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On the inclusion of light transport in prediction tools for Cherenkov light intensity assessment of irradiated nuclear fuel assemblies

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Abstract

The Digital Cherenkov Viewing Device (DCVD) is a tool used to verify irradiated nuclear fuel assemblies in wet storage by imaging the Cherenkov light produced by the radiation emitted from the assemblies. It is frequently used for *partial defect verification*, verifying that part of an assembly has not been removed and/or replaced. In one of the verification procedures used, the detected total Cherenkov light intensities from a set of assemblies are compared to predicted intensities, which are calculated using operator declarations for the assemblies.

This work presents a new, time-efficient method to simulate DCVD images of fuel assemblies, allowing for estimations of the Cherenkov light production, transport and detection. Qualitatively, good agreement between simulated and measured images is demonstrated. Quantitatively, it is shown that relative intensity predictions based on simulated images are within 0.5% of corresponding predictions based solely on the production of Cherenkov light, neglecting light transport and detection. Consequently, in most cases it is sufficient to use predictions based on produced Cherenkov light, neglecting transport and detection, thus substantially reducing the time needed for simulations.

In a verification campaign, assemblies are grouped according to their type, and the relative measured and predicted intensities are compared in a group. By determining transparency factors, describing the fraction of Cherenkov light that is blocked by the top plate of an assembly, it is possible to adjust predictions based on the production of Cherenkov light to take the effect of the top plate into account. This procedure allows assemblies of the same type but with different top plates to be compared with increased accuracy. The effect of using predictions adjusted with

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transparency factors were assessed experimentally on a set of Pressurized Water Reactor 17x17 assemblies having five different top plate designs. As a result of the adjustment, the agreement between measured and predicted relative intensities for the whole data set was enhanced, resulting in a reduction of an RMSE from 14.1% to 10.7%. It is expected that further enhancements may be achieved by introducing more detailed top-plate and spacer descriptions.

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

1 Introduction

The Digital Cherenkov Viewing Device (DCVD) is an instrument used by the International Atomic Energy Agency (IAEA) for measuring the Cherenkov light emissions of irradiated nuclear fuel in wet storage for nuclear safeguards purposes [1]. It can be used for *gross defect verification*, verifying that an item under study is an irradiated nuclear fuel assembly, but it is often used for *partial defect verification*, verifying that part of an assembly has not been diverted.

There are currently two methods in use for detecting partial defects with the DCVD. The first method is based on image analysis, and can be used to detect the removal of fuel rods from visible positions in a fuel assembly. The second method, which is the subject for this work, is based on quantitative measurements of the Cherenkov light emissions of a fuel assembly, and comparison to predicted intensities, based on operator declarations. Earlier simulations have found that a 50% substitution of fuel rods in an assembly with non-radioactive ones will reduce the measured Cherenkov light intensity by at least 30% [2]. Hence, if a measured intensity is more than 30% below the predicted one in a verification campaign, it is flagged as an outlier requiring further investigation. For this method to work, a method to accurately predict the Cherenkov light intensity of an assembly based on operator declared information is required. This work aims at making such predictions both more general and more accurate, as outlined in section 1.3.

1.1 Methods for predicting Cherenkov light intensities

The first method for predicting the Cherenkov light intensity of an assembly to be put in use was based on [4]. By means of simulations, the Cherenkov light intensity in an assembly was parametrised as a function of the assembly burnup and cooling time. The simulations included the propagation of the Cherenkov light to a detector position to investigate the total detected intensity, but neglected the effects of structural components in the assembly. Furthermore, only one fuel assembly type was simulated, based on a Boiling Water Reactor (BWR) assembly, thus neglecting differences in light production properties between fuel types. Later work [5] simulated not only the Cherenkov light intensity at a detector position, but also the image creation using a camera model. The developed methodology was used to investigate assemblies with various partial

defects, to quantify the impact of the defects on DCVD images, and the subsequent intensity measurements.

A recently developed prediction tool is described in [3] [6]. By means of simulations, the Cherenkov light production in an assembly is parametrized as a function of gamma and beta emission energy. The source spectrum is then calculated based on operator declarations, and this tool can thus take into account more details about the irradiation history of the assembly as compared to the first prediction tool. In addition, simulations are performed separately for different assembly types, to take into account the different light production properties caused by differences in e.g. fuel rod dimensions, cladding thickness and pitch. This tool however assumes that the measured intensity is proportional to the produced intensity, neglecting any light transport. It is also assumed that the proportionality constant can be found by a least-square fit of the measurements to the predictions. Furthermore, as the gamma emission spectrum of the assembly changes with cooling time, the intensity of the Cherenkov light produced at various positions in the assembly may also change over time. The top plate of the assembly will prevent a fraction of light from exiting the assembly and reaching the detector, and one may expect that this fraction will depend on the cooling time of the assembly.

1.2 Limitations to the implemented quantitative verification methodology.

The verification procedure used is based on comparing the relative measured intensities of the assemblies to predicted intensities. The measurement situation is shown schematically in figure 1a. After the measurements and predictions for all assemblies are available, a least-square fit is made to find the multiplicative constant relating the predictions to the measurements. This constant can be factored into components relating to the light transport through the fuel assembly and the resulting fraction of light absorbed by structural components such as spacers, top plate and lifting handle. The constant can be further factored into components containing information about the fraction of light absorbed in the water, and the detection efficiency of the DCVD.

Since a verification campaign is typically performed using one DCVD at one facility, of these factors only the light absorbed by structural components will vary between measurements. Consequently, one fit needs to be done per assembly type present, to find the multiplicative constant relating predictions to measurements for that type. As a result of using this fitting procedure, what is actually evaluated is the relative intensity of assemblies of the same type, to identify if any assembly has an intensity deviating from the expected one. However, measurement campaigns may include fuel types, of which there only exist a few items. Performing a relative evaluation of fuel assemblies in such a small group may be difficult, and calls for a need to introduce means by which they can be included in a larger dataset.

As a consequence of the fitting and procedure of grouping assemblies according to their type, it is sufficient that predictions correspond to the relative

Figure 1: Left: Schematic of a DCVD measurement of nuclear fuel assemblies. The assemblies are covered by around 10 m of water, and the DCVD is mounted 1-2 m above the water surface. Right: Schematic of a Pressurized Water Reactor (PWR) 17x17 fuel assembly, as has been studied in this work. The schematic shows the location of the fuel rods, the guide tubes, the central instrumentation tube and the simplified square spacer grid that has been included in the simulations.

intensities of the assemblies in a data set. For this reason, recent prediction tools [3] are based on the produced Cherenkov light intensity, and neglects its detection. However, if assemblies of different types are to be compared, it may be necessary to make corrections for the light transport properties of the different assembly types.

For assemblies of certain types, such as Pressurized Water Reactor (PWR) with fuel rods in a square 17x17 layout, assemblies produced by different manufacturers should be similar enough to allow them to be grouped into one dataset, although some notable differences in the design exist. One of the main physical differences for PWR 17x17 assemblies is the top plate, which to some extent prevents Cherenkov light from exiting it to be detected. Consequently, some systematic errors will be introduced when assemblies of the same type but with different designs are compared if these design differences are not corrected for. Currently assemblies of the same type would be grouped together and compared, and one of the goals of this work is to investigate ways of removing this systematic error, as further described in section 1.3.

Finally, one should note that PWR assemblies are sometimes stored with a control rod cluster inserted. These clusters block enough light that such assemblies cannot be compared to assemblies without an insert, and they need to be separated into their own data set in DCVD verification. However, if the predictions were to include an adjustment for the insert, it may be possible to compare assemblies with and without inserts.

1.3 Scope of this work

This work describes a simulation toolkit, based on the established simulation code Geant4 [7], which is used to simulate the production of Cherenkov light in a nuclear fuel assembly, its propagation to a detector position and the creation of an image.

One of the goals of this work is to seamlessly integrate the radiation and optical photon transport steps, as compared to the previously used image creation toolkit [5]. This is intended to simplify the simulation workflow, while allowing for more time-efficient image simulations.

A second goal is to investigate the assumption made in the prediction models of [3] [6], that the produced Cherenkov light intensity is proportional to the detected one. By comparing image simulations with the simulated light production, the error introduced by this assumption can be quantified. The magnitude of the error will provide information on whether the simpler production model can be used with sufficient precision for IAEA safeguards.

A third goal is to investigate the possibility of using image simulations to characterize systematic differences in the detected Cherenkov light intensity for assemblies of the same type but with different physical designs, in particular by considering the blocking of light by structural components in the assembly top plates. Experimental data are used to evaluate to what extent the intensity predictions for the assemblies can be adjusted to make all assemblies comparable despite physical design differences. Such a capability may be valuable when analysing assembly populations where assemblies of some designs are too few to be analysed separately, allowing them to be analysed together with other assemblies of the same basic type but of different designs with enhanced accuracy.

2 Simulation tools used in this work

To simulate a DCVD image, a three-step procedure has been adopted. In the first step, the fuel depletion code ORIGEN [8] is used to simulate the gamma emission spectra of the simulated assembly. In the second step, the Monte-Carlo radiation transport code Geant4 [7] is used to simulate the transport of radiation in a nuclear fuel assembly geometry, the Cherenkov light produced by this radiation, and the transport of this Cherenkov light to the top of the fuel assembly. Once a photon reaches the top of the fuel assembly it is saved, to be used in the third step. The third step consist of modelling the DCVD image based on the photon emissions from the top of the assembly, using a pinhole camera model. By using this three-step procedure, it is comparably computationally inexpensive to create DCVD images for various pinhole camera positions, since the more expensive second step only has to be done once.

2.1 Simulating the source spectrum

The first step in the adopted methodology is to simulate the gamma emission spectra of the assembly. In this work, ORIGEN [8] has been used for this pur-

pose, and the irradiation history simulated has been similar to the "standard" histories used in the prediction model currently in use by the IAEA [4]. This work has neglected the direct Cherenkov light contribution due to beta-decays, though it can in principle be handled in the same way as gamma-emissions in the methodology [3].

2.2 Monte-Carlo particle transport

The simulation code used for the second step is a further development of the code package used in [3], which in turn is based on the code package described in [9]. Following the methodology used in [10] and [3], the ionising radiation is simulated to be emitted from inside the fuel material, and the simulations keep track of the radiation interactions and subsequent production of Cherenkov light. This work however needs to consider the full 3-D geometry in the simulations with a higher level of detail, with regards to both geometry and source distribution, and it has thus been extended to allow such simulations:

- The geometry has been extended to consider the total length of the fuel rods, by introducing a simplified helium-filled gas plenum at the top of the fuel rod.
- A simplified spacer structure has been implemented, where the spacers consist of a square metal grid, as shown in figure 1b.
- A vertical source distribution has been implemented, corresponding to a typical vertical burnup profile of the rods, which is used to distribute the initial gamma rays along the length of the rod according to the axial profile.

The simulations were extended compared to the previous ones in [10] and [3], to include the propagation of the produced Cherenkov light inside the assembly. For this reason, all assembly surfaces are modelled as diffusely reflecting, with a user-specified reflectivity, here selected to be 10%, matching the reflectivity used in [5]. The optical Cherenkov photons are simulated until they reach the top of the assembly, where they are saved to file for the next step. The top structure of the assembly, i.e. the lifting handle and top plate, are not included in this simulation step; instead these structural components are considered in the final image creation step.

2.3 Image creation using a pinhole camera

The creation of a DCVD image based on the saved Cherenkov photon emission data from the top of the fuel assembly is done in this work by modelling the projection of the saved photons through a pinhole camera. After the camera position is defined, the propagation direction of each saved Cherenkov photon is compared to the direction towards the pinhole point. If the angle between the two directions is smaller than a selected threshold angle, its direction is adjusted

to be directed towards the pinhole, and it is then projected onto an imaging plane. If the angle is greater than the threshold, the photon is discarded. The angular threshold is necessary to detect any Cherenkov photons at all, since the camera opening is modelled as an ideal point, and no photon can be expected to hit this point exactly.

The advantage of using a pinhole camera model as compared to a more realistic lensed system is that it is a straight-forward geometric problem to project photons onto an imaging plane, making this step fast to compute. However, the model does not include effects seen in a real camera such as geometric distortions, or blurring and distortions caused by lenses and a finite sized aperture. While the pinhole camera model is considered to be sufficient for the investigations presented in this work, it would be fully possible, albeit more time-consuming, to use a more detailed camera model including lenses and apertures.

The top of a fuel assembly normally contains structures such as a lifting handle and a top plate to hold the rods in place, which block light from exiting the fuel assembly. The effects of the top structures are modelled by applying a mask to the simulated image, where the mask indicates which regions are covered by structures so that no photons can pass, and which regions are open, allowing the photons to pass through. The mask can either be applied when projecting the photons, or applied afterwards to the image, and for the relatively simple pinhole projection performed here, the two methods are equivalent.

Note that this projection procedure simplifies the situation by not taking into account the properties of the water, water surface, air and imaging optics of the DCVD. The most significant effect of these properties is a blurring to the image, which can be approximated by applying a Gaussian filter to the simulated image. In cases where more detailed modelling is desired, it would be possible in the Geant4 framework to include additional effects regarding the light transport to a detector, such as absorption in water, blurring, refraction, vignetting etc.

3 Simulation studies

3.1 Simulated assemblies and images

Simulations have been executed for a PWR 17x17 assembly, with dimensions matching those found in [3]. A total of 11 spacers were distributed at equal distances along the assembly length. ORIGEN was used to assess the gamma spectra of fuel assemblies with a burnup of 10 respectively 40 MWd/kgU (Megawatt-days per tonne of Uranium) and cooling times of 2, 10 and 40 years. Due to the computational expensiveness of the second step of the simulations, only two burnups and three cooling times were simulated. A simplified vertical burnup profile was assumed, which was constant along 335 cm of the assembly, and decreasing linearly along the last 25 cm at each end to have 15% of the maximum intensity at the tips. This simplified vertical burnup profile captures the essential behaviour of the typical distribution, with a reduced burnup near the rod ends. All fuel rod surfaces were modelled as 10% reflective with diffuse reflec-

Figure 2: a): An example DCVD measurement of a PWR 17x17 fuel. Using an intensity threshold, the dark parts of the image (where the top plate blocks the light completely) was identified. b): The mask resulting from a threshold set at 8% of the maximum image intensity.

tions, to be representative for the strongly absorbing oxidized surfaces normally encountered, and to correspond to the reflectivity used in [5]. Finally, the modelled pinhole camera was placed 11 m above the assembly, a typical distance encountered during a DCVD measurement.

Ideally, to create a mask representing the top plate and lifting handle, a high-resolution photo or a drawing of the assembly top structure should be used. Since neither of these were available in this work, the masks for each assembly design studied were instead extracted from a DCVD measurement of the corresponding assembly design. For each fuel design studied, a measurement of a comparatively high-intensity assembly was selected, having the highest contrast between dark and bright regions. An intensity threshold was then applied to the image, to separate the dark regions covered by the top plate and lifting handle from the bright regions that were not covered. The threshold was subjectively set to 8% of the maximum intensity encountered in a measurement, since this value was judged to give realistic masks. The resulting mask for one of the PWR 17x17 assembly designs studied is shown in figure 2.

3.2 Qualitative validation of simulated images

Figure 3 shows a simulated DCVD image, together with a measured image for comparison. The simulated image is 256x256 pixels, which is smaller but comparable to the size of the region of interest (ROI) in the DCVD image of 350x350 pixels. It was found that applying a 3x3 pixel Gaussian filter gave enhanced qualitative agreement between the simulated and measured images. This blurring represents various effects which blur the image that were not included in the simple image creation calculations, such as water turbulence.

Qualitative features that matched in both the simulated and measured images include:

- The shape of the intensities in the guide tubes and its variation as a function of the distance to the image center.
- The higher intensity near the center and the intensity decrease with distance from the center.
- The spacers can vaguely be seen in the region in between the rods.

Figure 3: a): An example DCVD measurement of a PWR 17x17 fuel. b): A simulated DCVD measurement, with a top plate mask applied and a 3x3 pixel Gaussian blur applied.

One identified difference between the measured and simulated image in figure 3 is the hole at the very center, which appears larger in the simulated image. This is a consequence of the higher brightness in the image near the center compared to the edges, thus more pixels near the edges of the center hole have an intensity above the threshold, compared to a similar hole further from the image center.

A threshold angle of 0.4° was selected when creating the image in figure 3, although angles in the range $0.3 - 0.6^\circ$ were found to give images with good qualitative agreement compared to the measured reference image. For values of the threshold angle larger than 0.6° , all guide tubes were found to evenly bright in the image with no gradients, and for values smaller than 0.3° the outer guide tubes become almost completely dark, which does not match the measurement.

3.3 Correlation between produced and detected intensity

As mentioned in section 1, when using predictions based on the intensity of Cherenkov light produced in the assembly, it is assumed that the detected intensity is proportional to the produced intensity. The proportionality constant

Figure 4: Comparison of the relative Cherenkov light intensity in a PWR 17x17 assembly, for intensities estimated based on Cherenkov light production (from [3]), and from simulated DCVD images of the same fuel assemblies. The statistical uncertainties due to the Monte-Carlo nature of the simulations are below 0.4% for the image intensities, and below 0.1% for the production intensities.

is found through a least-square fit of the predictions to the measured data. To test this assumption, two types of predictions were made, one prediction based on the simulated produced Cherenkov light, and one prediction based on simulated images of the assembly. The predictions were made for a PWR 17x17 assembly, for burnups of 10 and 40 MWd/kgU, and the results are shown in figure 4. Note that a least-square fit was made to find one multiplicative constant relating the two predictions, in a way identical to how the predicted and measured intensities are scaled to be comparable in the regular DCVD verification procedure.

The predictions of the two models in figure 4 agree to within 0.5% for the six mutual data points. This agreement can be compared to the uncertainty in the predicted values due to the Monte-Carlo nature of the simulations, which was 0.4% for the image intensities and 0.1% for the production intensities. This provides a strong indication that the produced intensity is representative for the image intensity, although more data would be needed to validate this conclusion more thoroughly. Considering the good agreement between the two models, predictions based on the production of Cherenkov light may be preferred for regular use since the simulations behind such predictions are computationally less demanding.

As discussed in section 1.1, one may expect that the fraction of light blocked by the top plate to vary with cooling time. However, the results show that this fraction does not strongly depend on the cooling time of the assembly. Thus, the fraction of light blocked by the top plate, i.e. its transparency factor, can be estimated using a single cooling time, and this factor was found to be accurate to within 0.6% for other cooling times. This result was found to hold for all

assembly designs and masks studied. Furthermore, the transparency factor changed less than 0.2% as a function of the burnup of the assembly, which was lower than the uncertainty in the simulations. Accordingly, when calculating the transparency factor of an assembly, it is sufficient to perform one simulation, and the results can be applied to assemblies with any burnup and cooling time, with a low loss of accuracy. Additionally, when verifying assemblies, these results highlight that assemblies of the same design can be compared, and a grouping of assemblies into data sets according to burnup or cooling time is not necessary.

The results also show that the fraction of light blocked by the mask in the simulations changes only little as a function of the threshold angle. For a threshold angle in the range $0.3 - 0.6^\circ$, the fraction of light blocked by the mask changes less than 4%, and the change is systematic for all masks studied, with the fraction of light blocked by the mask increasing with increasing threshold angle. Consequently, any threshold angle in this range is acceptable when simulating DCVD image intensities.

4 Experimental studies

As noted in section 1.2, assemblies of the same type are often grouped in the same data set and are considered to be comparable, despite that physical differences can exist in the design of the top plate. Using image creation simulations and top plate masks, it is possible to determine the fraction of light blocked by the top plate, and thus determine a transparency factor for the top plate. The predictions can then be adjusted by this transparency factor, to make the predictions for assemblies of different designs comparable. This procedure was applied to a set of experimentally measured assemblies of different designs, to determine whether the adjustments to the predictions improve the accuracy of the verification.

4.1 Measurement campaign

A measurement campaign has been performed at Clab (the Swedish central interim storage facility for spent nuclear fuel) in 2017 on a set of 20 PWR 17x17 fuels with a range of burnups and cooling times (being part of the SKB50 set of fuels selected for research involving the U.S. Department of Energy Next Generation Safeguards Initiative [11]). These assemblies were selected to represent a wide range of fuel assembly properties, which may be encountered at safeguards inspections. The assembly properties are summarized in table 1. A total of five different assembly manufacturers were represented in this set, and by means of visual inspection it was concluded that the top plates exhibited noticeable differences between manufacturers. It was also noted that the top plate design appeared similar for all assemblies by the same manufacturer, which was interpreted as only one assembly design was represented for each manufacturer. For confidentiality reasons the designs are denoted by letters A-E in table 1.

Table 1: Summary of the PWR 17x17 assemblies included in the SKB50 data set, which were measured in this work.

Assembly design:	A	B	C	D	E
Number of assemblies:	1	8	2	1	8
BU [MWd/kgU]:	46	28-48	47	44	19-46
CT [years]:	18	17-22	9	10	10-33

4.2 Defining top plate transparency factors

To create the masks representing the top plate for each of the five PWR 17x17 designs in the SKB50 set, one fuel assembly image recorded from each design was selected, and an intensity threshold was applied to select the dark parts of the image. Similar to the simulation studies described in section 3.1, the threshold was set to 8% of the highest intensity.

To calculate the transparency factors of these five top plate designs, image creation simulations were run for the five assembly designs, for a burnup of 40 MWd/kgU and a cooling time of 10 years. Since the fuel rod placement and dimensions are nearly identical for all assemblies, the fuel assembly geometry was assumed identical in the second step, thus saving considerable computing time by only executing the second step once. For each simulated image, the transparency factor was calculated as the fraction of light that could reach the detector, as compared to the amount of light that could reach the detector without any mask. The transparency factors calculated in this way are shown in table 2.

Table 2: Top plate transparency factors for the PWR 17x17 assemblies of the SKB50 set.

Assembly design:	A	B	C	D	E
Mask transparency factor [%]:	44	48	43	45	51

4.3 Results

A comparison between the predicted and measured Cherenkov light intensities for the assemblies measured in this work is shown in figure 5, for predictions with and without adjustments using the transparency factors. The predictions were made using the method of [3] [6], and the irradiation histories were made available to the authors, courtesy of Vattenfall who operates the Swedish PWR plants.

As can be seen in figure 5, adjusting the predictions using the transparency factors improve the predictions. This results in a better agreement between the predicted and measured intensities, when all assemblies are treated as part of the same group. This can also be seen from the Root Mean Square Error (RMSE) of the difference between prediction and measurement for the whole

Figure 5: Comparison of the deviations between predicted and measured intensities for the 20 PWR 17x17 assemblies in the SKB50 set. Predictions were made with and without adjustments according to the top plate transparency factors. Dashed lines indicate 30% deviations, and assemblies deviating more than this require additional investigation [2]. Lower-case, blue letters show predictions without transparency factor adjustments, and upper-case, red letters are predictions with the adjustment applied. The letter indicates the assembly design, from table 1.

assembly set, which is 14.0% without adjustments and 10.7% after applying the adjustments. While this is a significant improvement to the agreement between measurements and predictions, there still appears to be some remaining systematic differences between assemblies of different designs, suggesting that the adjustment procedure may be improved further. The cause of this remaining systematic differences may be caused by the crude intensity threshold procedure used to obtain the masks, since smaller details regarding the top plate and are not visible in the obtained masks. It is possible that the results could be further improved if a better top plate description, and consequently a more accurate mask was available.

The assemblies of design B and E are numerous enough that they can be analysed separately, and they show a RMSE of 6.0% respectively 8.1%. Thus, if the predictions including a transparency factor adjustment could fully compensate for the systematic differences between assemblies, one may expect it to be possible to reduce the RMSE to the same level, also when analysing the full data set, including assemblies of different designs.

5 Conclusions and Outlook

This work has demonstrated the capabilities of simulating DCVD images with good qualitative agreement to measured images, using a relatively simple pinhole

camera model. Quantitatively, predictions based on simulated image intensities of PWR assemblies with varying burnup and cooling time show excellent agreement with prediction based on the production of Cherenkov light in an assembly, and the prediction of the two models agree within about 0.5%. This justifies the assumption made in the production-based prediction model, that the measured intensity is proportional to the produced one [3] [6].

In [12] it was shown that there are some systematic differences between assemblies of the same type but of different designs, and it was suggested that image simulations could be used to quantify these differences. This work demonstrates the feasibility of such a procedure, showing that it is possible to obtain top plate transparency factors using simulations of images, and applying masks to represent the top plate. These transparency factors can then be used to adjust predictions based on Cherenkov light production only, to correct for differences in light transport between assembly designs. This procedure allows assemblies of different designs to be compared with enhanced accuracy, and is especially useful in situations where only one or a few assemblies of a certain design is available.

The performance of the adjusted predictions were evaluated based on measurements of a set of 20 PWR 17x17 assemblies of five different designs. The agreement between prediction and measurement was improved from an RMSE of 14.0% to 10.7%, when introducing the transparency factors, and when considering all assemblies as part of the same group. However, the procedure used to find the masks was relatively crude, and one may expect better results if the masks could be created using high-quality photos or design blueprints. An alternative procedure could be to measure assemblies of various designs under controlled conditions, to obtain experimental values of the systematic differences between designs, and use that instead of the transparency factors.

While this work has focused on quantifying systematic differences introduced when comparing assemblies of the same type but with different top plate designs, the procedure may also be used to quantify the fraction of light blocked by a control rod cluster inserted into a PWR assembly. Introducing similar transparency factors into the intensity predictions would allow for assemblies with an insert to be analysed in the same data set as assemblies of the same type but without the insert. Further experimental data would however be required to assess the accuracy of this method on such assemblies.

Another issue, which is encountered when characterizing instruments used for partial defect verification is the lack of documented assemblies with substantial partial defects. While it is relatively easy to find assemblies with one or a few rods removed and/or replaced, documented assemblies with more than about 5% of the rods removed or replaced are difficult to find. Since assemblies with more removed or replaced rods are unavailable for experimental measurements, simulations are required to assess the response of a DCVD instrument to such assemblies. This work has demonstrated the capabilities of simulating DCVD images with a relatively simple and time-efficient pinhole camera model, which opens up the possibility to make simulations of assemblies suffering from various partial defects. In the long term this may allow for further development

the partial defect detection procedure used in DCVD measurements.

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