IMPROVED CHERENKOV LIGHT PREDICTION MODEL FOR ENHANCED DCVD PERFORMANCE

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Abstract

The Digital Cherenkov Viewing Device (DCVD) is an instrument used to verify irradiated nuclear fuel assemblies in wet storage based on the fuel's Cherenkov light emissions. The DCVD is frequently used for partial defect verification, verifying that 50% or more of an assembly has not been diverted. The verification methodology is based on comparison of the measured Cherenkov light intensity to a predicted intensity, based on operator declarations.

For the last five years, a dedicated PhD project at Uppsala University has been aiming at enhancing and improving the verification capabilities when using the DCVD. The project is now approaching its end, and this paper summarizes the comprehensive work performed regarding improving the prediction capabilities.

A new prediction model has been developed, considering more fuel assembly details to ensure more accurate predictions. With the new model, the irradiation history of an assembly, the assembly design and the contributions from gamma and beta decays are taken into account. The model has also been extended to account for the radiation from neighbouring fuel assemblies, which can enter the assembly being measured and contribute to the measured Cherenkov light. The performance of the prediction model and the neighbour intensity prediction model has been validated against fuel measurements by the IAEA at a PWR facility with short-cooled fuel. The results show that the new model offers an improved prediction capability, allowing the fuel inventory to be verified with no fuel assemblies being identified as outliers requiring additional investigation. A simplified version of the prediction model will be implemented in the next DCVD software version, making it available to IAEA inspectors.

This development of the DCVD capabilities are in line with the fourth theme of the IAEA safeguards symposium, "Shaping the future of safeguards implementation", by resolving challenges related to the DCVD and by extending the capabilities of the instrument.

1. INTRODUCTION

This paper summarizes the research done within a PhD project at Uppsala University, dedicated to enhancing and improving the verification capability of the Digital Cherenkov Viewing Device (DCVD). This work has been performed as part of the Swedish support programme to IAEA safeguards. The DCVD is an instrument used to measure the Cherenkov light emitted by irradiated nuclear fuel assemblies in wet storage. The DCVD can be used for gross defect verification, where the presence and characteristics of the Cherenkov light is used to assess if an item is an irradiated fuel assembly or a non-radioactive item. The DCVD is more commonly used for partial defect verification, i.e. to verify that part of an assembly has not been diverted, and two procedures are used for this type of verification. The first procedure uses image analysis to detect removed rods in an assembly, based on the presence of Cherenkov light in positions that should be dark, due to a fuel rod blocking the light. The second method is based on a quantitative measurement of the Cherenkov light intensity emitted by an assembly, and on comparing this intensity to a predicted intensity. This method can be used to detect the substitution of irradiated fuel rods with non-radioactive ones. Earlier simulations have shown that a 50% substitution of irradiated fuel rods with non-radioactive steel rods will result in at least a 30% reduction in the Cherenkov light intensity of an assembly [1]. Thus, if a measured intensity is more than 30% below predicted, the assembly is flagged by the DCVD software as an outlier, requiring further investigation.

A crucial component of the adopted quantitative verification procedure is accurate predictions of the Cherenkov light intensity emitted by a fuel assembly, which are based on the operator fuel assembly declarations. Such a prediction model must be accurate, and the predictions must be fast to calculate on modest hardware, to allow for in-field use by the inspectors. The first-generation prediction model used by authority inspectors is based on the work of [2]. In this model, fuel depletion calculations and Monte-Carlo simulations of the emitted radiation in an assembly model is used to parameterize the Cherenkov light intensity of an assembly, as a function of its burnup and cooling time. While this prediction model has been successful, it makes some simplifying assumptions in the simulated model of a nuclear fuel assembly, which reduce the accuracy of the predictions in some situations. Since it only considers abundant and long-lived gamma emitting fission products, it is not sufficiently accurate for short-cooled fuels, when more, short-lived isotopes are still present. Furthermore, it assumes a “standard” irradiation history, matching the normal usage of an assembly in a reactor, which introduces an error when predicting intensities for assemblies with more unusual irradiation histories. It also assumes that the Cherenkov light production in a simulated BWR 8x8 assembly is representative of any assembly type, which neglects possible systematic differences between assemblies of different designs.

The IAEA has previously shown interest in having access to an improved prediction model, which is not limited by these shortcomings. Within this dedicated PhD project, a second-generation prediction model has been developed which consider these additional details in the predictions. The aim of developing the prediction model was to allow the DCVD to be used in situations where the first-generation prediction model would be unable to predict the intensity of an assembly accurately. The enhanced accuracy of the predictions will also make the DCVD more sensitive to fuel assemblies with an unexpected Cherenkov light intensity, increasing the performance of the verification methodology for partial defect verification.

2. SECOND-GENERATION PREDICTION MODEL

To determine which parameters affect the Cherenkov light production in a nuclear fuel assembly, and to quantify the effect, Monte Carlo simulations were performed [3][4]. The results of the simulations indicate that the following parameters should be taken into account in a prediction model, for enhanced performance compared to the first-generation prediction model:

- The assembly irradiation history,
- All gamma-emitting fission products,
- Fission products with high-energy beta decays,
- The fuel rod dimensions (pellet radius, cladding thickness),
- The fuel rod placement in an assembly (i.e. the physical design of the assembly),

At the same time, these factors should be taken into account without increasing the calculation time required for the predictions, to allow for in-field use by the inspectors. The recently developed second-generation prediction model was developed to include these parameters in the predictions. By means of comprehensive Monte-Carlo simulations using Geant4 [5], the radiation transport of fission-product decay radiation and the subsequent Cherenkov light production in a fuel assembly geometry were simulated. The simulations were used to parameterize the Cherenkov light production in an assembly as a function of the assembly gamma and beta emission spectra. While these simulations are time-consuming, they only have to be done once (in advance) for each assembly design, to construct a database of parameterized Cherenkov light intensities, as a function of assembly emission spectra and the physical configuration of the assembly. This parameterization allows for a fuel depletion program such as ORIGEN [6] to be used to calculate the gamma and beta emission spectra of the fuel assembly, based on the operator declared irradiation history. These spectra are then used as input in the calculations of the Cherenkov light predictions. Figure 1 describes the prediction method, with the extensive pre-calculations shown on top, and the procedure used by the inspector in the field shown below.

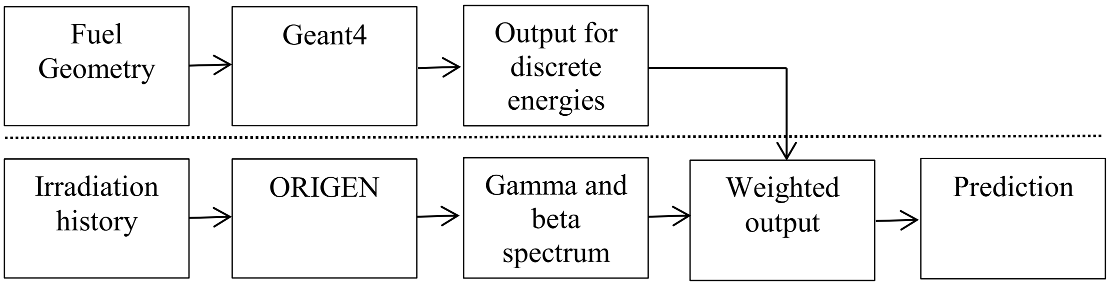

FIG. 1. Schematic of the second-generation prediction method. The top row contains the Monte-Carlo simulations to parameterize the Cherenkov light productions as a function of the radiation type and energy. The bottom row contains the calculations performed to obtain a prediction.

2.1. Predicting Cherenkov light from single assemblies

The first-generation prediction model makes predictions for isolated fuel assemblies only, neglecting other potential radiation sources. The second-generation model can be used in this way [4], although it will also consider the assembly geometry. In the second-generation model, once the irradiation history of an assembly is available, ORIGEN is used to calculate the abundance of fission products, and to produce a gamma emission spectrum of the assembly. This spectrum is used together with pre-calculated values describing the produced Cherenkov photon intensity by a specific gamma energy in an assembly of that design, to estimate the total produced Cherenkov light intensity by the gamma radiation. Note that once the irradiation history has been provided to the prediction tools by the inspector, the remaining steps in figure 1 can be done automatically. This keeps the inspector workload when making predictions at a similar level to that of the first-generation prediction model.

ORIGEN will also output the abundance of beta-decaying isotopes, from which a beta emission spectrum can be calculated. The contribution to the Cherenkov light intensity due to beta-decays can in principle be handled in the same way as gamma decays. However, if only a few beta-emitting isotopes are identified, it may be simpler to simulate the Cherenkov light production as a function of the isotope abundance, and then in the prediction simply multiply the ORIGEN-calculated abundance with this value.

By making the emission spectra calculations part of the prediction step rather than the parameterization step, it becomes possible to make Cherenkov light intensity estimations considering the irradiation history. Should the irradiation history be unavailable, it is possible to assume a “standard” irradiation history; this will however make second-generation predictions nearly identical to those based on the first-generation model. It should be stressed that for assemblies with short cooling times or unusual irradiation history, the irradiation history needs to be taken into account for accurate predictions, and therefore the second-generation model should be used in such cases. Furthermore, the ORIGEN calculations take about a few seconds to perform on a modern laptop, and combining the ORIGEN output with the parameterized Cherenkov light intensity values takes negligible time. Hence, the predictions are fast enough that they can be performed in-field.

The second-generation model for single assemblies, excluding beta decays, has been implemented in the next version of the DCVD software, which will be made available to inspectors shortly. This will allow the DCVD to be used regularly to verify assemblies with short cooling time or unusual irradiation history.

2.2. Predicting the Cherenkov light contribution from neighbouring fuel assemblies

Irradiated nuclear fuel assemblies are often stored closely together, allowing gamma rays from one assembly to enter a neighbouring assembly and create Cherenkov light there, which is the so-called near-neighbour effect. Consequently, part of the measured Cherenkov light emissions from an assembly is caused by radiation originating from other sources than the assembly itself. The IAEA has previously shown interest in having the capabilities of making predictions including this near-neighbour effect, and as part of the second-generation prediction model, a method to predict and compensate for this effect has been developed [7].

The methodology follows the one outlined in figure 1, but with the simulated fuel geometry now including the neighbouring assemblies. The Monte-Carlo simulations are used to parameterize the neighbour Cherenkov light production, taking the assembly emission spectra, assembly design, storage rack configuration and distances between fuel assemblies into account. The parameterization also needs to take into account which neighbouring positions are occupied by assemblies and which are empty, since the radiation originating from a neighbouring position may be attenuated in another neighbouring assembly before reaching the assembly under study. Beta decays can however be neglected in this case, since their range is too short to contribute to the Cherenkov light production in a neighbouring fuel assembly.

To make a prediction, the irradiation histories of all neighbouring assemblies are run through ORIGEN to obtain the corresponding gamma spectra. Then, the parameterized neighbour Cherenkov light intensity values are selected from the database for the configuration under study, based on the assembly type, storage configuration and storage rack configuration. These values are combined with the gamma spectra, to obtain a value of the estimated Cherenkov light intensity in the assembly under study caused by its neighbours. This predicted near-neighbour intensity value can then be used to compensate for the near-neighbour effect, ensuring that the verification procedure only considers the Cherenkov light emission of the assembly under study.

3. EXPERIMENTAL VALIDATION OF THE PREDICTION MODEL

Through the IAEA, the authors obtained a set of DCVD measurements of 9-month cooled PWR assemblies from an undisclosed nuclear power plant. These assemblies corresponded to the core inventory of the reactor, and had been irradiated for one to four cycles. Hence, the standard irradiation history assumed by the first-generation prediction model, which assumes that the assemblies have reached their discharge burnup, poorly match the assembly inventory where a majority of the assemblies were to be further used in the reactor. Consequently, this is a situation where the second-generation prediction model is expected to offer improved accuracy, due to its ability to consider the irradiation history.

Figure 2 shows the difference between the predicted and the measured intensity for the fuel assemblies. Due to the way the assemblies had been irradiated in the reactor, almost all assemblies had experienced one out of seven distinct irradiation histories, resulting in that the prediction for the assemblies sharing an irradiation history was nearly identical, and consequently such assemblies form vertical bands in figure 2.

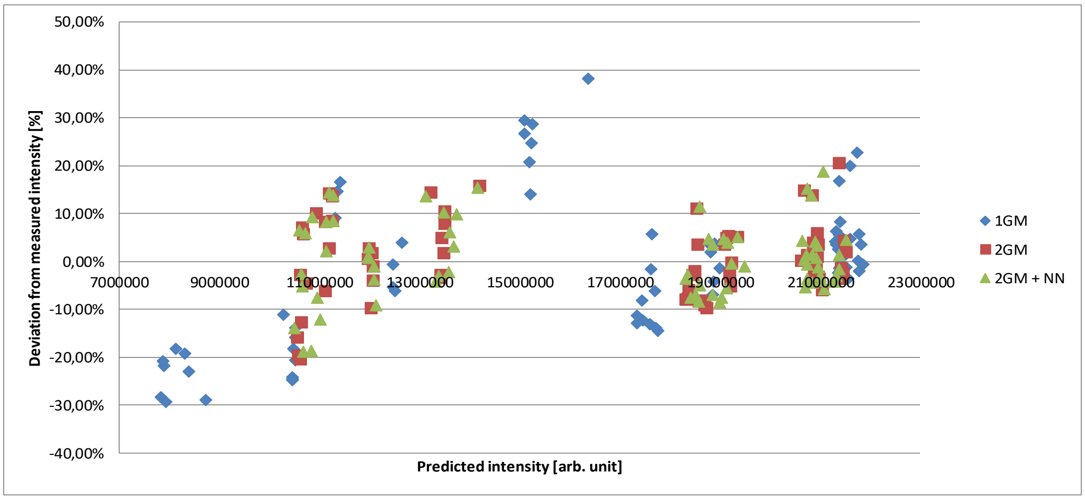

FIG. 2. Deviation between the predicted and the measured intensity for the first-generation model (1GM), the second-generation model (2GM) and the 2GM including compensation for the near-neighbour effect (2GM + NN)

As can be seen in figure 2, the second-generation model provides more accurate predictions compared to the first-generation one. Using the first-generation model, one assembly deviated more than 30% and was flagged as an outlier while for the second-generation model the maximum deviation was 21%, which provided a good margin to the partial defect detection limit. However, due to the relatively large distances between assemblies and the sparse storage configuration, the near-neighbour effect was relatively low, and on average 1.5% of an assembly intensity was predicted to be due to the near-neighbour effect. Consequently, for this measurement campaign, the contribution of the near-neighbour effect in the predictions was negligible.

The second-generation prediction model also provides an increased precision, as shown by the reduced Root Mean Square Error (RMSE) in table 1. The enhanced precision makes the DCVD more sensitive to assemblies with an unusual Cherenkov light intensity, with further enhances its ability to detect assemblies with partial defects. Further analysis of the performance of the studied prediction models can be found in [8].

TABLE 1. Root Mean Square Error (RMSE) of the difference between prediction and measurement, for the studied prediction models.

Prediction model	1GM	2GM	2GM + NN
RMSE	15.2%	8.1%	7.8%

4. CONCLUSIONS AND OUTLOOK

The second-generation prediction model, developed within a dedicated PhD project at Uppsala University, for estimating the Cherenkov light intensity from a fuel assembly extends the capabilities compared to the first-generation model. The model include more details regarding the assemblies, such as the complete gamma and beta spectrum, the assembly design and the irradiation history. These predictions allow the DCVD to be used to verify assemblies that could previously not be verified accurately, such as assemblies with short cooling time or unusual irradiation history. A version of the single assembly prediction model, excluding beta decays, will be made available to inspectors in the next DCVD software version. This prediction model is fast enough to be used by inspectors in the field, and does not significantly increase the inspector workload when calculating the predictions of relevance in a verification campaign. In the future, the implemented software may be extended to include beta decays in cases where it is relevant, and to include the near-neighbour effect.

The increased precision in the predictions makes the verification procedure more sensitive to assemblies with an unusual Cherenkov light intensity. This can be used to lower the detection limits of partial defect further, enabling the DCVD to detect partial defects at a lower level than currently achieved. However, such a lowering of the detection limits require a detailed investigation regarding different partial defect scenarios and its effects on the Cherenkov light emissions of an assembly, and further experimental validation of the accuracy of the prediction model and the verification procedure.

Other than the second-generation prediction model, the results of the PhD project also include a deeper understanding of which fuel assembly parameters affect the Cherenkov light production and to what extent, methods to allow Cherenkov light intensity comparisons of assemblies of the same type but with different designs with increased accuracy, and identification of background components present in DCVD measurements. These results are further described in [9].

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