Experimental study of background subtraction in Digital Cherenkov Viewing Device measurements

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Abstract

The Digital Cherenkov Viewing Device (DCVD) is an imaging tool used by authority inspectors for partial defect verification of nuclear fuel assemblies in wet storage, i.e. to verify that part of an assembly has not been diverted. One of the currently adopted verification procedures is based on quantitative measurements of the assembly's Cherenkov light emissions, and comparisons to an expected intensity, calculated based on operator declarations. A background subtraction of the intensity data in the recorded images is necessary for accurate quantitative measurements. The currently used background subtraction is aimed at removing an electronics-induced image-wide offset, but it is argued here that the currently adopted procedure may be insufficient.

It is recommended that a standard dark-frame subtraction should be used, to remove systematic pixel-wise background due to the electronics, replacing the currently used offset procedure. Experimental analyses show that a dark-frame subtraction would further enhance the accuracy and reliability of DCVD measurements. Furthermore, should ageing of the CCD chip result in larger systematic pixel-wise deviations over time, a dark-frame subtraction can ensure reliable measurements regardless of the age of the CCD chip. It can also help in eliminating any adverse effects of malfunctioning pixels. In addition to the background from electronic noise, ways to compensate for background from neighbouring fuel assemblies and ambient light are also discussed.

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

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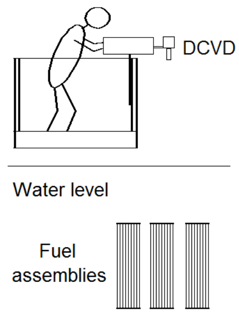
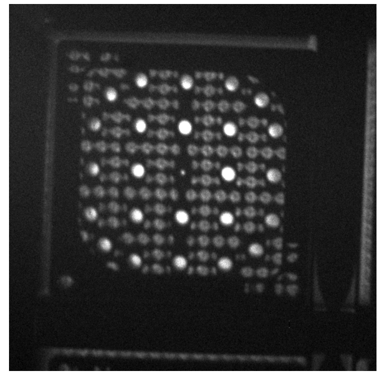


(a)



(b)

Figure 1: a): The typical measurement situation when using the DCVD. The DCVD is mounted on the railing of a fuel handling machine. The fuel assemblies are typically covered by about 8 m of water. b) An example of a measured DCVD image of a PWR 17x17 fuel assembly.

1 Introduction

The Digital Cherenkov Viewing Device (DCVD) is an instrument used by nuclear safeguards inspectors to verify the presence and properties of irradiated nuclear fuel assemblies in wet storage based on the Cherenkov light produced by the radiation emitted by the assemblies [1]. During measurements, the DCVD is typically mounted on a railing of a fuel handling machine, as illustrated in figure 1a. The DCVD is sensitive to UV light, since the intensity of Cherenkov light in water peaks in the UV range. The result of a measurement is an image of the Cherenkov light emitted by the assembly, and figure 1b shows an example measurement of a PWR 17x17 assembly. During the measurement, a region of interest (ROI) is manually selected in the image, containing only the fuel assembly being measured. After a measurement is finished, a background subtraction is applied to the image, and the currently used method is aimed at removing an offset introduced by the detector electronics. The background-subtracted total intensity of the assembly is then calculated by summing the pixel intensity values inside the ROI. This offset removal method does not take into account other light sources than the assembly being measured, which is further discussed in section 2.

The DCVD is frequently used for *Partial Defect Verification*, where expected intensities, calculated using operator-declared fuel data [2], are compared to the measured intensity of the assembly. Any measured intensity deviating more than 30 % from the prediction is flagged as an outlier, and requires additional investigation since it may suffer from a 50 % partial defect [3]. This procedure requires both accurate prediction models as well as accurate quantitative measurements of the Cherenkov light intensity emitted by the assembly.

The currently used partial defect detection procedure is applied to a set of assemblies with similar fuel design. Once predictions and intensity measurements of the total Cherenkov intensities are available for all assemblies under study, a least-square fit is done to calculate the multiplier (calibration constant) that relates the predicted to the measured intensities. As a consequence of this fitting procedure, the measured intensity of an assembly is ideally proportional to the predicted intensity, without any offset. Should however the measured intensity include a background component, a bias would be introduced in the comparison. Thus, an accurate background subtraction is necessary for the comparisons between measurements and predictions to be accurate.

This work analyses experimental Cherenkov light intensities measured from a population of PWR 17x17 fuel assemblies, including a relatively high background level. The background is characterized and quantified, and the performance of the currently adopted offset-removal method is compared to an alternative method, a standard dark-frame subtraction.

2 Background in DCVD measurements

In DCVD measurements, the light detected by a CCD chip pixel consists of several light components, where only the Cherenkov light emitted by the fuel assembly under study, $I_{assembly}$, is of interest, and all other components can be considered background. The intensity value reported by a pixel, I_c can be expressed by equation 1 (see [4] and [5]). Here $I_{neighbour}$ is Cherenkov light created in the assembly being measured due to radiation originating from neighbouring assemblies, and $I_{ambient}$ is the ambient light from facility lights. k is a proportionality constant relating the light intensity impinging on a pixel to the pixel intensity value reported. k can be further factored into constants relating to the exposure time, if any binning is used, the gain of the amplifier and how efficiently charge in the CCD chip is converted into an electric signal. Finally, the offset is a further contribution to the pixel intensity value caused by the detector electronics. Note that k and the offset are properties which may differ from pixel to pixel.

$$I_c = k \cdot (I_{assembly} + I_{neighbour} + I_{ambient}) + offset \quad (1)$$

The background subtraction currently implemented is aimed at removing the offset in equation 1, and will be referred to as the offset removal method in this work. The offset removal method works by finding the darkest pixel in the ROI, and assumes that this pixel value is the offset. Due to fuel assembly structures, the ROI is expected to contain regions which do not emit or reflect any light, thus this pixel value would only be affected by the offset. However, if no dark region exists or if the ROI contains dead or defect pixels, the offset removal method will be unable to accurately assess the offset. The offset removal method is not intended to remove any other sources of background in equation 1, but if any other source behaves as a flat component, affecting all pixels equally, the offset removal method will subtract also this component.

The partial defect detection procedure compares the Cherenkov light intensity of an assembly to a predicted intensity, and assumes that they are proportional. This comparison requires that the offset, $I_{neighbour}$ and $I_{ambient}$ are removed in equation 1. If any of these components remain in the analysis a bias is introduced in the comparison.

Additionally, light from any source can scatter in the water, producing a diffuse light whose origin is difficult to determine. Such scattered light will not have as strong directional dependence as compared to Cherenkov light emitted by an assembly [5]. In principle, scattered Cherenkov light originating from the assembly under study is part of the light intensity which should be measured, while all other scattered light is background, which should be removed or compensated for. Note however that if the diffuse component is flat, the offset removal method will find and remove also this component.

2.1 Neighbour light sources

Assemblies are often stored close to each other, and radiation from one assembly can enter a neighbouring assembly and produce Cherenkov light there. This light contribution is neglected in the current analysis, but a method to predict its intensity has been developed [6], which can be used to compensate for this contribution.

2.2 Ambient light sources

Ambient light can reflect from the surface of the water, or any reflective metal surfaces of the fuel assemblies, before being detected by the DCVD. The intensity of the ambient light, $I_{ambient}$ in eq. 1, depends on the type, number and placement of light sources in the facility. The DCVD optics contains a filter to remove non-UV light, which helps in reducing the ambient light contribution, but cannot remove any UV light caused by any facility light sources. The only reliable method to decrease or remove the ambient light is to turn off as much of the facility lights as possible, and inspectors usually ask to turn of lights if they find them to interfere. However, emergency lights can usually not be turned off.

A method to remove the ambient light proposed in [5] is to measure empty pool positions, so that the only light detected would be the ambient light. This may then be subtracted from all measurements, under the assumption that the contribution is constant. This is further evaluated in section 4.

2.3 Offset

The offset in equation 1 is caused by dark currents in the CCD chip, and is large enough to influence quantitative measurements unless removed. An alternative to the currently used offset removal method is to perform a standard dark-frame subtraction, by making a measurement when no light reaches the CCD chip [7]. A dark-frame characterizes the CCD, allowing for systematic pixel-wise intensity offsets to be removed, and eliminates the assumption that there exists a dark region in the image. Assuming that the dark frame is device-specific and constant for the same device settings, it is possible to measure a dark frame once and use it in subsequent dark-frame subtractions.

3 Experiment

In order to evaluate the existing background subtraction procedure and compare it to the suggested improvements described in section 2, the background in a DCVD-measurement campaign of spent nuclear fuel was analysed. A total of 25 PWR assemblies were measured with a DCVD, and these assemblies are the so-called SKB50 set of assemblies [8], which have previously been measured using various instruments. The SKB50 assemblies represent a wide range of physical designs, burnups, cooling times and irradiation histories. For the PWR 17x17 fuel type that is considered in this work, a total of 20 assemblies were measured, having five different physical designs. The burnup of the assemblies were in the range 19-47 MWd/kgU, and the cooling times were in the range 9-33 years. The irradiation history of the assemblies were made available to the authors, courtesy of Vattenfall, who operates the Swedish PWR reactors, and were used to predict the Cherenkov light intensities of the assemblies, following the method of [2] and the near-neighbour prediction method of [6].

The assemblies were measured with one DCVD and constant instrument settings. The assemblies were stored in baskets, each holding 9 assemblies, and the three baskets containing the SKB50 PWR assemblies were located next to each other. In addition to the assembly measurements, dark frames had previously been collected by the DCVD manufacturer. No dark frames were collected at the event of the fuel measurements, since no suitable instrument that could ensure complete blocking of any light was available, and since this instrument did not feature a shutter that could be closed in a controlled manner. Several empty positions, far away from any fuel assemblies, were also measured to assess the ambient and/or diffuse light.

In each fuel-assembly measurement, a ROI was manually selected to contain only the assembly under study, with a size of 340 by 340 pixels. Since all assemblies were at the same distance from the DCVD, they appeared to have the same size in all measurements and the same ROI size was applicable in all measurements.

The storage facility has lights used to illuminate the pool, and these lights were recently replaced with LED lights. Measurements were taken of a few assemblies with the pool lights on and off, and some earlier measurements were available from before the lights had been replaced. There were also fluorescent lights present used to illuminate the facility, and some empty position measurements could be done with the lights on and off.

Due to the difficulty of setting up an experiment under controlled conditions, no experiments were performed to assess the diffuse light component. It can also be noted that the water at the facility is comparatively clean, and with little impurities in the water to scatter light the diffuse component is expected to be

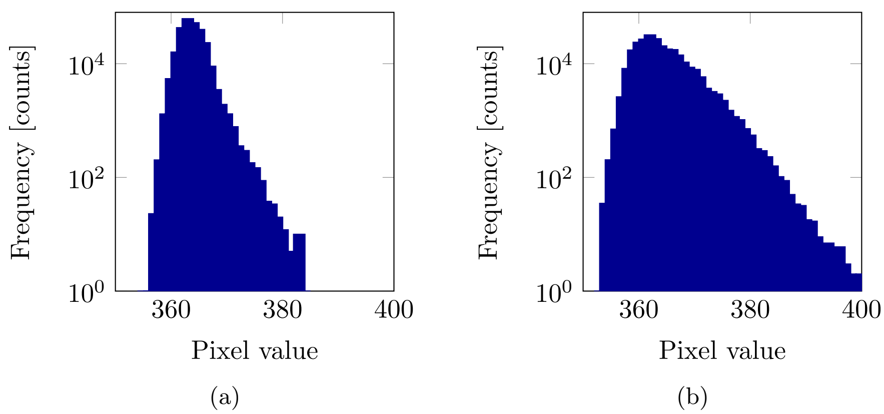


Figure 2: a): Histogram for the pixel intensity values of a dark frame. The lowest pixel intensity value was 355, and the highest 384. b) Histogram for the pixel intensity values of a measurement of an empty position. The lowest pixel intensity value was 353, and the highest 400.

low.

In the measurements, an unusually high background was found after the offset removal method had been applied, where low-intensity assemblies had a considerable contribution of their measured intensity caused by the remaining background. Typically, the background would be negligible after applying the offset removal method, such as in the data presented in [9].

4 Results

4.1 Dark-frame pixel intensities

The DCVD manufacturer has found the dark frame to be device-specific, and negligibly varying over time for the same device settings. A histogram of the dark frame pixel intensities for the DCVD used in this work is shown in figure 2a, where the minimum pixel intensity value was 355. Fitting a Gaussian curve to the histogram gives a mean pixel intensity of 363.8, with 363 being the most frequent pixel intensity.

The offset removal method can thus find a lowest pixel intensity value of 355 in a measurement, if the pixel is situated in a dark region within the ROI, which would give an average remaining background per pixel of $363.8 - 355 = 8.8$. Given the ROI size, this means that a remaining background of up to $1.0 \cdot 10^6$ counts can be present after applying the offset removal method. If this pixel is instead part of a bright region in a measurement, some other pixel would be the darkest one, and a different, higher offset would be found and subtracted.

Some systematic effects could also be seen in the dark frame, such as that the lowest part of the image has an intensity $0.5 - 1\%$ lower than the rest of the image. This is caused by the charge transfer in the CCD chip, and is expected to affect every measurement equally. Accordingly, the results of the offset removal method will depend on whether the ROI contains the lowest rows of pixels or not. A dark frame subtraction would remove this effect. For these measurements, no dead or stuck pixels were observed, though a dark-frame subtraction will remove any adverse effect of such pixels on the intensity measurements.

4.2 Neighbour contributions

Predictions were made for the near-neighbour effect for the assemblies measured using the provided irradiation histories. On average, it was predicted that an assembly had 9 % of its intensity caused by neighbouring assemblies, but the weakest assembly had an estimated 33 % of its emitted intensity caused by its neighbours. This near-neighbour contribution is significant enough that it should not be neglected. This can also be compared to the measurement in [9], where the near-neighbour intensity contribution was on average 1.5 % and at most 6 %, which was considered to be negligible. The reason for the large difference in contributions from near neighbours is the much closer storage geometry found in this measurement campaign. This highlights the need of estimating the maximum magnitude of the near-neighbour effect in each measurement campaign, and using the near-neighbour predictions if the effect is significant.

4.3 Facility ambient light

The fuel-handling machine at the facility has a set of lights used to illuminate the pool, which were recently replaced with LED lights. Before the bridge lights were replaced, it was necessary to turn them off before measuring with the DCVD, since otherwise the DCVD would only see UV-light emitted by these lights, reflected off the water surface. After switching to LED lights, the impact on the measurements of having the lights on or off was found to be negligible for the assemblies measured.

Fluorescent lights were also present to illuminate the facility, which provide some ambient UV background. It was suggested in [5] to assess its magnitude by measuring empty pool positions, where no Cherenkov light is present. These measurements however showed reflective spots on the pool bottom and reflective structural components, which cannot be seen in assembly positions. Consequently, empty position measurements cannot be used to assess the ambient light intensity seen in normal measurements, and the most reliable way of removing the ambient light is instead to turn off as much of the facility lights as possible. Figure 2b shows that for dark regions in the measurement, the empty position looks much as a dark-frame, i.e. the ambient light intensity is low for these measurements. However, the effect of the reflective spots is to increase the frequency of high-intensity counts compared to the dark-frame.

4.4 Intensity analyses based on offset removal and dark-frame background subtraction

Analyses of intensities were made for the PWR 17x17 assemblies in the SKB50 assembly set. Figure 3 shows the comparison between predicted and measured intensity, after background subtraction using the offset removal procedure respectively using a dark-frame subtraction. In both cases, the predictions took into account the intensity contributions due to the near-neighbour effect. For each data set, two least-square fits were made, to assess if the background had been removed. One fit assumed that the background had been satisfactorily removed and that the fitted line crosses the origin, and the other fit assumed that a constant background remained, and fitted this remaining offset. The results show that the dark-frame subtraction came close to removing the constant background, with the fitted offset being small enough ($2 \cdot 10^5$ counts) that it can be explained by measurement uncertainties. However, a least-square fit of the data after the offset removal was performed found a remaining background intensity of $1.2 \cdot 10^6$ counts, and the fit significantly deviated from the fit where the background was assumed to have been successfully removed. This indicates that the background was not completely removed by the offset removal method.

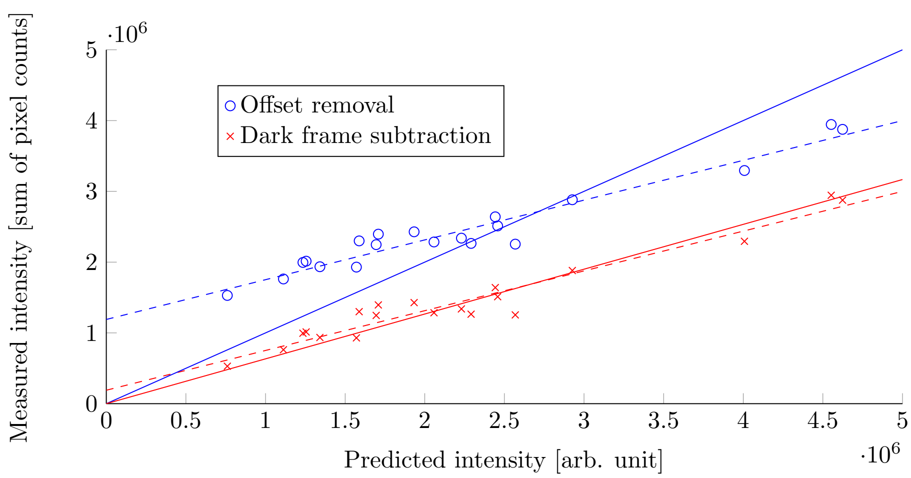


Figure 3: Predicted and measured intensities from the SKB50 PWR 17x17 fuel assemblies with linear correlations for the offset removal procedure and a dark-frame subtraction. Dashed lines show the least-square fits including a remaining constant background. Solid lines show fits where the background is assumed to have been successfully removed, thus passing though the origin.

As expected, the near-neighbour intensity predictions show that the low-intensity assemblies were more strongly affected by the near-neighbour effect compared to high-intensity ones. Consequently, if the near-neighbour effect is not compensated for, or if it is only partially compensated for, the low-intensity assemblies will be measured as more intense than expected, and the high-intensity ones will be measured as relatively less intense than expected. This will give rise to a similar effect as the offset seen in figure 3. Consequently, both a dark-frame subtraction and predictions taking the near-neighbour effect into account are required here for enhanced accuracy in the comparison between predictions and measurements.

The main outcome of DCVD assessments is the agreement between predicted and experimental data, which forms the basis for partial-defect verification. For the PWR 17x17 assemblies under study, table 1 shows the average difference between prediction and measurement, for the two studied background subtraction methods. As can be seen, a dark-frame subtraction results in better agreement between predictions and measurements. Also shown in table 1 is the Root Mean Square Error of the difference between prediction and measurement (unbiased estimate of the standard deviation). Using a dark-frame subtraction, the RMSE is reduced from 21.4 % to 13.6 %. This reduction is significant and such an enhancement in precision may lead to enhanced partial-defect verification capabilities.

Table 1: Average relative difference and Root Mean Square Error (RMSE) for the difference between predictions and measurements, for the SKB50 PWR 17x17 assemblies. The values are calculated for the two methods studied for removing the offset.

	Average difference	**RMSE**
Offset removal method [%]:	-13.4	21.4
Dark-frame subtraction [%]:	-2.9	13.6

5 Discussion

The measurements presented in this work include an unusually high level of remaining background after applying the offset-removal method. For previous measurements (such as [9]) the remaining background has been negligible. One potential explanation is that these measurements were performed using a development version of the DCVD, which has older electronics and could potentially suffer from age-related degradation of the CCD chip and readout electronics. However, the dark frame used for the analyses was recorded recently before the measurement campaign and should be valid for the device in its current status. If noise or systematic pixel intensity variations due to ageing equipment is the cause of the large background seen here, this can potentially become an issue in the future as the DCVD instruments become older, making regular dark-frame measurements and dark-frame subtraction highly relevant.

Due to the difficulty of setting up a controlled experiment and due to facility considerations it was not possible to experimentally measure the diffuse light component in this measurement campaign. One possible way of measuring this component is to use the developed calibration light source [10] and measure it for various depths, to try to assess how much light is lost, and how much is turned into diffuse light. Preferably, such measurements should be performed at several different facilities, to investigate the effect of various water qualities on the scattering of light. Such experiments can also provide information on the characteristics of the diffuse light. If it is relatively slowly varying but strongest near the source, it may be possible to separate the diffuse light caused by different assemblies. If the diffuse light is constant in all pixels in a measurement, for all sources, it may be preferable to assess and subtract the diffuse light.

6 Conclusions and outlook

The measurements presented in this work indicate that the offset removal method does not completely eliminate the background stemming from the electronics-induced pixel offset. Consequently, it is recommended that a standard dark-frame subtraction should be implemented to reliably remove this offset. Any offset remaining may create problems for partial defect verification which compares predicted to measured intensities, and assumes that the offset has been successfully removed. According to the experimental data, a dark-frame subtraction may significantly improve precision and thus verification capabilities.

There are indications that the dark frame changes little with time for the same instrument and settings, making it possible to measure dark-frames in advance and use those during the measurement campaign. Should ageing of the electronics result in more severe pixel-wise systematic offsets with time, a dark-frame subtraction can quantify and remove this offset, ensuring reliable measurements regardless of the CCD chip age. To follow up on possible ageing, it is also recommended that dark-frame measurements are included in regular quality control routines.

For these measurements, the light contribution from the neighbours was found to be significant, and needed to be included in the predictions for accurate results. In future measurement campaigns is recommended that the neighbour light contribution should be estimated for the assemblies expected to be the most affected by it. Unless its magnitude is negligible, predictions should be made taking the neighbouring light into account.

The empty position measurements have shown that the conditions at these positions do not correspond to conditions with an assembly present, and that these measurements cannot be used to assess the ambient light. Further studies are required in order to develop a method to identify and compensate for this component. Furthermore, facilities should be encouraged to switch to LED lights with low UV emissions, which will reduce or remove the problem.

If a dark-frame subtraction is included in the measurements, it should not be too difficult to also include a light-frame measurement, i.e. to make a flat field correction [7], to ensure that all pixels give the same response to the same light intensity. This would allow measurements taken with different DCVD:s, or measurements of the same assembly taken at different times or with different settings to be compared.

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