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Combining DCVD measurements at different alignments for enhanced partial defect detection performance

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ABSTRACT

In the current Digital Cherenkov Viewing Device (DCVD) measurement methodology, the DCVD is aligned over the centre of a fuel assembly when measuring emitted Cherenkov light. Due to the collimation of light, and due to the lifting handle of PWR fuel assemblies covering the fuel periphery, the DCVD is more sensitive to partial defects near the fuel assembly centre than near the periphery. Here, we investigate the sensitivity of the DCVD for detecting partial defects for different instrument alignments. By performing measurements at both the centre and near the assembly periphery, more accurate measurements near the periphery can be obtained.

DCVD images were simulated for different partial defect scenarios with 30% of the fuel rods removed or replaced with low, medium or high-density rods. Simulations were run with different DCVD alignments, and the Cherenkov light distribution in the images were quantitatively analysed and compared to simulated images for a fuel assembly without defects. The simulation results were also compared with measurements of intact spent fuel assemblies.

The simulations show that the local Cherenkov light intensity deviation due to a partial defect is not sensitive to the alignment. Hence, the current methodology is robust, and will not benefit from measuring at different alignments. Regarding the signal-to-noise ratio, combining measurements at different alignments can improve the measurements. However, the improvement is modest, and for the DCVD it may be preferred to simply use the current methodology and make longer measurements. For future autonomous Cherenkov measuring systems, combining images can be a way of improving the quality of the measurements.

Keywords: Nuclear fuel, partial defect verification, Cherenkov light, DCVD.

INTRODUCTION

Verifying spent nuclear fuel is one of the many tasks performed by international inspectors, to verify that no nuclear material has been diverted. A multitude of instruments have been developed to perform Non-Destructive Assay (NDA) on spent nuclear fuel [1], by measuring radiation emitted by the fuel. Due to the intense radiation emitted by the fission products and minor actinides, it is not possible to directly measure the low-intensity emissions from the fissile nuclear material. Instead, the measurement aims at verifying whether the emitted radiation signature is consistent with the presence of spent nuclear fuel material, and with operator declared fuel parameters such as Burnup (BU), Initial Enrichment (IE) and Cooling Time (CT).

One of the instruments available to international inspectors is the Digital Cherenkov Viewing Device (DCVD). The DCVD measures the Cherenkov light produced by a spent fuel assembly in wet storage. The Cherenkov light is produced predominantly by gamma-ray emissions from fission products in the fuel, which Compton-scatter on electrons in the water. If these electrons obtain sufficient energy, they will radiate measurable Cherenkov light in the water. Thus, the intensity and characteristics of the Cherenkov light can be used to determine whether an object is a spent nuclear fuel assembly or a dummy object (so-called gross defect verification). The DCVD is also capable of quantitatively measuring the Cherenkov light emissions, which can be used to verify that parts of the fuel assembly have not been diverted (so-called partial defect verification). Since measurements with the DCVD are relatively fast and non-intrusive (no fuel movement required, nothing inserted into the water), enhanced partial defect detection capabilities would allow the instrument to be more widely and it could also be a valuable alternative to other instruments that require longer measurement times or are more intrusive.

In the current DCVD measurement methodology, measurements are performed from one position above the spent nuclear fuel, aligned above the fuel assembly centre along the axis of the fuel assembly. However, due to the strong collimation of Cherenkov light inside the fuel assemblies, the light intensity distribution in the measured DCVD images will depend noticeably on the alignment, which is the most intense at the position above which the DCVD is aligned, and decreases with increasing distance from that point.

The goal of this work is to investigate whether using multiple measurements from different alignments can make the instrument more sensitive to partial defects, by providing higher-quality measurements of regions away from the centrally aligned position in the current methodology. Performing measurements from multiple alignments is a departure from the current methodology and will make the total measurement time per fuel assembly longer. However, it could possibly prove useful in certain scenarios where the current methodology is not sensitive enough and further assessments are required, or prior to placing fuel in difficult-to-access storage, where a more detailed verification may be warranted.

CURRENT DCVD MEASUREMENT METHODOLOGY

There are several methodologies used when analysing DCVD measurements, depending on the objectives; one targets gross defect verification and two targets partial defect verification.

- For *gross defect verification*, the light distribution and light collimation by the fuel assemblies is qualitatively investigated, to determine if the light distribution is consistent with that from spent nuclear fuel or from with a non-radioactive dummy object.
- One method for *partial defect verification* uses image analysis to automatically detect removed rods in visible positions, and highlights those to the inspector using a template detailing the expected fuel rod positions in the image. This method is predominantly used on BWR fuels, since the rods are not covered by a top plate.
- The other, more general *partial defect detection* methodology quantitatively estimates the Cherenkov light emissions, and compares the measured intensities to predicted intensities, based on the operator declared fuel parameters BU, IE and CT. Currently this methodology can be used to detect partial defects where 50% or more of the fuel rods have been replaced with non-radioactive substitutes. Such a diversion would lower the Cherenkov light intensity by at least 30% [2].

When performing a measurement of a fuel assembly, the DCVD is positioned centrally above the fuel assembly, along the axis of the fuel assembly. The fuel assembly axis may be slightly different from the vertical direction, should the assembly be slightly tilted. Once aligned, the inspector places a Region-Of-Interest (ROI) closely around the fuel assembly in the image. Five measurements are performed and averaged over, and after removal of the background (which is approximated as the lowest intensity pixel in the image created as an average over the five images), the pixel values inside the ROI are summed over to provide the total Cherenkov intensity. The averaging is done to reduce the effect of noise, such as ripples on the water surface distorting the image, and noise in the detector electronics. Once all fuel assemblies have been measured, a least-squares fit is used to find the multiplicative constant that relates the predictions to the measurements. This constant takes care of effects that are common for all measurements, such as Cherenkov light lost due to scattering and absorption in the water, distance between the fuel and the DCVD, and the efficiency of the detector electronics. After the fit, any assembly with a light intensity deviating more than 30% from the predicted one is identified and marked as a possible partial defect that requires further investigation. Due to the strong collimation of light by the fuel assembly structure, the DCVD detects less light and is thus less sensitive towards the peripheral regions of the assembly where partial defects are more difficult to detect [3].

The goal of this work is to investigate if measurements taken at additional alignments can provide useful data to more reliably detect substitutions in the peripheral regions. Due to the collimation, if a measurement is aligned e.g. over the periphery of an assembly, the periphery will be the most intense part. This could potentially improve the performance for detecting partial defects near the periphery, at the aligned position. By combining measurements taken at different alignments, the Cherenkov light intensity contribution from the periphery could be increased, allowing a more accurate analysis of the Cherenkov light in those regions, as compared with the current methodology.

DCVD IMAGES AT DIFFERENT ALIGNMENTS

To investigate the partial defect detection performance of the DCVD at different alignments, images from previously simulations of two partial defect scenarios [3] were used. 30% of the fuel rods in a PWR 17x17 assembly were substituted in different patterns, corresponding to 80 substituted rods in each case. The two cases are shown in Figure 1.

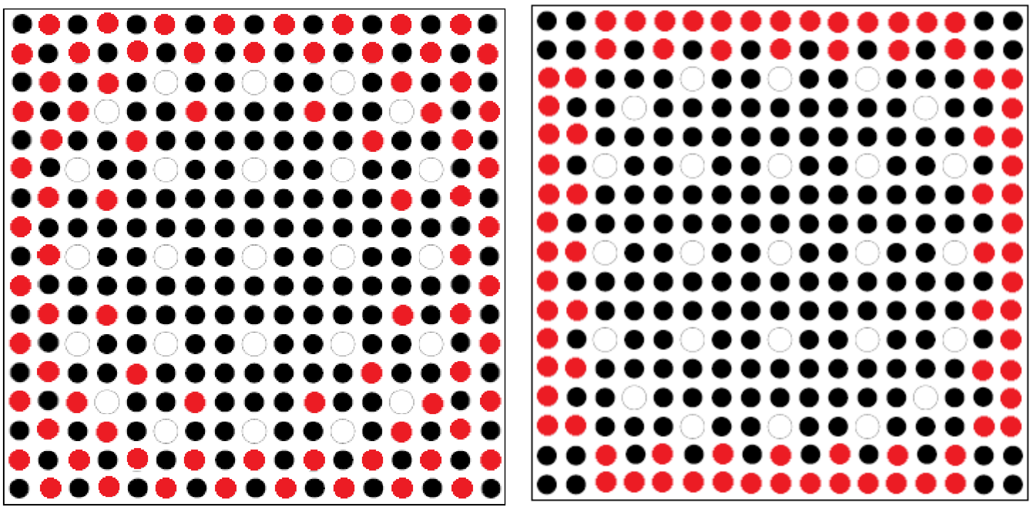

Figure 1. The two partial defect scenarios studied, scenario 1 (left) and scenario 2 (right). Black circles indicate normal fuel, red circles indicate substituted rods, and white circles indicate guide tubes and the central instrumentation tube.

The first case (Figure 1 left) is the same as case 6 in [4], where predominantly rods near the periphery were substituted. The second case (Figure 1 right) was found in [3] to be the most difficult to detect case for the DCVD, with substituted rods located only near the periphery, and with the corners intact to retain intensity in the top plate holes at the corners. Each case was run with three substitution materials: helium-filled rods, steel rods and unirradiated uranium rods, corresponding to a low, medium and high-density substitution case. Simulations were previously also run for rod removal without substitution. However [3] found that for a 30% removal, visible rods need to be removed which makes that case is easy to spot by an inspector, thus rod removal was not considered here.

For each simulated case, images were created using the procedure in [5]. In short, first the gamma emission spectra and intensity of a reference PWR 17x17 fuel assembly with a BU of 40 MWd/tU and a CT of 10 years was simulated using ORIGEN-ARP [6]. Secondly, the radiation transport was simulated in the fuel geometry using Geant4 [7], to obtain the Cherenkov light emissions from the top of the fuel assembly. In the third step, the Cherenkov photons were transported to a pin-hole camera, to form an image, and a mask representing the top plate was added. For this work, the steps 1 and 2 were re-used from earlier work such as [3], and the third step was repeated to obtain simulated images at various alignments. The simulated aligned positions started at the centre, and moved right or down in steps of 2 cm to a maximum of 10 cm in each direction. Due to the symmetry of the problem, alignment over the other quadrants is expected to be identical, with the exception of one corner that does not have a hole in the top structure, seen at the bottom left in Figure 2. Examples of simulated centred and 10 cm right-aligned, 0 cm down-aligned images are shown in Figure 2.

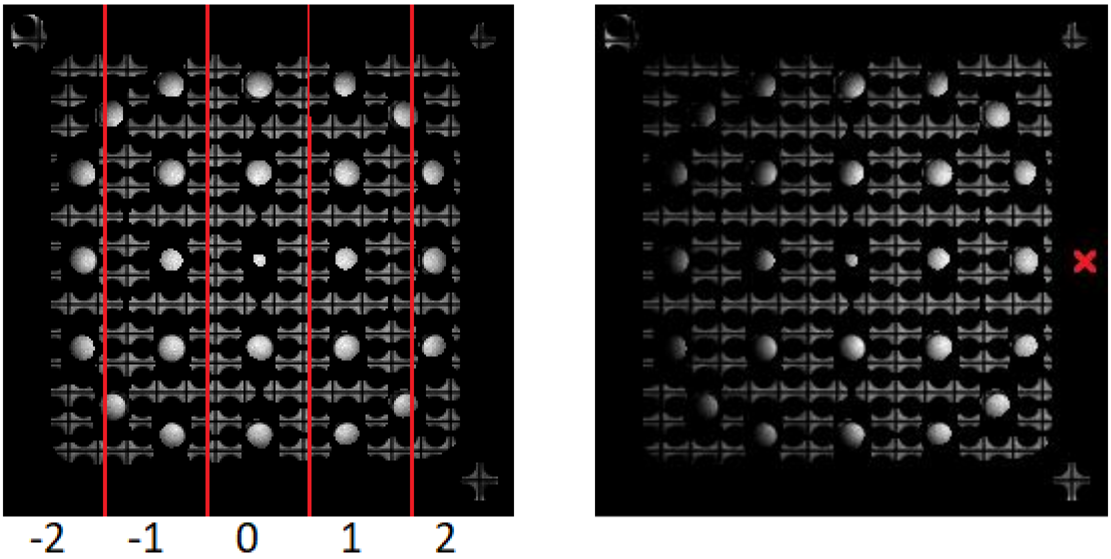

Figure 2. Left: A simulated DCVD image with a centred alignment. The ROI for the image is the entire image. The ROI has been divided into five strips, denoted from -2 to 2. Right: A simulated DCVD image aligned 10 cm to the right of the centre. The aligned position is marked with a red cross.

To analyse the light distribution locally in the images, and to investigate how both the alignment and partial defects alter the light distribution, the ROI was divided into five, equally-sized horizontal strips, shown in Figure 1 (left). The choice of vertical strips was made to analyse the changes in light distribution as the alignments move in the left-right direction, exemplified in Figure 2. Due to symmetry, analysing alignments in the up-down direction using horizontal strips is expected to give similar results. Similarly to the current analysis, the light intensity in each strip is the sum of the pixel values within it, after a background subtraction has been made. Since [3] notes that large ROIs are preferred to not introduce a significant amount of noise and uncertainty, five regions were chosen. Note that with this split, four guide tubes end up at the boundary between two strips, which may cause additional uncertainties in the analysis [3], since ripples on the water surface can stretch regions of an image and cause these guide tubes to “move” from one ROI strip to its neighbour. However, the development of a more robust and automated ROI placement to ensure that bright spots are systematically placed in the correct strip is outside the scope of this work, and for the simulated images such uncertainties do not occur.

In addition to the simulated images, measurements were available for 16 PWR fuel assemblies from the SKB50 set [8], the same as were analysed in [3]. For each assembly, nine alignments were measured, with five measurements per alignment. The alignments correspond to one centred alignment, and all combinations of moving ±6 cm in the horizontal and vertical direction from centre. The alignment was found by eye, by assessing that the image intensity maximum due to the collimation fell on the expected position in the image. Note however, that this procedure of manually identifying the intensity maximum to assess the alignment is only known to produce reliable alignment for a centred alignment. Hence additional uncertainty with respect to actual alignment is introduced for the off-centre measurements, and its magnitude cannot be assessed from the measurement data alone.

RESULTING TOTAL CHERENKOV LIGHT INTENSITIES

Dependence on alignment and partial defects

Figure 2 shows that the intensity maximum in the image moves with the alignment. From a partial defect detection point of view, what is of interest is how the partial defect reduces the Cherenkov light intensity in the five ROI strips, as a function of the alignment. The intensity reduction for the case of an alignment 10 cm to the right of the centre (seen in Figure 2) is shown in Figure 3.

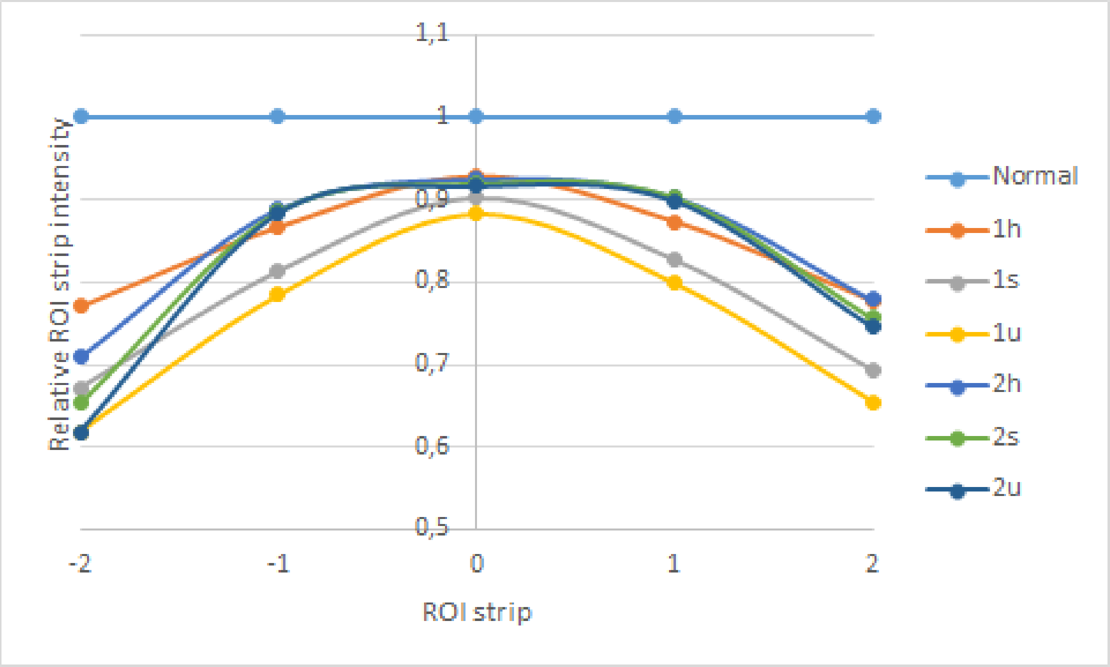

Figure 3. The reduction in Cherenkov light intensity in the five ROI strips due to partial defects, for an image aligned 10 cm to the right of the centre. The reduction is relative to the case of an intact fuel assembly. The legend numbers indicate if it is for partial defect scenario 1 or 2 in Figure 1, and the letter indicates if substitution was done with helium rods (h), steel rods (s) or unirradiated uranium rods (u).

Figure 3 shows that the two edge strips (denoted ±2) are the ones experiencing the largest reduction in intensity and are therefore the ones most affected by the partial defects. This is not surprising, since Figure 1 shows that these strips contain a larger fraction of the substituted rods in the simulated cases. The intensity deviation in the edge ROI strip -2, far away from the aligned position, is slightly more pronounced as compared to the edge strip at the aligned position in ROI strip 2. On one hand, a more pronounced intensity deviation makes it easier to spot, and hence makes the methodology more sensitive to the studied partial defects. On the other hand, due to the distance from the aligned position, the light intensity is very low in this ROI strip, typically around 5-7% of the total image intensity. Assessing partial defects in a region far from an aligned position is challenging, and even small amounts of noise or uncertainty would invalidate the results. If the fuel assembly is stored near other assemblies, radiation from the neighbouring assemblies may travel to the assembly under study and create Cherenkov light there. If this near-neighbour effect is on the order of a few percent of the assembly total intensity, it would entirely obscure the intensity reduction in this ROI strip. Hence, an analysis based on the light in the off-aligned edge strips does not seem feasible.

Further analysis of the simulated DCVD images reveals that the intensity reductions shown in Figure 3 look virtually the same for the other studied alignments. The only noticeable difference is when the alignment is moved in the right-left direction, which is partly due to the vertical alignment of the ROI strips. This creates the more pronounced intensity reduction in the edge ROI strip far from the alignment (ROI strip -2 in Figure 3). Measurements centred in the left-right direction but moving in the up-down direction are more symmetrical, without the pronounced decrease seen in Figure 3. Overall, this means that there are no inherent gains in performing measurements from different alignments, as the light reduction in different parts of the fuel remains constant for all alignments. On the other hand, it also means that the current methodology is very robust. Furthermore, if an automated routine for assessing the alignment is developed, this would open up for applying image analysis on different regions of the fuel to detect intensity deviations, which can be applied also to measurement at non-centred alignments.

Combining images with different alignments

While there are no inherent gains to performing measurements at different alignments to detect partial defects, combining measurements at different alignments can still improve the intensity of the background-subtracted signal, i.e. the signal-to-noise ratio, for regions close to the assembly periphery. To investigate this, three simulated images was used. One was aligned on the right edge, one just above the fuel centre, and one on the left edge (obtained by flipping the right-aligned image before adding the fuel top structure). Two different methods for assessing the signal-to-background ratio were used in the assessment of partial defects at the 30 % level. The first method is to analyse the average intensity values of the three images, and assess what impact this has on the signal-to-noise ratio for each ROI strip. The second method is to stitch together the three images, so that the three central ROI strips are taken from the centred image, and the edge ROI strips are taken from the corresponding aligned images.

For the averaged image, the total intensity in each ROI strip is 9-13% lower as compared to using only the centred alignment, for all simulated cases. The reason is that the regions away from the alignment have their intensity reduced more than the increase at the aligned regions. Hence, from a signal-to-noise ratio perspective, it would be preferable to measure longer (either longer exposure time or more images used for the final averaged image) with a centred alignment, than to use three different alignments. Thus, the centre alignment provides the best trade-off between intensity in the different regions and measurement time when, showing again that the current methodology is robust.

For stitched images, the light intensity at the edge ROI strips (+2 and -2) can be increased by 20-25% when using the images that are aligned over that edge. While this is an increase expected to improve the signal-to-noise ratio, it is rather modest. For the DCVD, it is unlikely to be worth the effort to perform three times as many measurements per fuel assembly for such a modest gain. However, other systems such as the autonomous XCVD robots [9] will naturally obtain measurements from different alignments as they move around the fuel pool. For such systems, stitching together images may be a useful way to ensure that the images of each region of the fuel assembly is of the highest possible quality. Should future XCVD developments allow for autonomous and quantitative measurements, stitching the images may be necessary to obtain high-quality images in the short time the robot is moving over the fuels. This will also ensure that the quantitative analysis can be made on the best available data.

Comparing modelled and measured light intensities at different alignments

To evaluate the performance of using different alignments and ROI strips, measurement data of 16 PWR assemblies from the SKB50 set [8] was used. Note that these assemblies do not suffer any partial defects. These assemblies are declared to be of two different designs, from two manufacturers, with eight assemblies per manufacturer. These are referred to as design B and design E, to match the notation in [3][10]. Thus, within each group, the assemblies are expected to have identical designs, and the DCVD measurements results can be directly compared, as was done in [3]. Each measurement had a background-subtraction done as in [10], which assesses what constant background level results in the best fit between predictions and measurements. The intensity predictions presented in [10] were also used here. Based on the simulated images, the relative intensity in a ROI strip to the total intensity was estimated. These intensity fractions were then multiplied with the predicted image intensity, to obtain predictions for each ROI strip. Measurements were available and analysed for a centred alignment, and for alignments approximately ±6 cm in the left-right direction.

The average difference between ROI strip predictions and the measured values (i.e. the average error) and the RMSE values are shown in Table 1 for a centred alignment, and in Table 2 for an alignment 6 cm to the right of the centre position.

Table 1. The average error and RMSE for the difference between predictions and measurements of the 16 SKB50 PWR fuels, for a centre-aligned measurement. The ROI strips are denoted -2 to 2 going from left to right, see Figure 2.

	ROI:	-2	-1	0	1	2
Average error	Design B	0.49%	0.06%	-8.20%	3.17%	-1.17%
	Design E	-6.49%	2.16%	-8.26%	3.56%	-7.36%
RMSE	Design B	13.16%	7.23%	10.60%	10.63%	19.77%
	Design E	16.72%	10.82%	7.92%	7.33%	12.65%

Table 2. The average error and RMSE for the difference between predictions and measurements of the 16 SKB50 PWR fuels, for measurement aligned 6 cm to the right of the fuel centre. The ROI strips are denoted -2 to 2 going from left to right, see Figure 2.

	ROI:	-2	-1	0	1	2
Average error	Design B	9.59%	8.09%	-14.85%	-1.19%	7.45%
	Design E	-2.06%	4.36%	-20.09%	8.27%	20.08%
RMSE	Design B	24.76%	13.57%	13.05%	10.51%	10.41%
	Design E	42.50%	18.36%	23.11%	13.13%	12.25%

Tables 1 and 2 show that for the centre ROI strip (strip 0), the average measurements are systematically below the predictions. Further analysis shows that this is partly caused by the modelling of the top structure near the central instrumentation tube. In the simulated images, this hole visually appears larger than in the corresponding measurements. For the right-aligned measurements, the hole is in some measurements difficult to see, especially for design E assemblies, while it is still pronounced in the simulated images, shown in figure 2 right. Should the systematic deviation in the central strip be corrected for, the average error would typically end up in the ±5% range for all ROI strips, although design E seems to have a bit larger uncertainties for the right-aligned case. The RMSE values typically end up in the 10-20% range, as compared to 6-8% when comparing predictions and measurements for the total image intensities for these measurements [3]. Hence, the smaller ROI strips and thus higher sensitivity to the placements of the strips results in higher uncertainties, and more variability in each ROI strip, as compared to the currently used methodology.

Comparing Table 1 and 2, the RMSE increases significantly in ROI strip -2 as the alignment moves right, while the central and right ROI strips have comparable, and sometimes lower RMSE values. Part of the increase in RMSE in the leftmost ROI strips is due to two outliers, one for each design. For design E, one fuel assembly has the centre strip measured to be 70% lower than predicted, and the leftmost strip has an intensity of almost zero, which means that although the absolute difference to the prediction is not high, the relative deviation approaches 100%. Design B has one such outlier, though the deviation is more modest, around 30-40 % for the centre strip and the strips left of it. The cause of these outliers is not fully understood. However, since the centred and left-aligned measurements of the same assemblies show no such deviation, it is likely to be due to the measurement or analysis of the specific right-aligned measurements. The most likely cause is that the right-aligned measurements were done further to the right than expected, due to that the DCVD could not be places at the intended location during a few measurements. This highlights the challenge of placing the instrument in the intended location above the fuel as well as of knowing what that location is, as pointed out earlier in this work. Thus a robust, automated alignment estimator could be useful, both in-field if measurements at other alignments are to be performed, and later for the analysis of the data.

Figure 3 shows that the methodology needs to be sensitive to an intensity change of 20% when measuring ROI strip -2, while being aligned over ROI strip +2, to detect all studied partial defects. If the uncertainty in the difference between prediction and measurement has standard deviation σ, the partial defect assemblies can be assumed to have a standard deviation 0.8σ

(same relative uncertainty and 20% lower intensity). To statistically separate the two distributions, with a maximum of 5% false positive/negative, we must have that $2(\sigma + 0.8\ \sigma) < 20\%$ or $\sigma < 5.6\%$. For the ROI strip -2, the RMSE is so much higher than this (24.76 % for fuel design B, 42.50% for design E) that a partial defect assembly cannot be determined to differ from an intact assembly. For ROI strip 2, which is at the aligned position, the RMSE is about twice this limit (10.41 % for fuel design B, 12.25% for design E). It is however clear that further improvements are required in both the measurement methodology and ROI strip prediction and analysis to reduce the RMSE values to be below 5.6%. This would be challenging but maybe not impossible.

CONCLUSIONS AND OUTLOOK

In the current DCVD measurement methodology, measurements are performed with one alignment over the fuel assembly centre. This work has investigated the possibility to perform measurements at multiple alignments, to determine whether more information or higher quality measurements could be obtained this way. Investigations were made for two different rod substitutions scenarios, with low, medium and high-density substitution rods.

Although the light intensity changes drastically with alignment due to the collimation, the intensity deviation due to a partial defect remains virtually constant as the alignment changes. Thus, there are no inherent gains in partial defect detection sensitivity from measuring at multiple alignments. It also means that the current Cherenkov light measurement methodology is robust, and provides a balance between an intense signal and short measurement time. With an automated alignment estimator, the current methodology could be adjusted to compensate for any misalignment, making the procedure more sensitive to intensity deviations caused by partial defect. Additionally, if image analysis methods are developed to analyse local light distributions and deviations from expected distributions in an image, such analyses would also be robust to other alignments than a centred one.

For increasing the signal-to-noise ratio of images, simply making longer measurements for the alignment at the fuel centre will provide better performance as compared to measuring at multiple alignments, and averaging over the images. Stitching together images from multiple alignments may potentially be the best way of obtaining a measured image with a high signal in all regions. For a DCVD, this procedure will probably be too time-consuming to be regularly used, since the inspector has to spend significantly more time aligning the instrument and measuring each assembly as compared to the current methodology, and since additional uncertainty may be introduced unless a robust alignment estimator is introduced. For other systems such as the XCVD robot, which moves around and measures at different alignments, image stitching may be of higher relevance. It may be especially useful if future developments allow the XCVD to perform quantitative measurements, which is currently only done by the DCVD for Cherenkov based systems.

Testing the procedure of using multiple alignments on measured images, the uncertainties in the measurements are too high to reliably allow a 30% partial defect to be detected, for the studied partial defect cases. Further improvements in measurement methodology may help in reducing the uncertainties. Also, development of improved intensity predictions for a segmented ROI could further help reduce the uncertainty, but such a prediction method needs to be validated against extensive experimental data, which is currently unavailable.

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