments and Methods A, Volume 575, Pages 20-27, 2014.
[4] V. Henzl, M.T. Swinhoe, S.J. Tobin, H.O. Menlove, Masurement of the Multiplication of a Spent Fuel Assembly with the Differential Die-away Method Within the Scope of the Next Generation Safeguards Initiative Spent Fuel Project, Journal of Nuclear Materials Management, Volume 40, Issue 3, March 2012, Pages 61-69
[5] T. Martinik et al., "Simulation of differential die-away instrument's response to asymmetrically burned spent nuclear fuel", Nuclear Instruments and Methods A 788, 79-85, 2015, Los Alamos National Laboratory Report LA-UR-14-21574 (2014).
[6] T. Martinik et al, "Design of a Prototype Differential Die-Away Instrument proposed for Swedish Spent Nuclear Fuel Characterization", Nuclear Instruments and Methods A, Volume 821, 11 June 2016, Pages 55-65. Los Alamos National Laboratory Report LA-UR-15-28331 (2015).
[7] T. Martinik et al., "Development of Differential Die-Away Instrument for Characterization of Swedish Spent Nuclear Fuel", Proceedings of 37th ESARDA Symposium, Manchester, United Kingdom, 2015, Los Alamos National Laboratory Report LA-UR-15-23345 (2015).
[8] T. Martinik et al., "Characterization of Spent Nuclear Fuel with a Differential Die-Away Instrument", Proceedings of IAEA Symposium on International Safeguards: Linking Strategy, Implementation and People, Vienna, Austria, 2014, Los Alamos National Laboratory Report LA-UR-14-28074 (2014).
[9] A.C. Trahan, Utilization of the Differential Die-Away Self-Interrogation Technique for Characterization and Verification of Spent Nuclear Fuel, Doctoral thesis at the University of Michigan, January 2016
[10] M. Åberg Lindell, "Proliferation resistances of Generation IV recycling facilities for nuclear fuel", Ph.Lic. thesis, Uppsala: Uppsala universitet, 2013.

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The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 300 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

**Strålsäkerhetsmyndigheten**
**Swedish Radiation Safety Authority**

SE-171 16 Stockholm
Solna strandväg 96

**Tel:** +46 8 799 40 00
**Fax:** +46 8 799 40 10

**E-mail:** registrator@ssm.se
**Web:** stralsakerhetsmyndigheten.se

Ale Tryckteam AB, Bohus, 2018