Experimental evaluation of models for predicting Cherenkov light intensities from short-cooled nuclear fuel assemblies

Erik Branger*, Sophie Grape, Peter Jansson,
Staffan Jacobsson Svärd,
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) is a tool used by nuclear safeguards inspectors to verify irradiated nuclear fuel assemblies in wet storage based on the recording of Cherenkov light produced by the assemblies. One type of verification involves comparing the measured light intensity from an assembly with a predicted intensity, based on assembly declarations. Crucial for such analyses is the performance of the prediction model used, and recently new modelling methods have been introduced to allow for enhanced prediction capabilities by taking the irradiation history into account, and by including the cross-talk radiation from neighbouring assemblies in the predictions.

In this work, the performance of three models for Cherenkov-light intensity prediction is evaluated by applying them to a set of short-cooled PWR 17x17 assemblies for which experimental DCVD measurements and operator-declared irradiation data was available; (1) a two-parameter model, based on total burnup and cooling time, previously used by the safeguards inspectors, (2) a newly introduced gamma-spectrum-based model, which incorporates cycle-wise burnup histories, and (3) the latter gamma-spectrum-based model with the addition to account for contributions from neighbouring assemblies.

The results show that the two gamma-spectrum-based models provide significantly higher precision for the measured inventory compared to the two-parameter model, lowering the standard deviation between relative measured and predicted intensities from 15.2 % to 8.1 % respectively 7.8 %.

The results show some systematic differences between assemblies of different designs (produced by different manufacturers) in spite of their

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

similar PWR 17x17 geometries, and possible ways are discussed to address such differences, which may allow for even higher prediction capabilities. Still, it is concluded that the gamma-spectrum-based models enable confident verification of the fuel assembly inventory at the currently used detection limit for partial defects, being a 30 % discrepancy between measured and predicted intensities, while some false detection occurs with the two-parameter model. The results also indicate that the gamma-spectrum-based prediction methods are accurate enough that the 30 % discrepancy limit could potentially be lowered.

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

1 Introduction

To deter from proliferation of nuclear weapons, and to ensure that nuclear material is not misused, nuclear safeguards measures are applied to nuclear facilities worldwide. The nuclear safeguards system is based both on verifying operator declared information as well as verifying that no undeclared activities take place. For the former purpose, inspections are carried out, and several instruments have been developed to allow the inspectors to independently verify the completeness and correctness of the operator-declared information [1]. One of these instruments is the Digital Cherenkov Viewing Device (DCVD), which is used to measure the Cherenkov light emissions from irradiated nuclear fuel assemblies in wet storage. The radiation emitted by the assemblies produces Cherenkov light in the surrounding water, thus the presence and intensity of the Cherenkov light can be used to indicate the presence and properties of the assemblies [2].

The most basic use of the DCVD is for *gross defect verification*, i.e. to verify that an item under study is an irradiated nuclear fuel assembly and not a non-fuel object, whereas a more advanced use is for *partial defect verification*, i.e. verifying that parts of the assembly have not been diverted. There are two methods in use to detect partial defects in irradiated nuclear fuel assemblies with the DCVD. The first method utilizes image analysis to identify positions where fuel rods are absent, based on the presence of Cherenkov light emissions where an expected fuel rod should block such emission. This first method can thus automatically detect removed rods in visible positions. The second method extends the detection capabilities to both removed rods in non-visible positions and rods substituted with other material. It involves the comparison of the total measured light intensity emitted by an assembly to what is expected for the assembly under study. This method requires an accurate model for predicting the Cherenkov light intensity of an assembly, which is the subject for this study.

The first prediction model brought into use was a two-parameter model, basing the predictions on declared integral burnup (BU)[1] and cooling time (CT)[2]

[1]Burnup: total energy released through fission per fuel mass unit.
[2]Cooling time: time since discharge from the reactor.

[3]. Recently, a new gamma-spectrum based model has been introduced for improved predictions of the Cherenkov light intensity [4]. This recent model takes more operator-declared data into account compared to the previously used two-parameter model, such as assembly geometry, Initial Enrichment (IE) and irradiation history (i.e. cycle-wise BU declaration). This model was developed to overcome limitations of the two-parameter model, such as more accurately assessing the abundance of short-lived isotopes in the assembly at short CT by taking the irradiation history into account. In addition, an extended gamma-spectrum based model has been developed, which also takes intensity contributions due to nearby assemblies into account, to better represent realistic measurement situations with assemblies stored close to each other [5]. The prediction models considered in this work are summarised in table 1.

Table 1: The Cherenkov light prediction models evaluated in this work. The irradiation histories used in this work consists of cycle-wise average BU and the CT after each cycle.

Description	**Declarations used**	**Reference**
Two-parameter model	Assembly BU and CT	[3]
Gamma-spectrum based model	Assembly geometry, IE and irradiation history	[4]
Neighbourhood model	Assembly and its neighbour's geometry, IE and irradiation history	[5]

This work aims at experimentally evaluating the performance of these prediction models, by applying them to a set of DCVD measurements conducted by the International Atomic Energy Agency (IAEA) on Pressurized Water Reactor (PWR) assemblies. All measured assemblies had a CT of nine months but varying BU, and thus varying fission product content. A preliminary analysis of this data was presented in [6], and this work extends beyond the previous work by performing a more complete analysis and by adding the neighbourhood model.

2 Cherenkov light prediction models

The intensity-based method for partial-defect verification using the DCVD is based on the fact that removal and/or replacement of fuel rods will alter the total amount of radiation emitted by the fuel assembly, and a substantial removal of rods will consequently impact the Cherenkov light emitted by the assembly. The currently adopted verification methodology groups assemblies according to design, so that each group contains assemblies with similar physical characteristics, to ensure that they are comparable. Currently, the methodology does not make any comparisons between assemblies of differing designs. When the measurements and predictions are available for a group of assemblies, a leastsquares fit is made to find a multiplier that best scales the predictions to match the measurements for the assembly design under study. As a consequence of this calibration, the predictions do not correspond to the absolute measured intensity, but to a relative intensity measure for assemblies of similar design. Additional details regarding the DCVD and the verification procedure can be found in [4].

Based on current IAEA requirements and demonstrated prediction capabilities, the threshold used to indicate a partial defect is a 30 % discrepancy between measured and predicted relative intensity [7]. Any assembly exhibiting a larger deviation requires further investigation.

In this context, one may note that improvements in the accuracy of the predictions can be used to reduce this 30 % limit, which would further enhance the sensitivity of the DCVD to partial defects. Furthermore, the prediction models should preferably allow for fast calculations, so that an inspector can make predictions for an entire fuel assembly inventory while in the field.

2.1 The two-parameter prediction model

For the past two decades, the prediction model used by inspectors was based on the model described in [3]. This two-parameter model is a parametrization of the detectable Cherenkov light intensity as a function of the BU and CT of a fuel assembly. It is the most operator-independent Cherenkov light prediction model of the three considered in this work. The parametrization was found by first simulating the gamma-spectrum for assemblies with varying BU and CT, assuming a standard irradiation history of four equal-power cycles. The simulated gamma-spectrum was then used as a source in a Monte-Carlo particle transport simulation, where the production of Cherenkov photons and the propagation of the photons to a detector position was simulated for a simplified BWR 8x8 geometry. The results were however expected to be valid for all assembly designs. Six fission product isotopes were found to contribute with more than 95 % of the total Cherenkov light production for the selected BU and CT, and only these isotopes were considered when developing this model.

When using this prediction model, the operator declared BU and CT are used to obtain an interpolated value of the intensity, based on the simulated values. This procedure is quick, it uses only the most basic information which should always be available to an inspector, and it takes into account the two parameters BU and CT, which most strongly affect the Cherenkov light intensity. However, it also involves relatively large simplifications, which may limit its precision, in particular for assemblies with short CT and assemblies with irregular irradiation history. The two-parameter model also assumes that all assemblies behave like a BWR 8x8 fuel assembly, neglecting the effects that different assembly geometries have on Cherenkov light production [4].

2.2 The gamma-spectrum based prediction model

To be able to perform more accurate verifications with the DCVD in general, and specifically for fuel assemblies with short CT, a new gamma-spectrum based prediction model has been developed, which takes more details into account compared to the two-parameter model. The method is briefly described here, whereas a more thorough description can be found in [4].

In this model, simulations are run using the Monte-Carlo particle transport code Geant4 [8], to parametrize the Cherenkov light production as a function of the energy of gamma rays produced by decays of fission products in the assembly. These simulations are time-consuming, however they only have to be done once per assembly design and they are done in advance so that tabulated values can be used to make rapid computations of predicted intensities. In this prediction model, simulations are performed for different geometrical assembly configurations in order to take into account differences in Cherenkov light production caused by the physical design of the assembly [4]. However, in order to finish these simulations in reasonable time, one fundamental simplification is made: that the detected Cherenkov light intensity is proportional to the produced intensity, i.e. the light transport from the assembly to the DCVD is omitted. This simplification is justified by the fact that each assembly geometry is analysed separately, so that differences in light transport properties are taken into account by the calibration procedure.

When verifying a fuel assembly inventory using this prediction model, the available information of each assembly such as design, IE and irradiation history is entered into ORIGEN-ARP [9], which calculates a gamma spectrum (including bremsstrahlung due to beta decays) produced in the assembly. The gamma spectrum is then combined with the pre-calculated values of how much Cherenkov light that is produced by gamma-rays of various energies, to obtain a prediction of the produced Cherenkov light intensity. The ORIGEN-ARP calculations can be done in a few seconds on modest hardware, and combining the gamma-spectrum with the pre-calculated intensity values takes minimal computational effort, thus allowing for use of the method during inspections when only limited computational resources are available.

2.3 The gamma-spectrum based prediction model including cross-talk

One of the main advantages of fuel assembly verification with the DCVD is that the assemblies can be measured where they are stored, so there is no need to move them to a dedicated measurement position. One disadvantage is that the assemblies are often stored close together, so that radiation from one assembly can enter a neighbouring assembly and create Cherenkov light there. This cross-talk, referred to as the near-neighbour effect, was investigated in [5], and a method to predict the intensity contribution due to the near-neighbour effect was suggested.

Similar to the gamma-spectrum based prediction model, the first step is to pre-calculate and parametrize the Cherenkov light production in an assembly due to gamma decays of various energies in neighbouring assemblies. When verifying an inventory using this prediction model, ORIGEN-ARP is used to assess the gamma-ray spectrum of all assemblies neighbouring the assembly being measured, based on operator declarations. These spectra are then combined with the pre-calculated parametrized values of how much Cherenkov light is produced in the assembly under study due to radiation originating in neighbouring assemblies, resulting in a prediction of the intensity of the Cherenkov light produced in the measured assembly due to its neighbours. The near-neighbour intensities are then added to the predicted intensity of the assembly being measured, to obtain a total Cherenkov light prediction. In this work, due to the large size and large spacing of the assemblies, only the eight nearest neighbours to an assembly were considered, while neighbours further away were found through simulations to contribute negligibly to the Cherenkov light intensity.

3 Experimental data set

The IAEA safeguards inspectors have much experience in performing measurements with the DCVD, but due to the shortcomings of the two-parameter prediction model, the DCVD has seldom been used for verification of assemblies with CT of one year or less. One such measurement campaign was however performed recently, and the data was made available to the authors, courtesy of the IAEA and the nuclear facility in question. The data was stripped of sensitive information relating to the facility and fuel assembly manufacturers.

The provided data included the irradiation history of each assembly at the facility, consisting of the start and end date of each irradiation cycle and the average BU during each cycle. The assemblies had been irradiated for one to four cycles, with a majority of the assemblies having been irradiated for one or two cycles. The CT of all assemblies was nine months.

A total of 71 assemblies were measured in the campaign, and the same DCVD was used for all measurements. All assemblies were PWR 17x17, and all were stored and measured with control rod inserts present. The provided data also included a pond map, giving each assembly position, which is necessary when predicting the near-neighbour effect.

The data declared that the measured assemblies were of three different designs, indicating that they may have been produced by three different manufacturers, although no information about the manufacturer was provided. Details on the number of fuel assemblies of different designs are found in tables 2 and 3.

Furthermore, as a consequence of the fact that assemblies being loaded at similar positions in the reactor core obtain almost identical irradiation histories, most of the measured assemblies could be divided into seven groups having a nearly identical declared irradiation history (the declared cycle-wise BU in each group was within a few %). Consequently, the assemblies in each of these groups can be expected to emit a nearly identical Cherenkov light intensity. The number of irradiation cycles for the identified groups are shown in table 2, together with the irradiation history experienced by the assemblies in each group. Group names starting with "1" indicate that the assemblies were irradiated for one cycle, "2" that they were irradiated for two cycles etc.

Table 2: Summary of the seven different irradiation histories shared by a majority of the measured fuel assemblies.

Group:	**1a**	**1b**	**2a**	**2b**	**2c**	**3**	**4**
Number of assemblies:	7	8	18	23	4	6	3
Assembly design:	A	A	B	B	B	B	C
Number of irradiation cycles:	1	1	2	2	2	3	4
BU per cycle in [MWd/kgU]	12	15	22 + 13	27 + 13	19 + 7	27 + 9 + 5	19 + 10 + 10 + 4

The remaining two assemblies with unique irradiation histories are presented in table 3. Note that the assembly called U2 was residing outside the reactor for one cycle. These unique irradiation histories may be a consequence of the assembly having some property differing from the majority of assemblies, or that it is part of a small set of assemblies having been irradiated at specific locations in the reactor, and only one assembly in the group was measured.

Table 3: Summary of the two fuel assemblies having a unique irradiation history.

Group:	**U1**	**U2**
Assembly design:	B	C
Number of irradiation cycles:	2	2
BU per cycle in [MWd/kgU]	27 + 5	23 + 0 + 11

4 Application of the prediction models

The predictions using the two-parameter model (see section 2.1) were made by the IAEA inspector performing the measurement campaign at the PWR facility, and for the evaluation performed in this paper the predictions were extracted from the data provided by the IAEA. Due to the unavailability of parametrized Cherenkov light intensity for fuel assemblies with a CT less than one year, a CT of one year was assumed when applying the two-parameter model. The predictions also contained additional corrections for the short CT, developed internally by the IAEA [10].

To make predictions for the measured assemblies based on the gamma-spectrum based model (see section 2.2), and to predict the neighbourhood contribution (see section 2.3), simulations were done for the declared irradiation histories and the assembly storage configuration of the facility. Since details such as assembly manufacturer, exact spacing between assemblies and details about the control rod inserts were not provided, these had to be estimated according to the following:

- The fuel assembly manufacturers remain unknown to the authors, so the simulations assumed the same PWR 17x17 as simulated in [4], based on a Westinghouse PWR 17x17 assembly, for all three assembly designs encountered in the measurements.

- The material composition of the control rod inserts was unknown, and a standard control rod type was used in the simulations, consisting of by weight 80 % Ag, 15 % In and 5 % Cd, with a density of 10 g/cm^3 [11]. The control rods could alternatively contain boron carbide or hafnium, which could alter the gamma-ray attenuation in the material, but the expected main effect of the inserts (i.e. to remove the water otherwise present in the guide tubes, preventing Cherenkov light from being produced there) is the same.

- There were fresh fuel assemblies present in the storage racks, that were not measured or declared in the data. It was assumed that all positions contained an assembly, though considering how the irradiated assemblies were stored in the pond there were only a few positions where the presence of a fresh fuel assembly could attenuate the radiation going from one assembly to a neighbouring assembly.

- The exact storage configuration was unknown, but based on experience from other facilities and based on images of the assembly surroundings, it was assumed that each assembly was stored in a compartment enclosed by a 5 mm thick stainless steel wall, with 30 mm of water separating each compartment from its neighbours.

5 Results

Using the operator-declared fuel assembly data, the three prediction models were applied to the measured assemblies and the predicted intensities were compared to the measured intensities. One calibration constant was calculated for each prediction model (see section 2), treating all assemblies as part of the same data set despite of the fact that there were three different assembly designs present. This matches the currently used verification procedure, where PWR 17x17 assemblies are considered to be similar enough that they can be grouped together and compared. Note that all results presented in this section are based on this single calibration constant calculated per prediction model.

Based on the modelling results, the near-neighbour effect was estimated to be relatively weak for this set of assemblies and this storage geometry. According to the calculations, the assemblies had on average 1.5 % of their Cherenkov light intensity caused by its neighbours, and the most affected assembly had just below 6 % of its intensity caused by its neighbours. Thus, it is expected that the neighbourhood model will only offer minor improvements compared to the gamma-spectrum based model.

5.1 Results for the complete fuel assembly set

Figure 1 compares the relative deviations of the predictions to the measurements, as a function of the measured intensity for the complete set of assemblies. As can be seen from the data, the gamma-spectrum based prediction model and the neighbourhood prediction model do a better job at predicting the measured intensity. For the two-parameter model, one assembly is flagged as an outlier, with a relative predicted intensity more than 30 % higher than measured, and several assemblies are close to the 30 % limit. For the gamma-spectrum based model, the maximum deviation between prediction and measurement is 21 %, and with neighbourhood compensation the maximum deviation is 19 %.

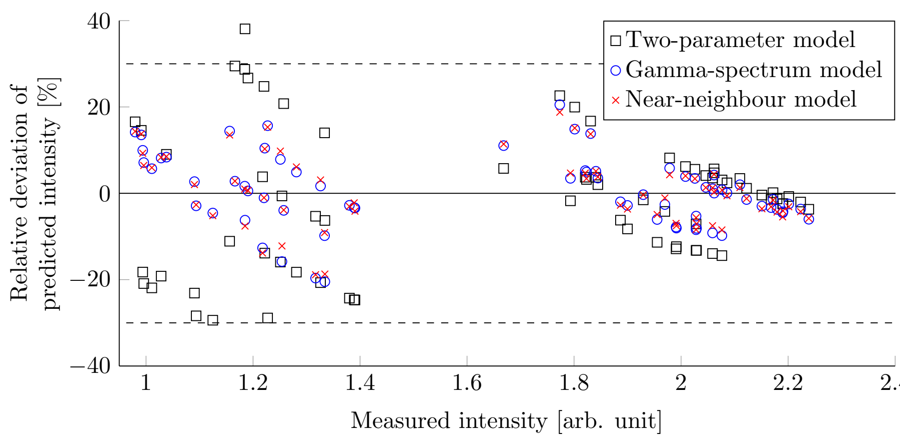

Figure 1: Deviations between the predicted and measured Cherenkov light intensities, for the three studied prediction models. Dashed lines mark the 30 % deviation limit, assemblies deviating more than 30 % are considered outliers and require additional investigation according to current IAEA inspection procedures.

Table 4 shows the one-sigma standard deviations for the relative difference between the measurements and the predictions of all the assemblies. Due to the calibration procedure used (see section 2), the average value of these deviations are close to zero, and the one-sigma standard deviations of the relative differences can be used to compare the precision of the prediction models. The substantially lower standard deviation of the gamma-spectrum based and neighbourhood models as compared to the two-parameter model is expected, since they were developed to overcome several limitations with the latter model, which are pronounced for short-cooled assemblies.

Table 4: Standard deviation (1σ) of the relative difference between predictions and measurements for the three prediction models.

Two-parameter model	**Gamma-spectrum based model**	**Neighbourhood model**
15.2 %	8.1 %	7.8 %

5.2 Results when grouping fuel assemblies by design

As presented in section 3, there are three different assembly designs present in the measured data set. The normal verification routine assumes that any systematic effects between assembly designs of the same configuration are negligible, and thus that all PWR 17x17 assemblies behave identically. In table 5 the average relative difference between prediction and measurement and the one-sigma standard deviation for the three designs and the three prediction models are presented. Note that due to the fitting done, the average relative difference for the complete set is close to zero, and the average relative difference for each assembly design provides information about possible systematic differences between designs. Furthermore, since a majority of the assemblies are of design B, the fitting done results in that these assemblies have the best match between predictions and measurements.

Table 5 shows that predictions for assemblies of design A by the two-parameter model are systematically lower compared to other assemblies, with an average relative difference between prediction and measurement of -21 %. This is however most likely a consequence of the fact that all assemblies of design A had been irradiated for only one cycle, and that the two-parameter model neglects short-lived isotopes. As a result, these assemblies suffer more from under-prediction of the Cherenkov light intensity compared to the others, since the neglected short-lived isotopes contributes much to the Cherenkov light intensity at these cooling times. For assemblies of design C, the large standard deviation is due to that there are few assemblies and several irradiation histories, and these irradiation histories poorly match the irradiation history assumed by the model.

For the gamma-spectrum based model and the neighbourhood model, the data in table 5 shows that the standard deviation within assemblies of designs A and B is larger than the systematic effects between the two designs. For both prediction models, it appears as if the design A assemblies are about 5 % less intense than design B assemblies, most likely due to the differences in physical design, resulting in about a 5 % over-prediction of the intensity of the design A assemblies as compared to the design B assemblies. The few assemblies of design C appear to have predictions systematically higher than the measurements, though there are not enough assemblies to say with confidence that this is not due to statistical uncertainties. However, these results suggest that there are systematic differences between assembly designs, and possible methods to address this issue are further discussed in section 7.

Table 5: Average relative difference between predictions and measurements, and the one-sigma standard deviation around the mean for the three fuel assembly designs. Due to the calibration procedure, the average deviation for the whole set of assemblies is close to zero.

	Design A	**Design B**	**Design C**
Two-parameter model			
Average difference [%]:	-21.0	3.2	2.8
1σ standard deviation [%]:	5.1	12.9	21.4
Gamma-spectrum based model			
Average difference [%]:	3.7	-1.6	12.9
1σ standard deviation [%]:	6.0	7.7	3.2
Neighbourhood model			
Average difference [%]:	3.8	-1.5	13.0
1σ standard deviation [%]:	6.0	7.3	3.0

5.3 Results when grouping fuel assemblies by irradiation history

Also mentioned in section 3 is that the majority of the assemblies can be divided into seven groups with similar irradiation histories (see table 2). The results when considering this division into irradiation groups are presented in figure 2, with dotted lines as a guide for the eye indicating assemblies belonging to one irradiation group. Since the declared irradiation history is similar in each group, the predicted intensity for each assembly in a group is also similar, but due to uncertainties in the measurements there is a spread in measured intensities. As a consequence the assemblies all lie on downward-sloping lines in figure 2. The average relative difference between prediction and measurement per group, as well as the one-sigma standard deviation around the mean of each group can be found in table 6.

For the two-parameter model, if an assembly has fewer irradiation cycles than the four assumed, the model will assume that the irradiation is spread out in time more than it actually is, and consequently overestimate the decay of fission products. As a result, the two-parameter model will systematically underestimate the intensity for assemblies with fewer cycles compared to the assumed four, and the fewer cycles, the more severe the underestimation becomes. Due to the calibration done, the fitting ensures that assemblies of group 2a and 2b have predictions close to the measurement since most of the assemblies are in these groups, while the one-cycle assemblies of group 1a and 1b are systematically under-predicted and the 3-cycle and 4-cycle assemblies in groups 3 and 4 are systematically over-predicted in table 6.

For the gamma-spectrum based model and the neighbourhood model, the average relative difference between prediction and measurement is much smaller as compared to the two-parameter model, and also smaller than the one-sigma standard deviation within each group, for a majority of the assemblies. Note that the assemblies in groups 1a and 1b are of design A, and the assemblies in the groups 2a, 2b, 2c and 3 are of design B. As found in the previous section, design A assemblies appear to be relatively over-predicted by about 5 % as compared to the design B assemblies. This is close to the average relative difference for the group 1a and 1b assemblies in table 6.

Two groups of assemblies appear to have predictions systematically deviating from the predictions when using the gamma-spectrum based and the neighbourhood model, group 2c and group 4. The assemblies in group 4 are over-predicted, but this is due to the fact that these assemblies are of design C. The four assemblies in group 2c appear to be systematically underestimated, but no explanation to this deviation could be found in the provided data. This could indicate that the prediction models fail to accurately predict these assemblies, or that there are additional properties to these fuels not considered in the prediction. Based on the provided data, there are eight assemblies in the total assembly inventory with this irradiation history, which may indicate that there is something unique to these assemblies, such as being loaded in certain reactor positions or containing burnable poisons at a concentration no other assembly has. Furthermore, should this deviation be due to incorrect fuel declarations, it can be noted that this is readily detected considering the systematic deviation of the assemblies. However, despite these systematic deviations, all assemblies in groups 2c and 4 readily pass the 30 % intensity deviation limit indicating a partial defect, and would also pass more stringent limits than those applied.

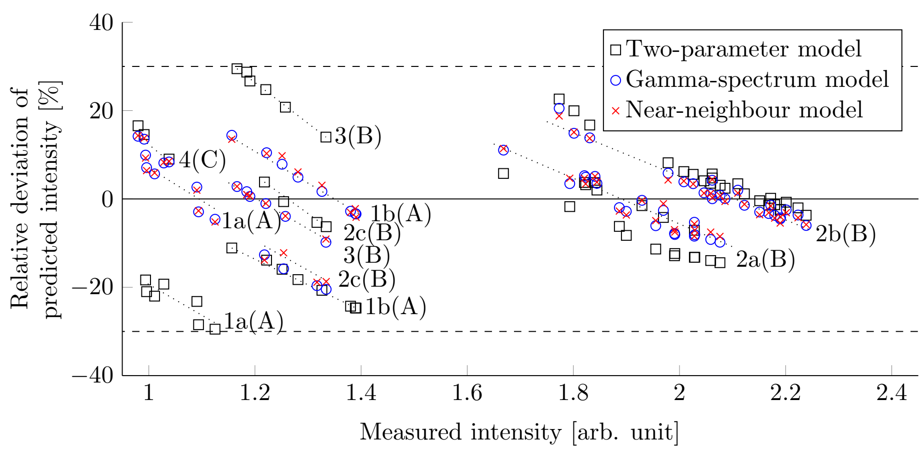

Figure 2: Comparison of the deviation between the predicted and measured Cherenkov light intensity, with fuel assemblies divided into seven groups based on the their irradiation history. The dotted lines are a guide for the eye, to indicate which assemblies belong to which group. The letter within parenthesis indicate the design of the assemblies in the group.

Since the assemblies in each of the seven groups have nearly identical declared irradiation history, the intensity within each group can be expected to

Table 6: Average relative difference and standard deviation between predictions and measurements for the seven main groups of fuel assemblies with different irradiation histories.

Group:	**1a**	**1b**	**2a**	**2b**	**2c**	**3**	**4**
Assembly design:	A	A	B	B	B	B	C
Two-parameter model							
Average difference [%]:	-23.1	-19.3	-5.8	3.9	-2.2	23.9	13.3
1σ standard deviation [%]:	4.0	4.9	7.0	6.9	4.0	5.3	3.2
Gamma-spectrum model							
Average difference [%]:	3.7	3.7	-2.1	1.6	-17.1	-1.7	12.0
1σ standard deviation [%]:	5.2	6.4	6.1	6.6	3.1	4.2	2.6
Neighbourhood model							
Average difference [%]:	3.4	4.1	-1.8	1.4	-15.9	-1.6	12.2
1σ standard deviation [%]:	5.2	6.4	5.8	6.4	2.9	3.9	2.6

vary only slightly. One may thus expect that the standard deviation in measured intensity within each group is predominantly caused by measurement uncertainties. However, there may also be uncertainties in the predictions, and the main source of uncertainty is expected to come from the operator-declared assembly parameters. These declared parameters do not take any details into account regarding any changes in reactor power level during operation, which could affect the accuracy of the predictions. Still, both types of uncertainties may be considered as representative for the underlying uncertainties when comparing measured and predicted data. In this evaluation, a one-sigma standard deviation between measurements and predictions of between 2.6 % and 6.6 % was obtained for the gamma-spectrum and neighbourhood prediction model, which provides an indication of the achievable precision in the verification procedure. While it is not expected that improved predictions will reduce the one-sigma standard deviation further in situations such as this one, it may still be possible that an improved measurement methodology could further improve the precision of the verification procedure.

On the other hand, the average relative difference between prediction and measurement of each group provides some indication regarding the accuracy of the prediction models for different assembly designs and/or different irradiation histories. In this evaluation the average deviation is smaller than the one-sigma standard deviation within each group for most of the groups when using the gamma-spectrum and the neighbourhood models, while for the two-parameter model the average deviation is often larger than the standard deviation, indicating poor prediction performance for the latter model. Since the majority of the assemblies are of design B, the fitting done will best match the predictions of these assemblies to the measurements, and for assemblies of Design A or Design C the fitting may introduce systematic errors. When considering the design B assemblies of group 2a, 2b and 3, the average relative difference per group is on the order of ± 2 % in table 6, which provides an indication of the achievable precision of these prediction models. The four design B assemblies in group 2c are the only ones deviating strongly from the other design B assemblies, but further information is required to identify the cause of this deviation.

5.4 Results for fuel assemblies with unique irradiation history

While a majority of the assemblies follow seven main irradiation histories, two assemblies had unique irradiation histories, as summarized in table 3. The performance of the prediction models for these assemblies are summarised in table 7. Since the irradiation histories are unique, it is not possible to determine if any deviations between predictions and measurements are due to systematic effects or due to measurement uncertainties, since no comparison can be made with other assemblies with similar irradiation history.

It is clear that the two-parameter model does a poor job of predicting these assemblies, mainly because the irradiation history does not match the assumed irradiation history or the history of the other fuel assemblies. These two assemblies are also the two which deviate the most.

For the gamma-spectrum based and the neighbourhood model, there also appears to be noticeable deviations. As found earlier, the design C fuels appear to be systematically over-predicted by about 13 % when using these models, explaining the deviation by assembly U2. The deviation for assembly U1 is small enough that it may be due to randomness in the measurements, and no indication suggesting that U1 should deviate was found in the provided data. The deviations for these two assemblies are however small enough that the assemblies readily pass the 30 % intensity difference limit indicating a partial defect.

Table 7: Difference between predictions and measurements for the fuel assemblies with unique irradiation histories.

Group:	**U1**	**U2**
Assembly design:	B	C
Two-parameter model Difference [%]:	37.9	-29.0
Gamma-spectrum model Difference [%]:	-6.3	15.6
Neighbourhood model Difference [%]:	-7.6	15.3

6 Conclusions

For the prediction models and experimental data analysed in this work, the gamma-spectrum based model and the neighbourhood model showed significantly better agreement to measured intensities compared to the two-parameter model. Accordingly, the current change from the two-parameter model to the gamma-spectrum based models for routine use during safeguards inspections with the DCVD is supported by this evaluation. With the latter methods, all fuel assemblies were confidently verified against the current partial defect detection limit of 30 % deviation between predicted and measured intensities.

The gamma-spectrum based model and neighbourhood model have been demonstrated to produce predictions with sufficient precision to be reliably used for partial-defect verification of short-cooled nuclear fuel assemblies. Despite the systematic deviation found between assemblies of different designs or manufacturers in section 5.2, all assemblies passed the partial defect detection limit with good margin, indicating that for this limit it is acceptable to group multiple assembly designs together and make one evaluation for the complete set.

Based the modelled results one can conclude that the near-neighbour effect was relatively weak for this set of assemblies. This is expected due to the physical properties of the storage situation, limiting the contributions from neighbouring assemblies, and because the radiation produced by each assemblies was fairly similar in magnitude. It was found in [5] that the near-neighbour effect in an unirradiated assembly caused by a single irradiated neighbour could be simulated with good accuracy (the simulated intensity was within 8 % of the measured intensity in the most pronounced cases). Thus it is expected that the neighbourhood model may perform well also in more challenging cases.

7 Discussion and outlook

The relatively small standard deviations between predicted and measured intensities for the gamma-spectrum based and the neighbourhood models for each assembly design indicate that employing a lower partial-defect detection threshold may be possible, thus allowing for the detection of even smaller partial defects. For a lowered partial defect detection threshold, and thus higher requirements on the accuracy of the predictions, it may be necessary to take the assembly design into account to eliminate the systematic differences identified in this study. One can foresee a few alternatives for the establishment of such a procedure:

- Experimentally measuring and quantifying the systematic deviation between assembly designs in a controlled environment and use the results for making corrections.
- Performing simulations including the photon transport of Cherenkov light from the point of emission to the DCVD, taking construction material altering the light transport into account, to quantify the systematic deviations and use these results for corrections.
- Separating assemblies according to their design in the analysis.

For the first two alternatives, these values can then be applied when making predictions, to ensure that all assemblies are comparable. The last alternative would be most straight-forward since it is already implemented, but it requires a relatively large set of assemblies of each design in a measurement campaign which may not always be available.

For this experimental data set, one group consisting of four assemblies with similar irradiation history deviated noticeably from the other assembles. This could indicate a shortcoming with the prediction model, though it could also be caused by effects not declared by the operator. Further data is required in order to assess and identify the cause of this discrepancy. However, despite the discrepancy, the assembles could be readily verified against the partial defect detection limit, and would also pass more stringent limits than those applied.

For this experimental data set, the neighbourhood effect is relatively small, and the gamma-spectrum based and the neighbourhood model gives similar results. While applying near-neighbour predictions does improve the predictions somewhat compared to the gamma-spectrum based model, the improvement is not statistically significant, and other effects than the near-neighbour effect dominate the discrepancies between predicted and measured values. As such, it may be preferable to use the gamma-spectrum based model when measuring a fuel assembly inventory such as this one, since it requires less data. However, for situations with a much stronger near-neighbour effect, the neighbourhood model may be required in order to verify the inventory. While the accuracy of the near-neighbour predictions presented here are encouraging, further validation against assemblies experiencing a stronger near neighbour effect is required in order to better understand and assess the performance of the neighbourhood prediction model.

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