Comparison of prediction models for Cherenkov light emissions from nuclear fuel assemblies

Erik Branger*, Sophie Grape, Staffan Jacobsson Svärd,
Peter Jansson, Erik Andersson Sundén,
Division of Applied Nuclear Physics, Uppsala University,
P.O. Box 516, SE-75120 Uppsala, Sweden

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Abstract

The Digital Cherenkov Viewing Device (DCVD) [5] is a tool used by nuclear safeguards inspectors to verify irradiated nuclear fuel assemblies in wet storage based on the Cherenkov light produced by the assembly. Verifying that no rods have been substituted in the fuel, so-called partial-defect verification, is done by comparing the intensity measured with a DCVD with a predicted intensity, based on operator fuel declaration.

The prediction model currently used by inspectors is based on simulations of Cherenkov light production in a BWR 8x8 geometry. This work investigates prediction models based on simulated Cherenkov light production in a BWR 8x8 and a PWR 17x17 assembly, as well as a simplified model based on a single rod in water. Cherenkov light caused by both fission product gamma and beta decays was considered.

The simulations reveal that there are systematic differences between the model used by safeguards inspectors and the models described in this publication, most noticeably with respect to the fuel assembly cooling time. Consequently, if the intensity predictions are based on another fuel type than the fuel type being measured, a systematic bias in intensity with respect to burnup and cooling time is introduced. While a simplified model may be accurate enough for a set of fuel assemblies with nearly identical cooling times, the prediction models may differ systematically by up to 18 % for fuels with more varied cooling times. Accordingly, these investigations indicate that the currently used model may need to be exchanged with a set of more detailed, fuel-type specific models, in order minimize the model dependent systematic deviations.

Keywords: Nuclear safeguards, Geant4, Cherenkov light, DCVD, Nuclear fuel

*Corresponding author. e-mail erik.branger@physics.uu.se

1 Introduction

The Digital Cherenkov Viewing Device (DCVD) is an instrument for measuring Cherenkov light produced in the water surrounding an irradiated nuclear fuel assembly in wet storage. The DCVD is regularly used by inspecting authorities, such as the International Atomic Energy Agency (IAEA) for the purpose of nuclear safeguards. When used to verify the presence of irradiated nuclear fuel, so-called gross defect verification, the presence and characteristic of the Cherenkov light is investigated. Two procedures are used to verify the completeness of the fuel assemblies under study, so-called partial defect verification: (1) empty rod positions are detected using image analysis, and (2) substitution of rods is detected by comparing predicted Cherenkov light intensities of the fuel assemblies to the measured intensities. The reliability of the latter procedure thus depends on the availability of accurate prediction models.

The prediction model currently used by the community is based on simulations of the Cherenkov light production in a BWR 8x8 fuel [10]. These results are assumed to apply for all types of irradiated fuel assemblies. It is here argued that by instead basing the predictions on simulations of the specific fuel configuration under study, the prediction accuracy may improve. Furthermore, enhanced prediction models with higher accuracy would allow for more stringent limits on the deviation between measured and predicted intensity, and thus to improved partial defect verification capabilities of the DCVD.

Previous studies [3] have shown that the dominant portion of the Cherenkov light produced by nuclear fuel assemblies in wet storage originates from gamma-decays of fission products. Furthermore the emission of beta particles may contribute by several percent to the Cherenkov light intensity, a contribution not included in the currently used model. These previous studies also showed a complex dependence between fuel rod dimensions, gamma-ray energy spectrum and the measurable Cherenkov light, suggesting that detailed models of the fuel would be required to produce more accurate results in the simulations. However, these studies were limited to Cherenkov light production from individual fuel rods, and a need for studies of complete fuel geometries was identified, which are covered by this work.

This work is a simulation study aimed at identifying differences between different prediction models, and to identify if the currently used prediction models may be enhanced through more detailed modelling. The goal is to identify to what degree simplifications in the simulations lead to a loss off accuracy, and for which situations a simplified model is sufficient to obtain acceptable results in the predictions.

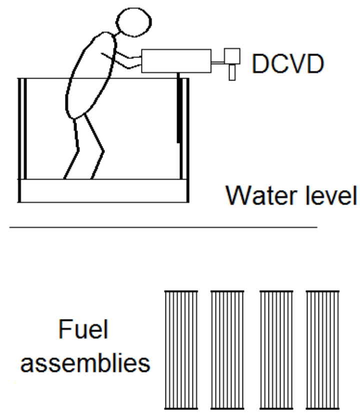

Figure 1: Schematic of the typical measurement situation when using the DCVD. Note that the top of the fuel assemblies are typically under several meters of water.

2 Verification of irradiated nuclear fuel assemblies in wet storage using Cherenkov light

2.1 Practical use of the DCVD

During a measurement campaign, the DCVD is typically mounted on the railing of a moveable bridge above the fuel storage pond, looking down into the pond, as illustrated in Figure 1. With this setup, primarily the vertically directed Cherenkov light produced inside the fuel may exit the fuel and propagate to the detector. More horizontally directed light will encounter fuel rod surfaces or other structural components, which will absorb the light rather than reflecting it, due to oxidation and CRUD deposits. Due to this situation, the Cherenkov light exiting the fuel assembly top is predominately upwards-directed, and the DCVD needs to be aligned with the fuel rods to measure the light emissions from its position above the pond. Only for highly reflective rods and specular reflection by the rods may a Cherenkov photon be reflected multiple times and exit the top of the fuel assembly to be measured. However, this does not occur for normal irradiated fuel, and the intensity of Cherenkov photons reflected this way is low in comparison to the unreflected vertical light.

The Cherenkov light intensity in water peaks in the soft-UV range, for this reason the DCVD measures light of that wavelength, and the optics contains a filter removing light with other wavelengths. This also helps in reducing the background caused by the facility lighting.

2.2 Currently adopted procedures for partial defect detection using the DCVD

At present, the partial-defect detection criterion applied by the IAEA for fuel assemblies being moved to difficult to access storage is that a diversion of 50 % or more of the fuel rods should be detected with at least 90 % probability. As mentioned briefly in section 1, two methods are currently used when performing partial defect detection using the DCVD; (1) removed rods in visible position are readily detected using image analysis, based on provided fuel geometry information. The implemented algorithm identifies bright regions that should be dark in the presence of a fuel rod; (2) for rods substituted with non-radioactive material, it is estimated from simulations that a 50 % rod substitution will result in at least a 30 % reduction in measured Cherenkov light intensity [6]. Thus, if a measurement of a fuel assembly gives a more than 30 % lower than expected intensity, a partial defect may be suspected. Central to this latter methodology is the ability to make accurate predictions of the intensity from a fuel assembly. The more accurate the predictions can be made, the better the capability to detect diversions will be.

The currently used DCVD inspection methodology predicts the Cherenkov light intensities of the fuel assemblies that are to be measured, based on their operator declared fuel parameters of burnup (BU) and cooling time (CT). In the analysis, fuel assemblies are grouped according to their geometry, and within each geometry group the predicted and measured intensities are linearly fitted to each other. The result of the fitting is a multiplicative constant relating the predicted value to the measured intensity. Accordingly, no absolute measures of the Cherenkov light intensities are used in this procedure, and the resulting calibration constants relate the measured intensities to the predicted intensities for each fuel type separately.

Thus, central to the use of predicted intensities is the calibration, which relates the predictions to the measurements. One may note that systematic differences between prediction models are of smaller importance when using such a procedure, what is important is that the prediction model gives accurate estimates of the relative intensities for the set of assemblies covered in each measurement campaign. In particular the predictions must be representative for the irradiation histories, burnups and cooling times of each set of fuel assemblies under study.

3 Prediction model currently used by end-users

End-users currently use a prediction model for the measurable Cherenkov light intensity from an assembly based on GEANT3 simulations of a BWR 8x8 fuel assembly [10]. The produced Cherenkov photons were transported to a detector position 5 m above the fuel, and a simplified expression is provided to convert the detected intensity to other detector positions. A "shadow factor" is introduced to model the photon absorption in spacers, fuel top structure and lifting

Table 1: Summary of simplifications in the simulations considered in this work, in terms of time saving and negative implication on accuracy.

Simplification	**Time saving factor**	**Negative implication on prediction precision**
(1) Excluding beta emission	1-2	Neglecting a source of Cherenkov light.
(2) One fuel assembly represents all types	10-20	Ignores the effect of fuel geometry.
(3) Single rod instead of complete geometry	10-100	Ignores the effect of neighbouring rods.
(4) Using total intensity rather than vertical	500-1000	Intensity not representative of what can be measured.

handle, since these were not modelled in the simulations. The reflectivity of the fuel surfaces was not specified. Furthermore, this model only considers the six isotopes found to be main contributors to the Cherenkov light production at modest cooling times, neglecting many short-lived isotopes in the fuel.

The simulations of Cherenkov light production was done for fuels with varying burnups and cooling times, and the results are used to interpolate the predicted intensity based on operator declared burnup and cooling time of an assembly. The inventory of the six considered isotopes was found by using ORIGEN [2].

Later investigations have considered the entire gamma spectrum of an assembly, and use a simplified geometry, often consisting of a single rod in water, simulated with Geant4 [4]. Due to the various simplifications considered in different prediction models, there is a need to identify any systematic bias existing between the models, as well as identifying the effect of the simplifications made. This paper aims to investigate the effect of these simplifications, and quantify the systematic deviations introduced in the predictions by basing the predictions on simplified models.

3.1 Comparison of computational effort required for different prediction models

Simulations of the Cherenkov light production performed with the complete geometry of a fuel assembly are expected to be accurate, but require substantial computational resources, and simplifications to a detailed model may be considered in order to allow the simulations to finish in reasonable time using modest hardware. In the simplifications investigated in this work, the effect on the total time needed to perform the simulations and the consequences regarding the accuracy is summarised in Table 1.

4 Simulations performed in this work

4.1 Scope of the simulations

In this work, we have simulated the Cherenkov light production in a BWR 8x8 assembly and a PWR 17x17 assembly, in order to compare the predictions based on the different models. Simulations were also run with a single rod in water, with dimensions matching the BWR and PWR case, to investigate the accuracy of single-rod models. The simulations were used to study:

- How the directional dependence of the produced Cherenkov light is affected by fuel geometry, which is of importance for the light component measurable with the DCVD (see Figure 1).
- How the Cherenkov light intensity caused by fission product decays of various energies is affected by the fuel geometry.
- To what extent fuels with different geometries exhibit different dependencies on burnup and cooling time.

The results of the simulations allow for comparisons of the different prediction models studied, and are used to investigate if there is any systematic deviation between the models.

4.2 Fuel geometries modelled

The BWR 8x8 fuel has 63 fuel rods in an 8x8 rectangular matrix, with a water channel instead of a fuel rod in one central position. The dimensions of the rods and the pitch was the same as for the simulations done for the currently used prediction model [10], to enable comparison of the results. For the PWR 17x17 case there are 264 fuel rods, 24 guide tubes and one central instrumentation tube in one assembly. The fuel configurations simulated are shown in Figure 2. The dimensions of the fuel assemblies are given in Table 2, and were taken from [9].

The simulations were done using an earlier developed toolkit [8] based on Geant4 (version 4.10.0) [1]. The simulations took into account the fuel geometry, including fuel pellet size, cladding thickness and pitch, as well as water-filled control-rod guide tubes (PWR) and water channel (BWR). The single-rod simulations included only one fuel rod in a large water volume.

4.3 Simulated radiation

The simulations performed have investigated gamma decays in the fuel material, for various gamma-ray energies. Simulations were also performed for beta decays of Y-90, which was identified as the dominant contributor to the total Cherenkov light intensity due to beta decays in fuel cooled more than a few years [3]. The contribution due to other beta-decaying isotopes were found to be negligible at these cooling times. The gamma spectrum and Y-90 contents of an assembly

Table 2: Dimensions of the simulated fuel geometries. The BWR dimensions are the same as in [10], the PWR dimensions were taken from [9]

	BWR 8x8	PWR 17x17
Number of fuel rods:	63	264
Fuel pellet diameter [mm]:	10.44	8.18
Cladding thickness [mm]:	0.91	0.57
Pitch [mm]:	16.3	12.6

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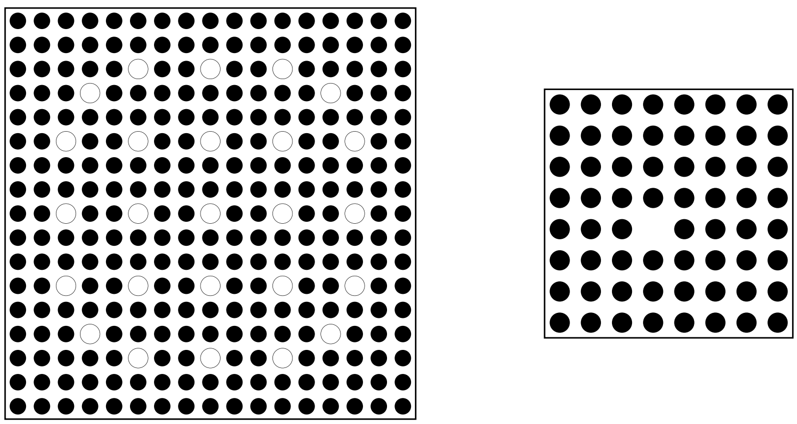

Figure 2: Left: The fuel configuration simulated for the PWR 17x17 fuel assembly, including 24 guide tubes and a central instrumentation tube. Right: The fuel configuration simulated for the BWR 8x8 fuel assembly, where one central rod position is empty to provide a water channel. Cherenkov photons produced inside the black square surrounding the fuel were counted in the simulations. The relative size of the fuel assemblies are to scale, showing the difference in size for the two configurations.

was estimated for fuels with various burnups and cooling times using ORIGEN-ARP [2]. The ORIGEN gamma spectrum also includes bremsstrahlung due to beta-decays in the fuel.

The simulations were executed with the initial particle emissions homogeneously distributed inside the circular cross-section of a fuel pellet. The initial particles were also started within a region of height 1 mm at the middle of the fuel rod height. Since this work considers Cherenkov light production in the fuel, the chosen central section will be representative of most heights in the fuel, with the exception of the rod ends. Due to the relatively short range of radiation in the fuel and the comparatively much longer rods, effects at the rod ends are expected to be negligible.

Only the vertically directed Cherenkov photons produced in the water was analysed in this work. The photons emitted within an emission angle ϕ less than 3 degrees from the vertical axis were selected to be representative of the vertical light component. Considering the typical measurement situation, with the DCVD aligned above the fuel assembly, only Cherenkov photons with an angle less than 0.6° to the vertical axis will exit the tip of the fuel assembly and reach the DCVD. This angle is however so small that it is difficult to obtain good statistics in the simulations, which is why a larger angle of 3 degrees was used. This angle was considered large enough that the simulations may finish in reasonable time, while narrow enough to represent the vertical light component.

4.3.1 Fuel irradiation histories simulated

To be able to compare predictions based on the different models, ORIGEN-ARP [2] was used to simulate fuels with varying burnups and cooling times and to extract its gamma emission spectra and Y-90 contents. The Y-90 content was found by extracting the abundance of Sr-90, which decays into Y-90. Due to the short half-life of Y-90 as compared to Sr-90, the Y-90 activity is the same as for Sr-90.

ORIGEN simulations were run for burnups of 10, 20, 30 and 40 MWd/kgU, and for cooling times from 0.25 to 60 years, corresponding to those used in [10], to allow comparisons to be made. The 10, 20 and 30 MWd/kgU were simulated as having four irradiation cycles of 312.5 days and an average power level of 8, 16 and 24 MW/tU, respectively. In between cycles there was a cooling period of 46 days. The 40 MWd/kgU case had a power level of 24 MW/tU, and was irradiated for five cycles with 333 days of irradiation and 32 days of cooling time. Note that the range of possible burnups, cooling times and irradiation histories for authentic fuel is much larger than this, but simplified histories are used here in order to limit the scope of the study, and to be comparable to previous results.

5 Basic properties of the Cherenkov light production in fuel assembly configurations

5.1 Directionality of Cherenkov light

Previous studies [3] showed that the Cherenkov light emission from a nuclear fuel rod stored in water is not isotropic, mainly due to anisotropic gamma emissions from the rod due to the strongly attenuating fuel material. Here, these studies have been extended to complete fuel assemblies. The intensity of the produced Cherenkov light as a function of the angle to the vertical direction is plotted in Figure 3 for the BWR and PWR assemblies, for three different initial gamma-ray energies and for Y-90 beta decays. As can be seen, the Cherenkov light produced inside a fuel assembly is not isotropic, and that the directionality changes with initial gamma-ray energy. Furthermore, systematic differences exist between the BWR and PWR model, most noticeable for Y-90 decays and

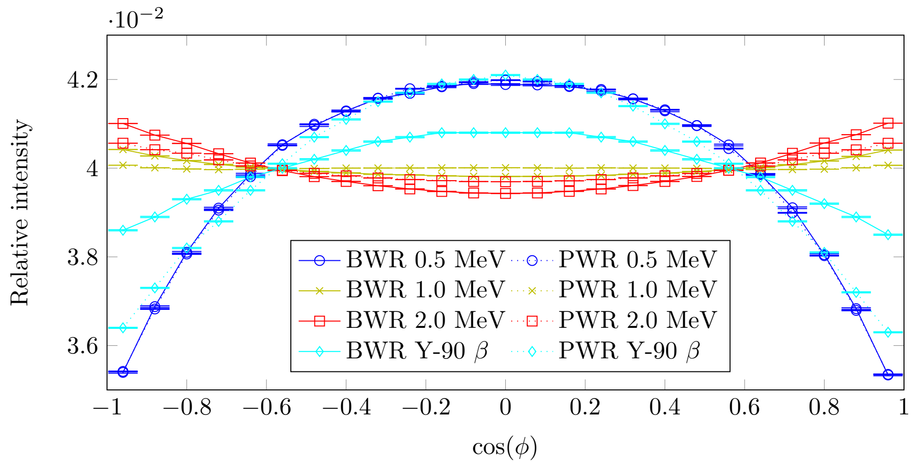

Figure 3: Intensity of the Cherenkov light produced inside the two simulated fuel assembly configurations as a function of the cosine of the angle to the vertical direction. Three different initial gamma energies and Y-90 beta decays are presented. The intensities are scaled to the same total intensity. For an isotropic distribution, the intensity distribution would be flat. In the plots, the $cos(\phi)$ values are divided into 25 bins.

for high-energy gamma-rays. This shows that there will be a loss of accuracy if one fuel assembly model is considered representative of all assembly types.

5.2 Energy dependence of the vertical Cherenkov light production

The intensity of vertically directed Cherenkov light produced inside the studied BWR and PWR fuel configurations due to gamma-ray emissions of various energies is shown in Figure 4, normalized to the number of gamma-ray emissions. Also shown is the ratio of Cherenkov light per emitted gamma quantum for the two configurations. The PWR case includes 25 non-fuel positions (24 guide tubes and a central instrumentation tube), as compared to one for the BWR case (one rod removed to provide a water channel), and as a result has a larger relative water content. The net effect of the relatively larger water content per fuel rod in the PWR geometry is a stronger Cherenkov light production per gamma decay. Since the gamma spectrum of a fuel assembly will change with time, the non-constant ratio in Figure 4 shows that the two models will behave differently as a function of cooling time.

5.3 Source distribution in the fuel rod

The distribution of fission products in an irradiated fuel rod will affect the Cherenkov light production. This is of importance for long-cooled fuel, where

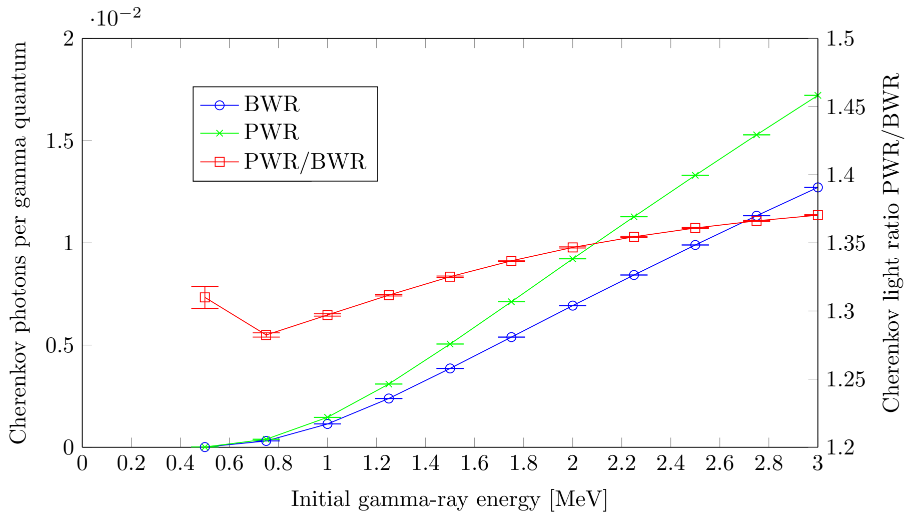

Figure 4: The produced vertically directed Cherenkov photons per emitted gamma quantum inside a BWR 8x8 and a PWR 17x17 fuel assembly as a function of initial gamma-ray energy (left y-axis). Also plotted is the ratio of the vertical Cherenkov light per emitted gamma quanta of PWR/BWR (right y-axis).

relatively low-energy 662 keV gamma rays from Cs-137 decays cause a vast majority of the Cherenkov light production, and cesium may migrate towards the fuel rim if the rod is subjected to high temperatures. A simulation was run for the BWR fuel configuration, using the two Cs-137 distributions presented in [7], where one distribution corresponds to normal fuel from a commercial reactor, showing a homogeneous distribution of the cesium, and the other corresponds to a fuel that had experienced a power bump and a severe temperature-driven cesium migration. The simulations show that for a fuel where each rod had experienced temperature-driven migration, on average 5 % more Cherenkov light is produced per decay as compared to an assembly with homogeneously distributed cesium. This value may serve as an upper limit on the uncertainty in intensity for long-cooled fuel due to not knowing the exact source distribution.

Cherenkov light caused by Y-90 beta decays contributes to the total Cherenkov light intensity, and this contribution strongly depends on the Y-90 radial distribution in a rod. Due to a high-burnup structure forming on the fuel pellet rim, the concentrations of fission products on the rim can almost double, leading to the Y-90 Cherenkov light production contribution also doubling. Simulations were run for Y-90 decays in the BWR fuel configuration, confirming that this holds true for Cherenkov light production in an assembly. This shows the importance of modelling the radial fission product distribution in order to obtain results representative of real fuel assemblies.

Table 3: Contribution of Y-90 beta decays to the total Cherenkov light intensity from a fuel with a burnup of 40 MWd/kgU. The BWR fuel was simulated with a cladding thickness of 0.91 mm as compared to 0.57 mm in the PWR case, and the cladding stops most beta particles from entering the water.

% of Cherenkov light intensity due to Y-90			
Cooling time	5 years	10 years	40 years
BWR 8x8	0.33%	0.63%	1.0%
PWR 17x17	2.2%	4.2%	6.7%

6 Model dependencies in predictions of DCVD intensities

As presented earlier in Table 1, several simplifications can be considered to speed up the simulations. In this section, these simplifications are investigated, to identify to what degree the simplifications introduces additional systematic deviations in the predictions.

6.1 Beta-decay contribution to the Cherenkov light intensity

To investigate the direct Cherenkov light production due to Y-90 decays, simulations were run for Y-90 beta decays in a BWR 8x8 and a PWR 17x17 assembly configuration. Only the vertically directed Cherenkov light produced by electrons passing through the cladding and entering the water was investigated in the simulations. Beta decays may also produce Cherenkov light indirectly by emitting bremsstrahlung when stopped in the fuel, and the bremsstrahlung can in turn end up producing Cherenkov light. However this can be considered to be gamma emissions from the fuel and are covered by the gamma-ray simulations. Furthermore, the gamma spectra calculated by ORIGEN includes the bremsstrahlung from beta-decays, thus taking the indirect Cherenkov light production into account.

A comparison between the gamma-induced vertical Cherenkov light intensity to the Y-90 beta-induced intensity is given in Table 3, for a fuel assembly with a burnup of 40 MWd/kgU. The results show that for modern fuel designs with thinner claddings and smaller pellet radii compared to older fuels, the contributions from beta particles exiting the fuel may have to be considered for highly accurate predictions of the Cherenkov light intensity. A prediction model not incorporating Y-90 beta-decays may systematically underestimate the intensity for long-cooled fuel by up to 7 %, as compared to short-cooled fuel, for the cases studied here. However, the magnitude of the relative contribution is strongly dependent on the fuel rod dimensions.

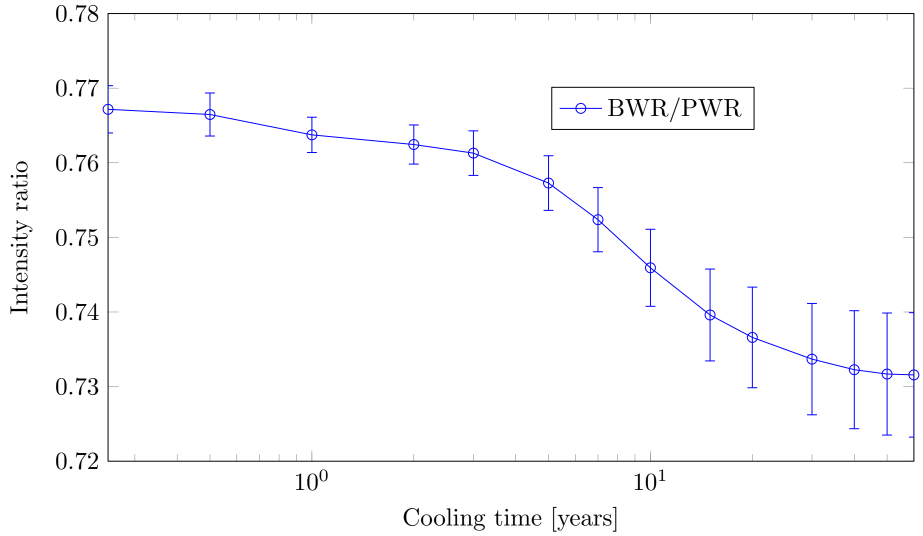

Figure 5: The ratio of the predicted vertical Cherenkov light intensity for the BWR 8x8 and the PWR 17x17 model. Systematic differences between the models result in a non-constant ratio.

6.2 Comparison of PWR and BWR model

One simplification made when using the prediction model in [10] is that it is assumed that all fuel assembly configurations behave similarly, and that any differences between the models are small enough to be neglected. In Figure 5 the Cherenkov light intensity predictions are compared for the BWR 8x8 and the PWR 17x17 models, for a fuel with 40 MWd/kgU burnup. As can be seen, there is a systematic deviation between the two models as a function of cooling time. The largest deviation would occur if measuring a population of mostly long-cooled fuel assemblies, with a few short-cooled assemblies present. The systematic deviation between the prediction models will then be up to 5 %. For low-burnup fuel, this systematic deviation is increased slightly in magnitude, and may be up to 7 %. Note that the increase in uncertainty with cooling time in Figure 5 is due to the softening of the assembly gamma spectrum with cooling time, and the low Cherenkov light production per decay in long cooled fuel leads to higher uncertainties in the simulations.

6.3 Comparison of complete and single-rod model with identical fuel rod dimensions

One simplification considered earlier [4] is to replace the fuel assembly in the simulations with a single rod with the same rod diameter and cladding thickness as a rod in the assembly. In Figure 6, predictions based on the complete fuel

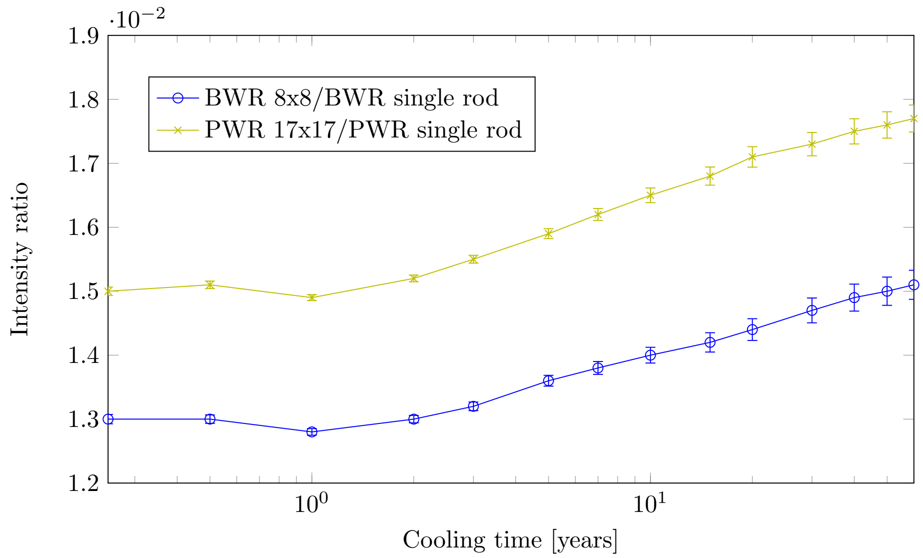

Figure 6: The ratio of the predicted vertical Cherenkov light intensity for complete fuel assembly models, and single rod models using the same rod dimensions as in the complete model case. Systematic differences between the models result in a non-constant ratio.

assembly are compared to predictions based on a single rod in water with the same dimensions, for a fuel with a burnup of 40 MWd/kgU. The predictions in both cases include contributions from gamma and beta decays. Due to differences in the two models, there is an overall factor separating them, which will be taken care of by the calibration procedure during a measurement.

Even though the rod dimensions are identical, the predictions deviate noticeably with cooling time, seen by the non-constant ratio in Figure 6. The single rod models overestimate the intensity of short-cooled fuel relative to the predictions of long-cooled fuel, compared to the complete assembly predictions. The most severe case would occur if measuring a population of mostly long-cooled fuels, with a few short-cooled fuels present. In this case, the single-rod model would systematically overestimate the Cherenkov light intensity from the short-cooled assemblies by up to 17%.

Note that due to the large volume of water considered in the single rod case, and the relatively longer range of gamma-rays in the absence of fuel rods, much more Cherenkov light is produced per gamma decay for a single-rod model as compared to a complete model. The contribution due to Y-90 decays is as a result relatively minor, and less than 0.5 % for all burnups and cooling times. For this reason, the Y-90 contribution is neglected in all single-rod models considered in this section. It is unlikely that the relative Y-90 contribution to the vertical intensity can be modelled accurately by a single-rod model.

6.4 Comparison of prediction models using total and vertical Cherenkov light

Due to the DCVD measurement setup, being situated directly above the fuel assembly, it is expected that predominately the vertical Cherenkov light component may reach the DCVD and be measured. As shown earlier in Figure 3, the ratio of vertical to total Cherenkov light is affected by the initial gamma-ray energy, and as a result this ratio will change with cooling time.

To analyse the differences between predictions based on the vertical and total intensity, predictions were made for a 40 MWd/kgU assembly using the BWR and PWR models, as well as for models with a single rod with the BWR and PWR dimensions, and the results are presented in Figure 7. As can be seen, the ratio is fairly constant for the complete BWR and PWR model, suggesting that predictions based on either vertical or total light intensity will give similar results. A worst-case scenario would be comparing a few short-cooled fuels to many long-cooled fuels, where the total intensity model will systematically underestimate the short-cooled fuel intensity by 3 %. The single-rod models appears to be much more sensitive, and in the same worst-case scenario the systematic deviation reaches 9 % for the BWR single rod case, and 8 % for the PWR single rod case.

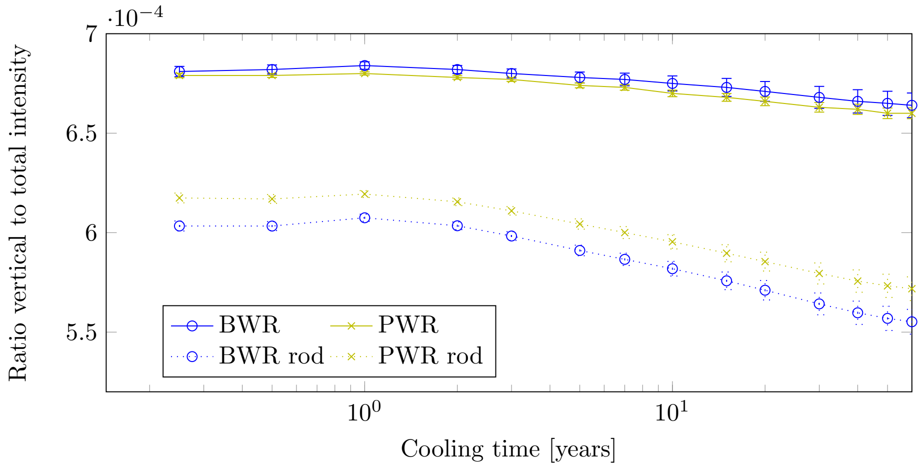

Figure 7: Ratio of the predicted Cherenkov light intensity based on the total and vertical component of the produced Cherenkov light, for fuels with varying cooling times. The predictions are based on a complete BWR and PWR model, and for a model based on a single BWR or PWR rod. The fuel assembly had a burnup of 40 MWd/kgU. A constant ratio implies that the models will give the same predictions after calibration.

Although the model difference as a function of cooling time is noticeable, the difference as a function of burnup is low, and in all cases it is lower than the uncertainties in the values.

7 Comparison of the model currently used by end-users to models simulated in this work

A complete fuel assembly model is expected to produce more accurate results compared to a simplified model. Accordingly, it is relevant to compare the complete models with the highest degree of detail studied in this work with the currently used prediction model, which incorporates some simplifications. Still, one should bear in mind that the models should be further evaluated using experimental data before conclusions can be drawn regarding their validity.

In Figure 8 the predicted intensity of a 40 MWd/kgU assembly is compared for the currently used prediction model based on [10], to the BWR and PWR models simulated in this work. The deviation between models at short cooling times (less than 5 years) is due to that the model in [10] ignores many short-lived isotopes, which contribute to the Cherenkov light intensity at short cooling times. For this reason, the predictions based on the simulations done here, which include all gamma-ray emissions and Y-90 decays predict a relatively higher intensity for short-cooled fuel.

For fuels with a cooling time longer than 10 years, the relatively flat ratio in Figure 8 suggest that all models will, after calibration, give similar results regarding the predictions. For these cooling times, the largest systematic deviation between the models occurs when comparing 10-year cooled fuel to 40-year cooled fuel. In this case, the BWR model deviates systematically up to 3 %, and the PWR by 5 %, as compared to the currently used model. The relatively modest deviations show that results based on the vertical intensity in a BWR and PWR model, are relatively close to the results obtained when the Cherenkov photons are transported to a detector position, as done by the currently used model. Note that part of the discrepancy at cooling times longer than 10 years is due to the models here includes the contribution from Y-90 beta decays passing through the cladding, where the currently used model only considers bremsstrahlung from Y-90.

Comparing 10-year cooled fuel with 40-year cooled fuel having a burnup of 10 MWd/kgU, the systematic deviation between the models increases to 7 % for the BWR model and 8 % for the PWR model. This shows that the deviation between the models depend on both burnup and cooling time.

8 Conclusions

As has been shown by the simulations performed in this work, there are differences between the studied prediction models, which may lead to a systematic bias in predictions of the Cherenkov light intensity of fuel assemblies. It has been argued that such bias will be most noticeable when measuring a population of fuel assemblies with vastly different burnups and cooling times. The simplifications considered for a detailed model and the effects on the prediction are:

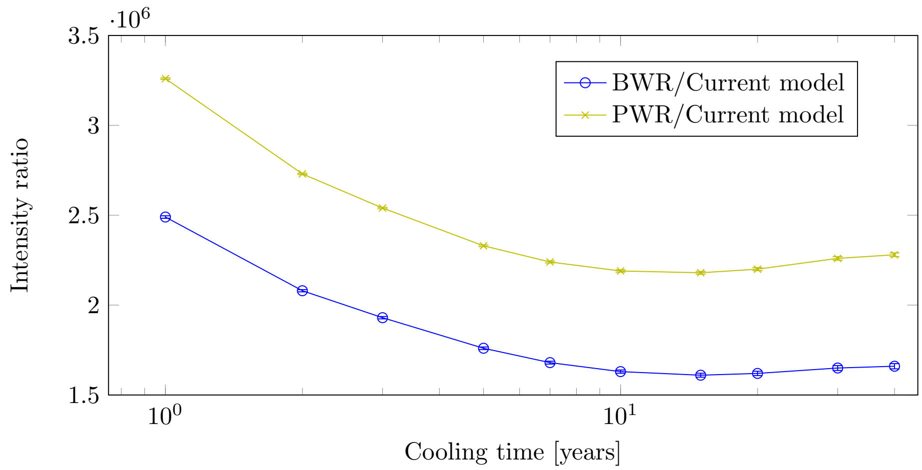

Figure 8: Ratio of the predicted Cherenkov light intensity based on a complete BWR and PWR model to the predictions based on the currently used model [10]. The fuel assembly has a burnup of 40 MWd/kgU. Systematic differences between the models result in a non-constant ratio.

- Neglecting Y-90 beta-decays may result in up to 7 % overestimation of the intensity of short-cooled fuel, as compared to long-cooled fuel, depending on fuel rod dimensions.
- Comparing prediction of a BWR 8x8 and a PWR 17x17 model, there is a systematic deviation in the predictions which may be up to 8 % when comparing fuel assemblies of different burnups and cooling times.
- Comparing the predictions of a complete model to a single rod model with the same rod dimensions, a 17 % overestimation of the single rod predictions for short-cooled fuel can be found, as compared to long-cooled fuel.
- Using a model based on total Cherenkov light intensity rather than vertical intensity, the intensity for a short-cooled fuel may be underestimated by 3 % for a complete model, and up to 10 % for a single-rod model, as compared to long-cooled fuel.

Note that the bias presented here is the worst-case bias, and for real measurement the fuel assemblies tend to be more homogeneous with respect to burnup and cooling time. Thus, the currently used prediction models may be of sufficient accuracy for those cases. However, for cases when comparing long-cooled to short-cooled fuel, the bias is expected to be noticeable, and the detailed models may be preferred.

Of all simplifications considered in the simulations, using the total Cherenkov light production rather than the vertical appears to have a small impact on the prediction accuracy, but results in substantially quicker simulations. Thus, this simplification may be acceptable if there is a need to speed up the simulations. The other simplifications should be avoided if possible due to the large bias introduced.

The uncertainty in the predictions due to not knowing the exact radial distribution of the fission products was estimated to be on the order of 5 % for a detailed model. This value sets an upper limit on the uncertainty in the prediction model due to uncertainties in the fission product distribution, since the radial fission product distribution is not readily available during inspections.

9 Outlook

While predictions of the Cherenkov light intensity in a fuel assembly based on the complete geometry are expected to be more accurate than predictions based on the currently used model, or models incorporating simplifications, this must be verified against experimental data. Such experiments should cover fuel assemblies with a wide range of burnups and cooling times.

Furthermore, the prediction model could be extended to not only consider the production of Cherenkov light, but also its transport to a detector position. This will ensure that the predictions are based on the detectable Cherenkov light. Such simulations will require additional information regarding fuel spacers, top structure, reflectivity of fuel surfaces and detector response.

This work has only considered direct Cherenkov light production by Y-90 beta decays, which is the predominant high-energy beta-decaying source in fuels with modest cooling times. For short-cooled fuel other beta-decaying isotopes may still be present, which will contribute to the Cherenkov light intensity. Further studies are required to identify these elements, and investigate their contribution to the measurable intensity at short cooling times.

This work has only considered the Cherenkov light production in an isolated assembly, but in reality the fuel assemblies are stored close together and radiation from one fuel may enter a neighbouring assembly and produce Cherenkov light there. Assessing the magnitude of the intensity contribution due to neighbouring fuels requires both an estimate of the Cherenkov light intensity in all the neighbours, and information about how the Cherenkov light intensity contribution behaves as a function of the intensity of the neighbouring assemblies. Finding the intensity of the neighbours requires either measuring all the neighbours, of if this is an infeasible amount of measurements, predicting the intensity of the neighbours using the prediction models developed in this work. Further research is required to investigate and quantify this effect, in order to develop a method to take it into account.

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