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Partial defect detection using the DCVD and a segmented Region-Of-Interest

Erik Branger*, Sophie Grape, Peter Jansson
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 safeguards instrument available to international nuclear safeguards inspectors. It is frequently used to verify fuel on the gross defect level, and approved for partial defect verification, i.e. to assess that parts of a fuel assembly have not been diverted. The current limit for partial defect verification with the DCVD is on the 50% level. In the verification process, an analysis methodology is used where the inspector places a Region-Of-Interest (ROI) around the fuel assembly and assesses the total Cherenkov light intensity within this region. The intensity is then compared to a predicted value, and deviations from the predicted value are used to flag fuel assemblies for further investigations.

In this work, we investigate a slightly different analysis approach, where the ROI is split into two or three segments to more accurately capture changes in light intensity in different regions of the captured image. The purpose is to increase the sensitivity of the DCVD to partial defects below the 50% level. Based on simulations of a Pressurised Water Reactor 17x17 fuel assembly, we conclude that a partial defect on the 30% level decreases the Cherenkov light intensity by at least 15% using one single ROI, by at least 20% using a ROI with two segments, and by at least 22% using a ROI with three segments. The analysis approach using two or three ROI segments instead of one thus appears to be more sensitive to partial defects, and can enable more accurate detection of partial defects on the 50% level as well as partial defect detection below the 50% level.

Validation of the approach using a limited set of measurement data of intact fuel assemblies supports that detection of light intensity reductions by 20% and 22% is possible, while ensuring that the false positive rate is kept sufficiently low. However, an optimization of ROI segment splits as well as a more extended validation of the approach is required before the method can be considered reliable and applicable to all fuel assemblies that the DCVD can verify today.

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

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1 Introduction to the DCVD partial defect analysis methodology

One of the many safeguards tasks undertaken by international inspectors from authorities such as the International Atomic Energy Agency (IAEA) or EURATOM is to measure spent nuclear fuel assemblies to verify that no nuclear material has been diverted. To aid the inspectors, a multitude of instruments have been developed [1], and one of the instruments available is the Digital Cherenkov Viewing Device (DCVD) [2]. The DCVD measures the Cherenkov light emitted by a spent fuel assembly stored in water. The detection of Cherenkov light is used to confirm that the object under study is highly radioactive [3]. The DCVD measures in the soft-UV range, where the Cherenkov light intensity is the highest in water.

When performing measurements with a DCVD, the instrument is typically mounted on the railing of a fuel handling machine, looking down into the water pool. The assemblies are measured where they are stored, and there is no need to move the assemblies. The result of a DCVD measurement is an image of the detected Cherenkov light emitted by a fuel assembly. By qualitatively analysing the presence and characteristics of the Cherenkov light, an inspector can verify that the object under study is a fuel assembly as opposed to a dummy object [2]. This is called gross defect verification. By quantitatively analysing the Cherenkov light emissions, the DCVD can also be used to perform partial defect verification, verifying that part of the fuel assembly has not been removed. However, partial defect verification requires a more comprehensive analysis of the measured data [4].

There are two methods used to detect partial defects in a spent fuel assembly using the DCVD. The first one is based on image analysis, where the DCVD software automatically identifies empty rod positions. This is done by comparing the recorded DCVD image with a template indicating the expected rod positions, and identifying bright spots that should be dark due to the presence of a fuel rod blocking the light. This method is predominantly used for BWR fuel assemblies, since they feature a more open top structure, and most rods can be visually identified. However, for rods covered by a lifting handle or other top structure, this methodology is of limited use.

The second method, which is the focus of this work, is based on comparing a predicted Cherenkov light intensity, calculated based on operator declarations, to the measured intensity [4]. Based on the simulations performed in [4], it is estimated that substituting 50% of the rods in an assembly with non-radioactive steel rods will reduce the Cherenkov light emission by at least 30%. Hence, if any measured intensity differs by more than 30% from the expected value, the assembly is flagged as an outlier requiring additional investigation, since it cannot be excluded that it may suffer from a partial defect.

Once the predictions and measurements are available, the assemblies are divided into groups where each group contains assemblies of the same fuel assembly design. Since all assemblies in a group are measured with the same instrument, in the same facility and share the same physical design, the relative intensities of the assemblies can be directly compared. For each group, a least-square fit is done to find the multiplicative constant that best relate the predictions of Cherenkov light emission to the measurements of the Cherenkov light intensity. This constant essentially takes into account how the measured Cherenkov light intensities are affected by the DCVD instrument properties, scattering and absorption of Cherenkov light in the water and Cherenkov light absorption in the fuel assembly.

Due to the fuel assembly design with long rods that tend to absorb most light rather than reflect it, the Cherenkov light emitted by an assembly is strongly collimated. Thus, when the DCVD is centred above the assembly, along an axis parallel to the rods, the measured intensity comes from the water within the assembly. To obtain the total emitted intensity of an assembly, the inspector must manually place a Region-Of-Interest (ROI) around each assembly using the DCVD software. All pixel values inside the ROI are then summed to provide a measure of the total Cherenkov light intensity, since the pixel values (after calibration) are proportional to the detected light intensity. The methodology of calculating the total intensity inside an ROI and comparing the value to a predicted value is applicable to any fuel assembly regardless of the physical design of the assembly, as any effects related to the design are taken into account by grouping the assemblies. The use of a single ROI is intuitive and straightforward, and not very sensitive to noise such as deformations in the measured image due to ripples on the water surface.

Due to the collimation of light, a correctly aligned DCVD measurement will see the centre of the assembly being brighter than the peripheral regions, with the central water-filled regions of the fuel assembly contributing the most. This was also noted for the simulation studies of a 50% partial defect, where the most difficult case to detect was the removal of rods near the periphery, requiring a 30% light reduction limit even when 50% of the rods are replaced [4]. Furthermore, in the case of a Pressurised Water Reactor (PWR) fuel assembly, the relative contribution of rods near the periphery is not only suppressed by the collimation, but also by the presence of a lifting handle that covers the peripheral regions of the fuel assembly top, blocking light from exiting. Hence, to improve upon the 50% partial defect limit, the analysis methodology need to be more sensitive to a light reduction near the periphery of the assembly, which is difficult to achieve with a single ROI. For this reason, we have investigated the partial defect detection performance using a segmented ROI, aimed at better capturing details on the light distribution in a measurement.

The aim of this work is to determine how the light intensity changes for a segmented ROI for fuel assemblies suffering a partial defect. We have chosen to use relatively few and large segments, both as a first step in investigating the performance of a segmented ROI, and also since the performance of a few, large segments should be similar to that of the single ROI with respect to noise and

other measurement errors. Based on simulated partial defects, we determine intensity limits for the various ROI segments, to be compared to the 30% light reduction limit currently applied for a 50% partial defect.

This paper is structured as follows: This section introduces the current DCVD verification methodology, based on an analysis using a single ROI. Section 2 explains the different ROI segmentations that were studied and section 3 presents the simulated partial defect cases studies. Section 4 presents the results of applying a segmented ROI to the partial defect cases, and section 5 summarizes the key results.

2 Segmented ROIs

While the radiation emitted by a single rod can produce some Cherenkov light at any location within the assembly, it will predominantly produce Cherenkov light in the immediate vicinity of the rod. This is a consequence of the presence of nearby fuel rods, which will significantly attenuate the gamma radiation further away from the rod emitting the radiation, and hence suppress the Cherenkov light production further away from the rod. Hence, in principle it would be ideal to split the ROI in as many segments as there are rods, with one small ROI covering each rod and its immediate surroundings but not any other nearby rods, as was done in [5]. This will achieve the maximum sensitivity to possible manipulations of individual rods. However, such an ROI would be relatively small, on the order of 20 pixels by 20 pixels, which in turn would make the ROI sensitive to noise. In addition, ripples on the water surface can deform the image so that part of the rod may be entirely inside an ROI in one measurement but partly outside it in the next for such a small ROI, thus introducing a significant systematic error. It would also be sensitive to details in the construction of the assembly top plate and lifting handle, meaning that the exact design must be known and considered in the analysis. Thus, the method would no longer be directly applicable to all measured fuel assemblies, and would require adaptations for each measured fuel design.

As a compromise, we consider splitting the ROI into two or three segments instead of one. These segments will be large enough to have low sensitivity to noise and structural details and therefore be applicable to any fuel assembly design, while still providing additional details about the intensity distribution in a measurement. As mentioned in the previous section, due to the collimation of light, the centre of the assembly will give the largest contribution to the total Cherenkov light intensity, and the intensity will decrease as the distance to the centre is increased. To better capture this light distribution, we have in this work considered four different ROI segmentations, two of which have two segments and two having three segments. In each case, one circular and one squared segmentation is investigated. The circular split is meant to capture the light distribution due to the collimation, while the squared geometry better captures the square lattice of the rods in the studied PWR assembly. The segmented ROIs are shown in Figure 1. In the remainder of this work, the ROI

segmentation will be referred to by a number and a letter (i.e. 2c, 2s, 3c, 3s), where the number identifies the number of segments, and the letter is “c” for a circular segmentation or “s” for a square one. An example of a simulated and a measured image with the ROI segments marked is shown later in figure 4.

Figure 1: The four ROI segmentations studied in this work. Each segmentation is referred to by a number, indicating the number of segments, and a letter “c” or “s”, indicating circular or square segmentation.

To determine the size of the segments, two different methods were tried:

1. equal surface area for all segments,
2. equal predicted total light intensity for all segments based on simulated DCVD images of a PWR 17x17 fuel assembly as described in [6].

When applying the equal-area segmented ROI to the simulated image, it was found that for the 3c and 3s segmentations, the outer segment ended up covering predominately the lifting handle. Consequently, the outer region corresponding to 1/3 of the top plate area contained less than 3% of the total intensity in these cases, which made it far too sensitive to noise to be useful. Thus, the second method was used, where each segment is expected to contain the same Cherenkov light intensity. The relative area of each segment found in this way is shown in Table 1. Further studies are required to assess if the segment sizes are suitable for all assembly designs, or if there is a need to have different segmentation options for assemblies of significantly different designs, such as Boiling Water Reactor (BWR) and PWR assemblies.

Table 1: Relative area of the ROI segments in Figure 1. Each segment contains the same Cherenkov light intensity when applied to a simulated PWR 17x17 DCVD image. Segments in the table are denoted “out” for the outermost segment, “mid” for the middle one and “in” for the inner one.

ROI type	1	2c		2s		3c			3s		
Segment	-	out	in	out	in	out	mid	in	out	mid	in
Area [%]	100	70	30	72	28	61	20	19	60	23	17

3 Simulated partial defects

The aim of this work is to investigate the possibility of reliably detecting partial defects below the 50% level using the segmented ROI approach. Since there are no assemblies suffering from significant partial defects with rod substitutions available to the authors for this analysis, the performance of the segmented ROI analysis to detect partial defects needs to be assessed based on simulated DCVD images. We have chosen to simulate partial defects on the 30% level for a PWR 17x17 fuel assembly, since it is a noticeable improvement from the 50% level, while still being a significant partial defect that is expected to affect the Cherenkov light intensity. Furthermore, currently used safeguards instruments can perform partial-defect detection on the single-pin level using Passive Gamma Emission Tomography, PGET [7] and on the 50% level using the DCVD or the FORK [8], hence the verification of spent fuel assemblies could be further enhanced by the availability of instruments capable of detecting partial defects in the 10-40% range [9].

The simulations were performed using the methodology outlined in [6], consisting of three steps. First, the burnup of a nuclear fuel assembly was simulated to assess the abundance of radioactive fission product isotopes in the fuel material, using the program ORIGEN-ARP [10]. Second, the radiation was transported in a PWR17x17 geometry using the Monte-Carlo code Geant4 [11], where Cherenkov light was produced in the water and propagated to the assembly top. In the third step, a pin-hole camera was simulated, to turn the Cherenkov photons into an image.

Two different partial defect patterns on the 30% level have been studied for the PWR 17x17 fuel assembly, shown in Figure 2. For both patterns, three rod substitution cases corresponding to different substitution materials were considered: fresh fuel rods, compact steel rods and helium-filled rods. These substitutions were selected to represent a high-density, a medium-density and a low-density substitution case. The substituted rods were simulated with the same optical surface properties as the regular rods (90% absorption, 10% diffuse reflection, as in [6]). Other reflectivities may be considered, but are outside the scope of this work. A fourth partial defect scenario was also simulated where the rods were removed without replacement, leaving a water gap in the fuel assembly.

The partial defect pattern denoted as case 1 in Figure 2 is the same as that used in [12]. The substitution is symmetric and concentrated to the edges of the assembly, making the case one of the more difficult ones for the DCVD to detect. The second simulated case, referred to as case 2 in Figure 2, was created to be even more challenging for the DCVD. In case 2, the rods are primarily substituted in the outermost regions, with as many rods as possible in the centre remaining intact. Since the lifting handle covers much of the outermost rods, these rods will contribute the least to the detectable Cherenkov light intensity. Furthermore, the corners of the assembly remain intact, since Cherenkov light from three corners are visible due to holes in the top structure.

In this work, only the total light Cherenkov intensities in the selected ROI

Figure 2: The two simulated partial defect patterns on the 30% level. Black circles represent low-enriched uranium spent fuel rods. Grey circles represent manipulated rods (substituted or removed rods). The guide tubes are shown as white.

segments are analysed. Detection of partial defects by analysing changes in the expected symmetrical light intensity distribution is not considered. Such studies would however open up for additional ways of detecting partial defects both with other (more non-symmetrical) substitution patterns as well as partial defects on other levels, but are outside the scope of this work.

4 Results

4.1 Predicted Cherenkov light intensity reductions for partial defects on the 30% level

In this work, the total Cherenkov light intensity was estimated for each of the segmented ROIs as well as the default non-segmented ROI, for both an intact fuel assembly and the case 1 and case 2 modelled partial defect patterns. Tables 2 and 3 show the reduction of the Cherenkov light intensity as compared to the Cherenkov light intensity from the intact fuel assembly, for each ROI segment of case 1 and case 2 and for all four substitution materials. Due to the Monte-Carlo nature of the simulations, the simulated intensity values in each ROI segment have a statistical uncertainty in the order of 0.4%. Hence, the values presented in Tables 2 and 3 are expected to have a statistical uncertainty that is less than one percent unit. Systematic errors and uncertainties are not assessed, as this is difficult to do based on simulations only and since no measurements of these partial defect assemblies exists. Some systematic sources of uncertainty are identified and discussed in section 4.3.

As previously noted, the current partial defect detection methodology is based on detecting a 30% reduction in the Cherenkov light intensity, corre-

sponding to a partial defect level of at least 50%. As seen in Table 2 and 3, for the two partial defect cases, no intensity change reaches 30% with the unsegmented ROI. Thus, irrespective of substitution material, these partial defect cases cannot be detected with the current methodology. The substitution case most difficult to detect is with helium rods, where the Cherenkov light reduction is only 13%, well below the current 30% limit.

Table 2: Modelled Cherenkov light reduction for an ROI split into two segments for the partial defect cases 1 and 2.

ROI type	1	2c		2s	
	-	outer	inner	outer	inner
Intact fuel	0%	0%	0%	0%	0%
Case 1, fresh fuel	21%	33%	10%	32%	11%
Case 1, steel	18%	28%	8%	27%	9%
Case 1, helium	13%	20%	6%	20%	6%
Case 1, removal	-28%	-48%	-1%	-51%	-5%
Case 2, fresh fuel	14%	24%	4%	24%	4%
Case 2, steel	14%	24%	4%	24%	4%
Case 2, helium	13%	22%	4%	22%	4%
Case 2, removal	-9%	-21%	3%	-21%	3%

Table 3: Modelled Cherenkov light reduction for an ROI split into three segments for the partial defect cases 1 and 2.

ROI type	1	3c			3s		
	-	outer	middle	inner	outer	middle	inner
Intact fuel	0%	0%	0%	0%	0%	0%	0%
Case 1, fresh fuel	21%	36%	21%	7%	34%	23%	7%
Case 1, steel	18%	31%	18%	6%	29%	19%	6%
Case 1, helium	13%	23%	12%	5%	22%	13%	5%
Case 1, removal	-28%	-53%	-41%	8%	-53%	-40%	9%
Case 2, fresh fuel	14%	29%	11%	3%	30%	10%	3%
Case 2, steel	14%	27%	12%	3%	30%	9%	3%
Case 2, helium	13%	24%	12%	3%	27%	9%	3%
Case 2, removal	-9%	-36%	6%	2%	-37%	8%	2%

For the segmented ROIs, the outer segments, where the rod substitutions occurs, are the ones mostly affected by the substitution. For the ROI split into two segments, shown in Table 2, the outer segment shows a Cherenkov light reduction of 20% or more, while the inner segment is less affected and can have a reduction of only 4% depending on substitution material and practically no change for removal without substitution. Hence, the outer ROI segments is noticeably more sensitive to the partial defect cases compared to a single ROI. In general, case 2 results in a lower Cherenkov light reduction, with exception if

the rods are substituted with helium rods. For both partial defect cases, helium rod substitutions result in the lowest reduction, and are thus the most difficult cases to detect. The partial defect cases where the rods are removed without replacement show a negative reduction i.e. an increase in light intensity, which is caused by a combination of the extra water in which Cherenkov light can be created and a reduced gamma-ray attenuation. This case is however expected to be identified by an inspector doing a visual inspection, as the removal without substitution will create easily identifiable bright spots in the assembly. In order for the removal to not be easily visually identified, all removed rods must be located under the lifting handle, and this cannot be done if 30% or more of the rods are removed.

For the case of an ROI split into three segments, shown in Table 3, the reduction in Cherenkov light intensity is more pronounced than for the 2s and 2c ROI cases, and with replacement of steel or fresh fuel rods, the reduction in the outermost ROI segment is close to 30%. Assuming that the ROI segments are large enough to not significantly be more affected by noise as compared to the single ROI, i.e. that the detected count rate in each segment is reasonably large, these results suggest that verification on the 30% partial defect level is possibly in these cases. The most difficult to detect case is substitution with helium rods, where an intensity reduction of about 22% can be expected.

For partial defect case 2, the ROI splits into square segments tend to be more sensitive to partial defects, but this is mainly due to that the partial defect follows the ROI segmentation. For the first partial defect case, the substitutions have a similar effect on both types of ROI segmentations. Hence, with respect to partial defect detection performance, either type of segmentation can be used, though the choice of segmentation may be affected by other parameters.

4.2 Predicted Cherenkov light intensity reductions for partial defects levels other than 30%

Investigations of partial defects on other levels than 30% were studied only for the case when the diverted spent fuel rods were replaced with fresh fuel rods. For substitutions with other materials with different gamma attenuation properties, dedicated simulations are required for each partial defect substitution pattern, which is computationally expensive. However, for substitution with fresh fuel rods, the Cherenkov light contributions can be considered on a per-rod basis, and included in the final result for all non-substituted rods in the assembly. This procedure facilitates studies of practically any partial defect level, where substitution is made with a non-irradiated material with similar gamma attenuation, based on a single simulation. Since there are no known fuel assemblies suffering a partial defect, it is difficult to assess how reasonable this substitution scenario is. However, it does seem reasonable that the substituted material will have the same weight, density, and similar gamma attenuation properties, hence there is reason to consider this scenario.

Figure 3 shows the Cherenkov light intensity reductions in the various ROI segments as a function of the fraction of substituted rods. The individual rods

Figure 3: The largest reduction in Cherenkov light intensity in any ROI segment as a function of the fraction of rods substituted with rods having the same attenuation as spent nuclear fuel. The rod substitution is done to minimize the intensity reduction for the unsegmented ROI, corresponding to the most challenging case for the current methodology to detect. The statistical uncertainty is too small to be seen in the plot.

were substituted in an order that reflected their relative contribution to the total intensity, as measured by an unsegmented ROI. Hence, the resulting partial defect case identified in this way is the most difficult one to detect using the current methodology. For the segmented ROIs, Figure 3 shows the intensity reduction in the segment suffering from the largest reduction, which in this case is always the outer segment. Note that in Figure 3, the statistical uncertainty due to the Monte-Carlo nature of the simulations are too small to be seen.

Experience with the currently used methodology shows that a 30% intensity difference is a feasible limit, and since the segmented ROI used here has relatively large segments the performance of the segmented ROI is expected to be similar compared to the single ROI. A reasonable first approach is then to assess the performance of the segmented ROI on a 30% intensity difference level. As can be seen in Figure 3, analysis using any segmented ROI is more sensitive to partial defects compared to using an unsegmented ROI. The currently applied partial defect detection limit of 50% results in a 28% light intensity reduction using an unsegmented ROI, but in light intensity reductions of 47% to 58% using the segmented ROIs. The rods contributing the least to the total intensity are found predominantly near the periphery of the assembly, and the outermost segment in a segmented ROI are more sensitive to diversions in this region as compared to a single ROI. Hence, the segmented ROI approach appears to be able to both detect partial defects on the 50% level with greater certainty compared than with a single ROI, and to be able to detect partial defects below the 50% level.

In Figure 3 we can see that a 30% light intensity reduction occurs for a 52% partial defect using an unsegmented ROI approach. The same light intensity reduction corresponds to a 39% partial defect level if the ROI is split into two segments, and to around a 34% partial defect level if the ROI is split into three segments. Assuming that the intensity from a segment can be both predicted and measured with a comparable accuracy as the intensity of the single ROI, this suggests that an improved analysis using segmented ROIs can make the DCVD sensitive to partial defects on the 30% level for this substitution scenario. This is a significant improvement in partial defect detection capability. However, replacement with fresh fuel rods is not the most difficult-to-detect case, and more stringent limits will be required when assessing a partial defect with other substituted materials for arbitrary substitution patterns, as noted in Table 2 and 3.

4.3 Validation of results with measurement data from intact spent nuclear fuel assemblies

To test the performance of segmented ROI analysis on experimental data, a set comprising measurements of 16 PWR 17x17 fuel assemblies were used. None of these assemblies are known to suffer from partial defects, but can be used to evaluate the performance of Cherenkov light analysis using one or multiple ROIs. The assemblies are part of the so-called SKB50 set, and have been measured using several different safeguards instruments [13]. The 16 assemblies are of two different designs (manufacturers) with eight assemblies per design. The most significant difference between the designs with respect to DCVD measurements was found to be the different top plate designs, which to different extent prevent Cherenkov light from exiting the fuel assembly and be detected. The assemblies with the same design were visually determined to be indistinguishable. The two assembly designs will be referred to as design B and design E, following the convention used in [6].

For each assembly, the expected intensity as predicted in [6] is used. The predictions are easily adopted to the ROI segments used proposed here, since all ROI segments are expected to contain the same fraction of the total light intensity. Hence, for every ROI, the predicted total light intensity is distributed equally over the segments. The predictions in [6] include prediction for the light intensity caused by the near-neighbour effect, i.e. that Cherenkov light in an assembly is caused by radiation originating from a nearby assembly. These near-neighbour predictions takes into account how the storage situation affects the measurements. Since the distribution of the near-neighbour Cherenkov light within the segmented ROI in a measurement is not entirely known, it is naïvely assumed that the contribution is evenly spread out over the whole image and thus affect each ROI identically.

The results of applying an ROI with two segments to the measurement data is shown in Table 4. The table shows the average difference between measured and predicted Cherenkov light intensity for the two groups each containing eight fuel assemblies, together with the root mean square error (RMSE) in the dif-

ferences, showing the accuracy of the methodology of comparing measurements and predictions.

Table 4: Average difference between measured and predicted Cherenkov light intensity for an ROI with two segments, and the RMSE of the difference. The predictions assume that the near-neighbour contribution is spread out evenly across each ROI segment. A positive value for the average error means that the measured intensity is higher than the prediction.

ROI type	1	2c		2s	
	-	outer	inner	outer	inner
Design B					
Average difference	-0.8%	2.9%	-5.0%	8.6%	-12.6%
RMSE	8.2%	9.0%	7.6%	9.6%	6.7%
Design E					
Average difference	-1.4%	-1.7%	-1.2%	4.7%	-8.6%
RMSE	6.3%	5.7%	7.4%	5.3%	9.0%

Table 5: Average difference between measured and predicted Cherenkov light intensity for an ROI with three segments, and the RMSE of the difference. The predictions assume that the near-neighbour contribution is spread out evenly across each ROI segment. A positive value for the average error means that the measured intensity is higher than the prediction.

ROI type	1	3c			3s		
	-	outer	middle	inner	outer	middle	inner
Design B							
Average error	-0.8%	14.9%	-16.1%	-6.9%	11.2%	-10.4%	-6.5%
RMSE	8.2%	9.3%	8.9%	7.1%	9.4%	6.6%	9.8%
Design E							
Average error	-1.4%	11.6%	-18.1%	-2.3%	8.6%	-15.3%	-0.8%
RMSE	6.3%	5.1%	9.0%	8.0%	5.5%	10.8%	6.9%

It can be seen in Table 4 that for an ROI split into two segments, the outer segment has a measured Cherenkov light intensity systematically above the prediction, i.e. a positive error, and the inner segment is systematically below the predictions, i.e. a negative average error. Likewise, for an ROI split into three segments, Table 5 show a similar result, with the middle segment having measurements below the prediction to a higher degree compared to the inner segment. A visual analysis of the measured images with ROI segmentation, as shown in figure 4, suggests that this is caused by a slight difference between the simulated and measured fuel assembly sizes compared to the used ROI size, where the ROI is slightly smaller in the measurements. For both the circular and squared ROI segmentations, the simulated image has bright guide tubes close to the segment edges. In the measurements, since the ROI is slightly smaller the

guide tubes tend to be located more towards the outer regions. Furthermore, the PWR assembly has top structures covering the edges. In the measurements, the slightly smaller ROI results in that part of these top structures are outside of the ROI, hence a larger fraction of the pixels in the outermost region are of non-covered parts of the assembly, leading to a systematically higher intensity than predicted. A comparison between the simulated and a measured image is shown in figure 4.

Figure 4: Left: A simulated DCVD image of a PWR 17x17 assembly, with the 3c ROI marked. Right: A measured image of a PWR17x17, with the 3c ROI marked.

While it is possible to manually adjust the ROI positions and size in this analysis for the best possible match, we have here chosen to use the same ROI placement as was used in the original measurement in order to base the analysis on realistic data. Another solution to this issue would be to choose the ROI segment sizes and boundaries based on the assembly design, to ensure that any bright spots or features are kept clearly inside a specific ROI segment. In principle, an optimal ROI segmentation can be found and applied for each fuel assembly design, ensuring robust measurements. While an optimized split could mean that some ROI segments have a lower intensity compared to others and hence could have a higher uncertainty in the measurements, the method is expected to be more robust, which could potentially further reduce the RMSE values of the segments. Software for automatic ROI resizing and positioning could also help in systematically ensuring a good ROI placement.

Another issue that is observed is that in the measured images, the assemblies are sometimes slightly rotated, while the ROI is never rotated, as exemplified by Figure 5. As a result, water and storage rack structures around the fuel assembly are sometimes visible in the periphery of the ROI. For a segmented ROI analysis approach, this would affect the intensity in the outer segment. Structural components result in dark regions in a measured image, whereas water gaps adds Cherenkov light intensity to the ROI. Here, this issue is easily overcome by ignoring pixels very close to the edges if they are bright, since

the edges should contain parts of the fuel assembly covered by top structure, and hence be very dim. However, especially for BWR assemblies which do not have any such structure covering the edges, a careful placement of the ROI is necessary to ensure that regions outside of the assembly are not included inside the ROI. The development of software to automatically place and rotate the ROI could help ensure that only the spent fuel assembly is within the ROI, without requiring additional inspector work during a measurement campaign. This would also further reduce the RMSE of the outer segment, making the method more reliable.

Figure 5: Left: An ROI placement that contains only the fuel assembly. Right: An ROI placement where the ROI is rotated with respect to the fuel assembly. The blue regions are outside the assembly, and may contribute additional light that is expected to be excluded. Note that this image does not feature the top plate or lifting handle, which would cover the periphery of the assembly.

Tables 4 and 5 present results for predictions assuming that the near-neighbour effect is evenly distributed across the assembly. However, it can be expected that the range of gamma rays originating from neighbouring assemblies decrease with increasing distance from the neighbouring fuel assembly. If the predictions are adjusted so that the near-neighbour contribution only affects the outer segments instead of all segments equally, the average difference between measured and predicted Cherenkov intensity for design B fuels decrease somewhat, while for design E fuels the average error instead increases. Note that the assembly prediction for this comparison is still distributed evenly across the ROI segments. It is thus concluded that the best match between prediction and measurement is expected to occur for a more sophisticated near-neighbour model that distributes the near-neighbour contribution as a function of distance. However, the development of such a model would require access to more measurement data and significantly more computational resources, and is outside the scope of this work.

In the current partial defect detection methodology, a 50% partial defect level is estimated to cause at least a 30% reduction in intensity, and the dif-

ference between measurements and predictions is compared to this 30% limit. For the 30% partial defect cases simulated here, Tables 2 and 3 shows that the methodology needs to be able to detect a 20% intensity reduction in the outermost segment for an ROI with two segments, or a 22% intensity reduction in the outermost segment for an ROI with three segments. The RMSE values in 4 and 5 are at most 9.6% and 10.8% respectively, and 95% of all assemblies are expected to fall within twice the RMSE. Thus, for fuel assemblies with an uncertainty as found in Tables 2 and 3, 95% of all assemblies are expected to deviate less than 19.2% and 21.6% respectively, which are below but very close to the limits of 20% and 22%. Thus, for fuel assemblies with this level of uncertainty, it is possible to apply the 20% and 22% intensity limits, while ensuring a less than 5% false positive rate. Since we do not have any measurements of fuel assemblies suffering a 30% partial defect, we cannot assess the false negative rate experimentally. For this reason, we only compare measured intact fuels to the intensity limits set by the partial defects studied, following the procedure used in [4].

Furthermore, out of the 16 measured fuel assemblies in Tables 4 and 5, only one fuel assembly deviates more than 20% and 22% respectively for the outermost region. This significant deviation is partly explained by the systematic under-prediction seen on the outer region. With more accurate predictions of the intensity per ROI segment, this assembly will still be found to be more intense than expected, but within the intensity limits. Hence, it seems feasible to apply these detection limits for a segmented ROI approach, while keeping the false positive rates low when using the current verification methodology of comparing predictions to measurements. However, an improved ROI segment intensity prediction is required for reliable results. Additionally, more measurement data is required to reliably assess the performance of the methodology with segmented ROI:s to verify that a false positive rate below 5% can reliably be achieved.

5 Conclusions and Outlook

The result of a DCVD measurement is an image of the detected Cherenkov light, emitted from a spent fuel assembly. In the current partial defect detection methodology, aimed at detecting partial defects on the 50% level, only the total Cherenkov light intensity from one unsegmented ROI is used, although the image itself contains more information. In this work, we have investigated the possibility of splitting the single ROI into two or three segments, in order to study the feasibility for the DCVD to also detect partial defects on lower levels than the current 50% level. Two and three segments were chosen to ensure that the methodology was not significantly more sensitive to noise or presence of structural details compared to the currently used methodology. That means that the analysis methodology with multiple segmented ROI:s may be directly implemented in the evaluation procedure today.

Two different partial defect patterns were studied, where 30% of the rods

were substituted with either fresh fuel rods, steel rods, helium filled rods or removed without replacement. For the simulated PWR 17x17 geometry, the DCVD is less sensitive to substitution of rods near the periphery of the fuel assembly. This is due to that the light emitted from the top of the assembly is highly collimated and that the lifting handle covers this region. The simulation results indicate that neither of the studied partial defect cases would be detected by the currently used methodology, since the Cherenkov light intensity reduction in the most challenging case is only 13%, which is considerably lower than the currently required 30% reduction limit (on the 50% partial defect level). However, using the segmented ROI approach, it is clear that the reduction in detected total Cherenkov light is more significant in peripheral regions, and can be detected more easily by a segmented ROI. However, the reduction is 20% for a ROI with two segments and 22% for a ROI with three segments, which is lower than the current 30% limit. Whether or not the DCVD is able to reliably detect Cherenkov light intensity reductions on the 20% level or not remains to be experimentally verified on a large data set.

Applying the segmented ROI methodology to a limited set of experimental data, it appears that the uncertainty in the difference between prediction and measurement is low enough that a 20% deviation for an ROI with two segments or a 22% deviation for an ROI with three segments can reliably be detected. However, a larger experimental data set is required to verify that the proposed methodology is robust and reliable. Additional data is also required to ensure that the methodology is applicable to all fuel assembly designs, and not only to PWR 17x17.

The segmented ROI approach would benefit from automated fuel assembly detection and ROI positioning, to ensure that the ROI boundaries match the measured assembly without additional inspector intervention. It may also be necessary to use different ROI segment sizes or boundaries for different assembly designs, to ensure that no bright or dark region in an assembly end up in the periphery of an ROI segment, where ripples on the water surface may shift its position from one ROI segment to another. This work has considered two simple segmentations, a square and a circular one, but more sophisticated segmentations can be considered to optimize the robustness of the methodology, both with respect to the number and the shape of the segments. However, if smaller segments are used than here, it will become important to assess the effect of ripples on the water surface deforming the image, and the systematic errors that are introduced due to this effect. It may also be reasonable to create an optimized ROI segmentation for every fuel assembly design, to ensure robust results for any design encountered in a measurement campaign.

Further studies are also required to better characterize the near-neighbour effect, and especially the range of this additional Cherenkov light contribution, to accurately compensate for the effect in all ROI segments. It must also be investigated how the different partial defect scenarios affect the near-neighbour contribution, and how they impact the intensity reduction limits.

Finally, the segmented ROI methodology is a direct development of the currently used methodology, but it should be investigated if other methodologies

analysing the global light distribution can give similar or even better results. Such methodologies could be based on for example image analysis, or in fitting an expected, global intensity profile to the assembly intensity distribution.

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