Verifying PWR assemblies with rod cluster control assembly inserts using a DCVD

Erik Branger, Sophie Grape, Peter Jansson

Uppsala University, Uppsala, Sweden
E-mail: erik.branger@physics.uu.se

Abstract:

One of the instruments available to authority inspectors to measure and characterize the Cherenkov light emissions from irradiated nuclear fuel assemblies in wet storage is the Digital Cherenkov Viewing Device (DCVD). Based on the presence, characteristics and intensity of the Cherenkov light, the inspectors can verify that an assembly under study is not a dummy object, as well as perform partial defect verification of the assembly.

PWR assemblies are sometimes stored with a rod cluster control assembly (RCCA) inserted, which affects the Cherenkov light production and transport in the assembly. Such an insert will also block light from exiting the top of the fuel assembly, which will affect the light distribution and intensity of the Cherenkov light emissions. Whether or not this constitutes a problem when verifying the assemblies for gross or partial defects with a DCVD has not previously been investigated thoroughly.

In this work, the Cherenkov light intensity of a PWR 17x17 assembly with two different RCCA inserts were simulated and analysed, and compared to the Cherenkov light intensity from an assembly without an insert. For the studied assembly and insert types, the DCVD was found to be able to detect partial defects on the level of 50% in all studied cases with similar performance, though with a higher measurement uncertainty due to the reduced intensity when an RCCA insert is present. Consequently, for the studied assembly and insert types, assemblies with inserts can be verified with the same methodology as used for assemblies without inserts, with similar partial defect detection performance.

The simulation approach used also made it possible to investigate the minimum Cherenkov light intensity reduction resulting from partial defects of other levels than 50%, in the PWR 17x17 fuel assembly with and without RCCA inserts. The results for the simulations without an insert were in agreement with previous results, despite differences in substitution patterns, substitution materials, modeling software and analysis approach.

Keywords: DCVD; partial defect verification; Rod cluster control assembly, Cherenkov light; Geant4

1. Introduction

One of the many safeguards inspection tasks undertaken by authority inspectors is to measure irradiated nuclear fuel assemblies to verify that all nuclear material is present and accounted for. To aid the inspectors, a multitude of instruments has been developed. One of the instruments available is the Digital Cherenkov Viewing Device (DCVD), which measures the Cherenkov light produced in the water surrounding an assembly. The characteristics and quality of the Cherenkov light can be used to perform *gross defect verification*, verifying that the assembly under study is a spent nuclear fuel and not a dummy object. The DCVD is more frequently used for *partial defect verification*, verifying that 50% or more of the rods in an assembly have not been diverted. In such a verification, the Cherenkov light intensity emitted by the assembly is integrated to provide a value corresponding to the total light intensity of the assembly. Based on earlier simulations, it is estimated that a 50% substitution of irradiated fuel rods in an assembly with non-radioactive steel rods will decrease the total Cherenkov light intensity of the assembly by at least 30% [1]. Hence, by comparing the measured intensities to predicted ones, assembly intensities deviating more than 30% can be identified. Recent prediction methods account for the irradiation history of the assembly, i.e. its cycle-wise burnup and cooling time, as well as the physical design of the assembly [2]. Any assembly having an intensity deviating more than 30% from expected is flagged as an outlier, and further investigations and measurements are called for to confirm whether the assembly is subject to a partial defect, or if the deviation is caused by something else such as erroneous declarations.

PWR assemblies in wet storage are in some cases stored with inserts, such as a rod cluster control assembly (RCCA) insert. For such storage cases, the neutron absorber rods of the RCCA are stored inserted into the guide tubes of PWR fuels. This can help save storage space, since no additional space is needed to store the RCCA. In addition, when inserted into a fuel assembly, the RCCA helps ensure sufficient limits to criticality. Before placing spent nuclear fuel in a difficult-to-access storage, the assemblies must be verified for partial defects [3]. It is reasonable to assume that the fuel assemblies will be verified in their current state, with any RCCA inserts still present during the verification measurements.

The presence of an RCCA is believed to affect the Cherenkov light in such fuel assemblies in two ways. Firstly, it prevents Cherenkov light from being created in the guide tubes, as the water inside the guide tubes is substituted by absorber material. Secondly, the RCCA will partly cover the top of the assembly, preventing a significant fraction of Cherenkov light from exiting the assembly to be detected.

Against this background, the objectives with this work is to i) verify the 30% intensity reduction limits of [1] for a 50% partial defect using different simulations codes and partial defect scenarios, since the limit in [1] is an estimate based on 30% rod substitutions. And ii) investigate how RCCA inserts affect the 30% intensity reduction limit assumed for a 50% partial defect level. As a consequence of the methodology chosen to investigate this, it becomes possible to also to study the minimum Cherenkov light reduction resulting from other partial defect levels, ranging from 0-100% substitution of the irradiated rods in an assembly.

2. Simulating the effect of top plates and inserts

To simulate DCVD images of PWR 17x17 assemblies, the three-step method of [4] has been used. These three steps are:

1. In the first step, the gamma emission spectrum of the assembly is simulated using ORIGEN-ARP [5]. In principle, beta decays may contribute, but their contribution has been shown in [2] to be minor and they were therefore neglected here.
2. In the second step, the gamma transport and interaction in a fuel assembly geometry is simulated using Geant4 [6], using a simulation toolkit based on [7]. In this process, Cherenkov light is created and transported to the top of the assembly. Once a Cherenkov photon reaches the top of the assembly, its position and direction is saved. The simulation model considers the full 3-D geometry and axial burnup distribution of the assembly.
3. In the third step, the saved photons are projected onto an imaging plane, using a pinhole camera model, to simulate a DCVD image.

Note that in the second step, the top plate, lifting handle and other structures at the assembly top are not included. The effect of these structures are instead included in the third step. This allows for the computationally expensive second step to be run only once, and different top plates and other structures at the assembly top can quickly be simulated in the third step. The effects of the top structures are studied by applying a mask, detailing where structure material is preventing the Cherenkov light from exiting the fuel assembly, and where light can pass through to be detected.

It was found in [4] that the burnup and cooling time of an assembly will not strongly influence the light distribution in a simulated image. For burnups of 10-40 MWd/kgU and cooling times of 1-40 years the total intensity of the simulated image will change at most 1% due to the changing light distribution. Consequently, in this work one PWR 17x17 assembly with a burnup of 40 MWd/kgU and a cooling time of 10 years was chosen, which is expected to be representative for assemblies with other burnups and cooling times. Using ORIGEN-ARP, the gamma spectrum of the assembly was simulated in the first step, and in the second step the gamma emissions from the fission products were simulated in a fuel geometry. Two different geometries were simulated: one where all guide tubes were filled with water, corresponding to the absence of an insert, and one where all guide tubes were filled with In-Ag-Cd, corresponding to control rod material. Depending on the design of the RCCA, some or all guide tubes will contain absorber material. By applying the top plate mask to the simulations without control rods and with control rods, the extreme values are found for the Cherenkov light intensity in the simulated images. The case of some guide tubes containing control rods are expected to fall between these extreme values.

In the simulations of the second step, the light contribution from each rod in the assembly was stored separately. Thus, it was easy to include only the light contributions from selected rods in the final image. This facilitates studies of partial defect verification, where irradiated fuel rods are substituted by non-irradiated rods with similar density containing natural uranium, depleted uranium or low enriched uranium. Using this approach, it is thus possible to investigate the resulting total Cherenkov light intensity as a function of various rod substitution patterns, and to assess the DCVD capability to detect such substitutions.

2.1 Masks used

To obtain a mask representing the regions of the assembly covered by the top plate, a photograph of a PWR assembly top plate was used. Using the photograph, the covered regions could be manually identified and traced, and converted into a binary mask. The photograph and the resulting mask obtained is shown in Figure 1.

Two different RCCA inserts were studied in this work. For the two RCCA inserts, DCVD images of assemblies with inserts were used to identify which additional regions were covered. This information was used to manually design a mask for assemblies with such inserts. One of the studied inserts had a comparatively large frame for holding the control rods, and consequently covered a substantial fraction of the assembly top, as seen to the left in Figure 2. This

RCCA will be referred to as the “thick insert” in this work. The other studied insert had much finer features, and was relatively more open, as can be seen to the right in Figure 2. This insert will be referred to as the “thin insert” in this work. The thin insert is likely the insert described in [8].

3. Sensitivity of DCVD verification of partial defect in assemblies with inserts

The effect on the total Cherenkov light intensity of substituting irradiated rods with non-radioactive rods is shown in Figure 3. These values show the minimum Cherenkov light intensity reduction for partial defects of a given magnitude. In order to find the most challenging partial defect case to detect, the rods were substituted in an order reflecting their contribution to the total light intensity, starting with replacement of the least significant rod. The rod substitution pattern was estimated individually for the studied cases based on the identification of the fuel rods contributing the least to the total intensity, and the patterns thus differ between the cases. Hence, Figure 3 shows the minimum intensity reduction in the total Cherenkov light intensity for various levels of partial defects, with replacement rods having similar gamma attenuation as the original rod and otherwise identical properties. Thus, for all other substitution scenarios, the intensity reduction will be larger and should be easier to detect.

As mentioned, there are different RCCA designs. In some cases, fuel assemblies with RCCA inserts may have control

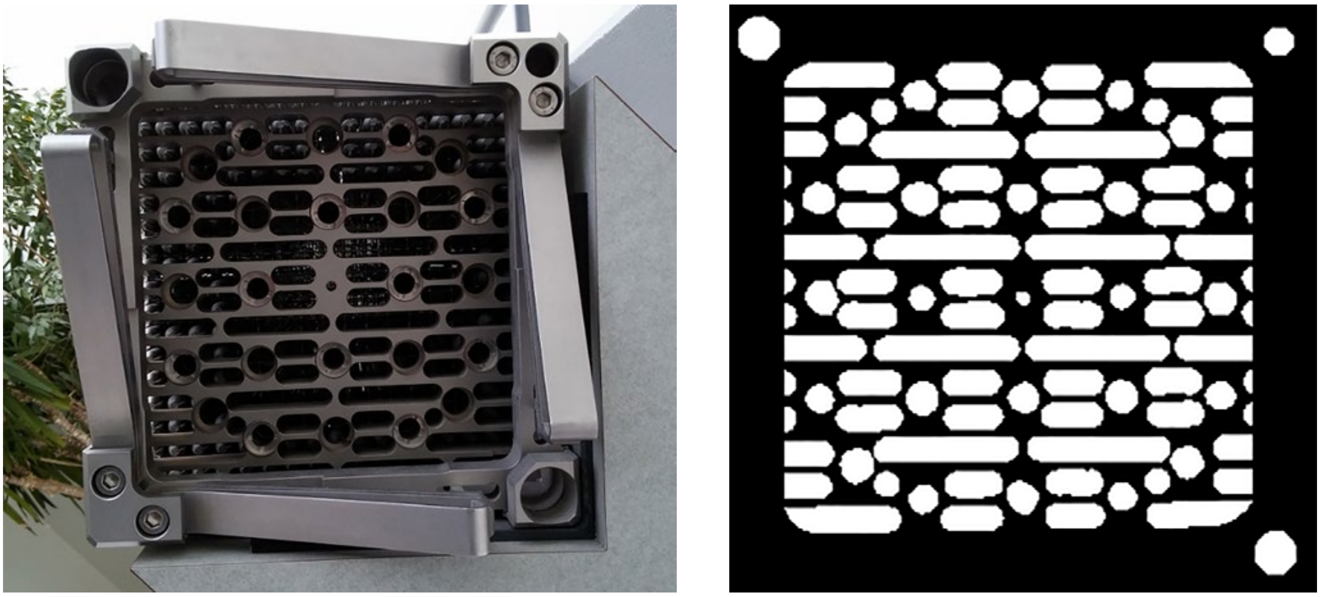

Figure 1 Left: a photograph of the top structure of an assembly model. **Right:** the mask created based on the photograph, to indicate which regions are covered by the top plate and lifting handle.

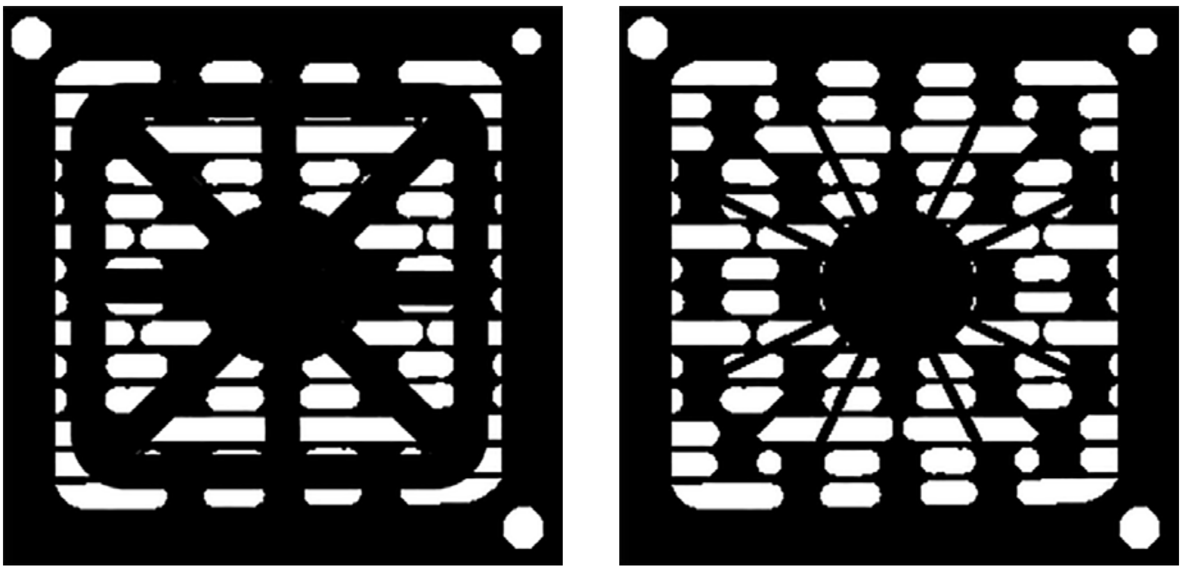

Figure 2 Left: The top plate mask with the addition of the thick RCCA insert, covering a substantial part of the assembly top. **Right:** the top plate mask with the addition of a second, thin type of RCCA insert, having smaller features and covering relatively less compared to the mask on the left. A picture of this insert can be found in [8].

rods inserted into all guide tubes, while in other cases only some of the guide tubes have control rods while others are water-filled. To investigate the impact of this variability on the light intensity, the masks from Figure 2 were applied to the simulated fuel assembly with all control rods present, and to the fuel assembly with only water-filled rods in the guide tube positions. The results for an assembly with an RCCA insert having control rods at only some of the available positions are expected to fall between the results of these two cases. The results show that as the control rods are removed, the light reduction due to a partial defect increases slightly. For both types of RCCA inserts, the light reduction could be up to 1 percent unit higher if the control rods are missing, as compared to if all control rods are present, shown in figure Figure 3. Hence, the case of an RCCA with a full complement of control rods is the most challenging one, and can conservatively be used to estimate the minimum light intensity reduction that a partial defect in an assembly with a RCCA causes.

	No insert	Thick insert	Thin insert
Intensity reduction	27%	27%	29%

Table 1: Cherenkov light intensity reduction at a 50% partial defect level for the studied partial defect cases.

In [1], partial defect detection using the DCVD was studied using simulations. Partial defect levels of 30% (where fuel rods were substituted with stainless steel rods) were studied, with resulting reductions in total Cherenkov light ranging from 15% to 40% depending on the diversion pattern. In [1], it was also estimated that a 50% partial defect would result in at least a 30% intensity reduction. For the case studied here, where partial defects on the level of 30% (where fuel rods are substituted with natural uranium, depleted uranium or low-enriched uranium) are modelled, it is found that the Cherenkov light intensity will be reduced by at least 10%. Partial defects on the level of 50% gives a Cherenkov light intensity reduction of at least 27%, as seen in Table 1 . Both studies hence give rather similar results, despite using different substitution patterns, substitution materials, modeling software and analysis approach.

For the cases of RCCA inserts, the DCVD verification methodology is found to actually be slightly more sensitive to a 50% partial defect, compared to the case of no insert, since the total Cherenkov light reduction is slightly higher. For the thick insert (Figure 2 left), the intensity reduction is at least 27%, and for the thin insert (Figure 2 right) the intensity reduction is at least 29%. Hence, for partial defects at the 50% level, the same partial defect detection criteria in terms of required light intensity reduction can be used for both the insert case as in the non-insert case.

The reason for the higher sensitivity in the RCCA case has to do with the light distribution in a DCVD image. Since the light emitted by the assembly is highly collimated, the central region vertically below the DCVD will be the brightest, and regions further away will appear dimmer. Consequently, in an image without an insert, a rod in the central region will contribute more, in relative terms, to the total Cherenkov light intensity, as compared to a rod near the edge. In

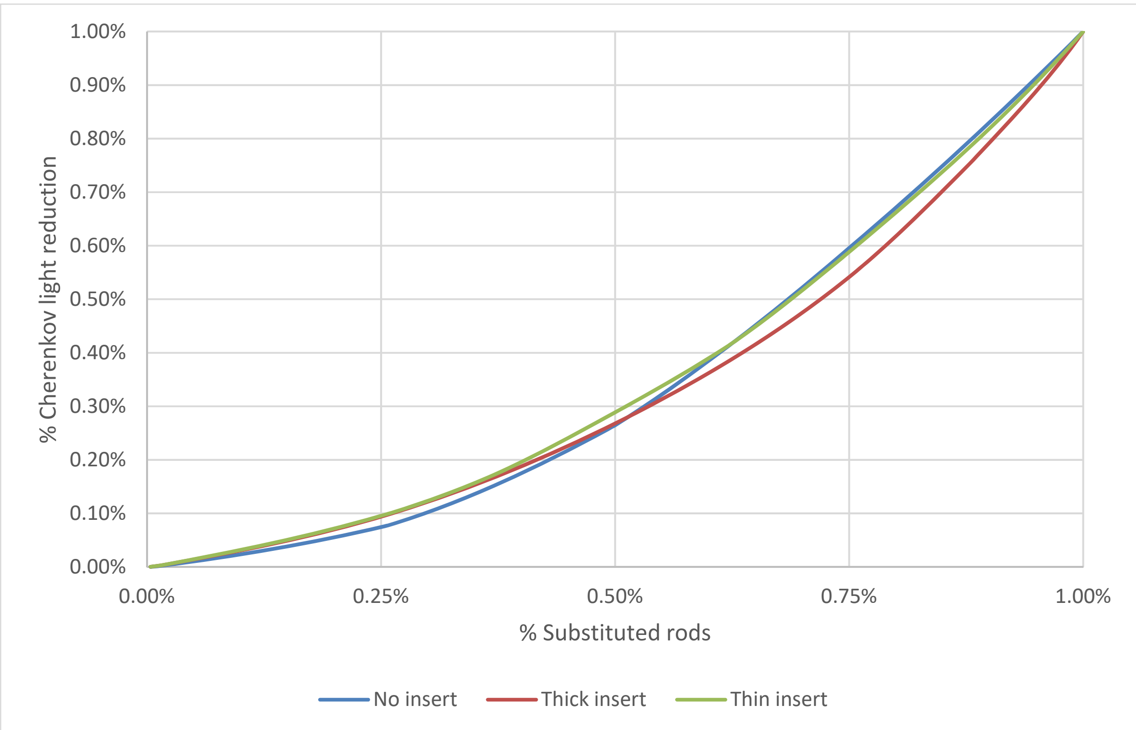

Figure 3: Reduction in Cherenkov light intensity as a function of the fraction of rods replaced with non-radioactive substitutes. Rods contributing the least to the total intensity were removed first, and accordingly the rod substitution pattern differs in all three cases.

addition, since the lifting handle covers the edges, the intensity contribution from a rod at the edge is further suppressed. When an RCCA is present, it will cover large parts of the central region, and consequently suppress the intensity from the otherwise brightest regions at the center. As a result, the distribution of light over the measurement image will be more even, and the relative intensity contributions from the rods will vary less when an RCCA is present.

For the studied cases with and without an RCCA insert, the DCVD verification methodology is least sensitive to substitution of rods near the assembly edge. As noted above, this is a combined effect of the collimation and of the lifting handle obstructing the view. For the more centrally located rods, the contribution per rod to the total intensity varies significantly, depending on which parts that are covered by the RCCA insert. Thus, for partial defect on the order of 50%, the rod substitution pattern that is most challenging to detect using the DCVD, will differ depending on the presence or absence of an RCCA insert, and will be different for RCCA of different designs.

While the inserts do not significantly change the intensity reduction limits, they do change the total Cherenkov light intensity of the image. The simulated total intensity reduction for the two RCCA cases is compared to the non-insert case in Table 2. As can be seen, the insert will significantly reduce the intensity of the Cherenkov light reaching the DCVD detector, and consequently the measurement uncertainties in the RCCA insert case will be higher, for otherwise identical assemblies. Thus, care must be taken when verifying low-intensity assemblies with inserts. Without inserts such assemblies may have a sufficiently high Cherenkov light intensity to be verified for a 50% partial defect level, but with an RCCA present, the intensity may be too low to allow for an accurate measurement, and thus an accurate verification. For the case of a RCCA insert with only a few control rods, the relative intensity is slightly higher, and can increase up to 40% for the thick insert and up to 50% for the thin insert (an increase with 3 percentage points in both cases). These values are similar enough that the assemblies can be readily compared, even if their RCCA inserts contain a different number of control rods, as long as the physical design of the top of the RCCA is the same. The main cause of the change in Cherenkov light intensity in the RCCA case is that more parts of the top of the assembly are covered, the effect of having RCCA inserts with differing number of control rods is less significant.

	No insert	**Thick insert**	**Thin insert**
Relative intensity	100%	37%	47%

Table 2: Relative measured Cherenkov light intensity for an assembly without an RCCA insert and for the same assembly with a thick respectively a thin insert present. The values are scaled so that the intensity of the no-insert case is 100%.

4. Conclusions and outlook

PWR assemblies in wet storage can be stored with an RCCA inserted, which will alter the characteristics and detected total intensity of the Cherenkov light produced inside the assembly. This work has investigated the partial defect detection capability of the DCVD for one PWR 17x17 fuel assembly. A regular fuel assembly has been modelled, as well as the same fuel assembly with two different kinds of RCCA inserts. The minimum expected reduction in total Cherenkov light has then been modelled for partial defects ranging from 0% to 100% for the fuel assembly without as well as with RCCA inserts. The substitution scenario considered is that the irradiated rods are replaced by non-irradiated rods, having identical gamma attenuation properties. Such replacement rods could for example be made of low-enriched uranium, natural uranium or depleted uranium.

The simulation results indicate that the studied partial defect scenarios affects assemblies with and without RCCA inserts in a similar way. Consequently, the currently adopted partial defect verification method using the DCVD can be used also to verify partial defects also in the case of assemblies with inserts, with similar partial defect detection performance. Furthermore, the previously established detection requirement of a 30% reduction in the measured Cherenkov light intensity (for a partial defect level of 50%) compared to the predicted one, can be applied also to the RCCA insert cases. Some RCCA inserts do not have control rods in all available positions, but the simulation results show that this has a comparatively small effect on the total Cherenkov light intensity, and does not pose any additional problems to the verification methodology.

For the studied PWR 17x17 assembly, the rods closest to the edges contribute the least to the detected Cherenkov light intensity. This is due to the collimation of the Cherenkov light, coupled with the positioning of the DCVD during a measurement, and due to the lifting handle covering rod positions around the edges of the fuel assembly. It may be possible to compensate for the collimation by performing measurements with the DCVD aligned over the edges of the assembly. Alternatively, it may be possible to model the effect of the collimation on the light distribution in an image, and use that information to compensate for the collimation effect. Both these procedures could potentially increase the DCVD verification methodology sensitivity to rod substitution near the assembly edges. However, care must be taken to consider Cherenkov light produced in an assembly due to radiation originating in neighbouring assemblies, since such radiation will not travel far to reach a neighbouring assembly, and will hence predominately create Cherenkov light near the edges of an assembly.

In addition to RCCA inserts, assemblies may be stored with other inserts, such as a flow stoppers. The methodology developed here could be applied to assess how such an insert affects the partial defect sensitivity of the DCVD verification methodology. Ideally, all types of inserts that frequently occur should be investigated in this way, to ensure that the standard DCVD verification procedure will accurately verify such assemblies.

5. Acknowledgements

This work was supported by the Swedish Radiation Safety Authority (SSM), under contract SSM2012-2750, and SSM2017-5979. The computations were performed on resources provided by SNIC through Uppsala Multidisciplinary Centre for Advanced Computational Science (UPPMAX) under project p2007011.

6. References

[1] J.D. Chen et al., "Partial defect detection in LWR spent fuel using a Digital Cerenkov Viewing," *Institute of Nuclear Materials Management 50th annual meeting,* 2009.

[2] E. Branger, s. Grape, S. Jacobsson Svärd and P. Jansson, "Comparison of prediction models for Cherenkov light emissions from nuclear fuel assemblies," *Journal of instrumentation,* 2017.

[3] International Atomic Energy Agency, "Special Criteria for Difficult-to-Access Fuel Items. SG-GC-Annex-04," Vienna, Austria, 2009.

[4] E. Branger, S. Grape, P. Jansson and S. Jacobsson Svärd, "On the inclusion of light transport in prediction tools for Cherenkov light intensity assessment of irradiated nuclear fuel assemblies," *Journal of Instrumentation,* vol. 14, 2019.

[5] S. Bowman, L. Leal, O. Hermann and C. Parks, "ORIGEN-ARP, a fast and easy to use source term generation tool," *Journal of Nuclear Science and Technology,* vol. 37, pp. 575-579, 2000.

[6] Agostinelli, S, et al (the Geant4 collaboration), "Geant4 - a simulation toolkit," Nuclear Inst. and Meth. in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 506, Issue 3, 1 July 2003, Pages 250-303.

[7] S. Grape, S. Jacobsson Svärd and B. Lindberg, "Verifying nuclear fuel assemblies in wet storage on a partial defect level: A software simulaiton tool for evaluating the capabilities of the Digital Cherenkov Viewing Device," Nuclear inst. and Meth. A, Volume 698, 11 January 2013, Pages 66-71, ISSN 0168-9002, 10.1016/j.nima.2012.09.048.

[8] Westinghouse Nuclear, "Enhanced Performance – Rod Cluster Control Assemblies (EP-RCCAs). Data sheet.," 10 2014. [Online]. Available: http://www.westinghousenuclear.com/Portals/0/flysheets/NF-FE-0047%20Enhanced%20Performance%20RCCAs.pdf. [Accessed 04 04 2019].