# Partial Defect Verification of Spent Fuel with the new IAEA Cerenkov Viewing Devices

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**Abstract**

The neXt generation Cerenkov Viewing Device (XCVD) was authorized in 2019 for gross defect verification of spent nuclear fuel in wet storage. The XCVD's increased sensitivity has enabled more efficient and reliable verifications, especially of low-burnup, long-cooled spent fuel. The XCVD digital recording capability also enables inspection review and image post-processing. Due to its performance and cost-effectiveness, the XCVD is slated to replace the Improved Cerenkov Viewing Device (ICVD) for gross defect verification.

The characteristics and performance of the XCVD would also enable its use for partial defect verification of spent fuel. At the beginning of 2023, the DCVD was the only instrument authorized for partial defect verification of spent fuel and places a significant burden on inspectors and facility personnel. The XCVD is significantly lighter, more efficient and less costly compared to the DCVD, making the XCVD an excellent non-intrusive technical solution for partial defect verification of spent fuel assemblies. The XCVD also can be deployed as the instrument payload of the Robotized Cerenkov Viewing Device (RCVD), offering unprecedented gains in efficiency and data quality.

Beginning in 2022, the IAEA has thoroughly evaluated the XCVD's quantitative performance compared to the DCVD. This paper describes the main outcomes of this comparative evaluation, using data collected in the laboratory and in the field to draw conclusions about the feasibility and advantages of using XCVD for partial defect verification.

## 1. Introduction

Under comprehensive safeguards agreements, States are obliged to declare the uranium and plutonium content of spent nuclear fuel. One of the verification methods used by the IAEA to confirm the presence of declared items in the spent fuel pond employs Cerenkov viewing devices (CVDs), which are robust, efficient and minimally intrusive. CVDs are used both for routine verifications confirming the presence of declared items through attribute testing (gross defect) and for the higher-sensitivity partial defect testing verification method [1] for special circumstances, such as when spent fuel is transferred to dry storage facilities. For attribute testing, the CVD is used to confirm the emission of Cerenkov light resulting from the intense radioactive decay of fuel underwater. For partial defect testing, the total amount of Cerenkov light detected from the fuel assembly is compared with a prediction obtained by simulation based on operator records of cooling time and burnup cycles. The predicted intensity values are normalized via linear regression to the measured intensity values. This relative measurement is used when calculating the deviation between the prediction and the measurement values. While Cerenkov light can, in principle, be emitted from activated non-fuel items, matching the overall Cerenkov light of spent fuel at the time of verification would be extremely challenging, primarily because the date of verification would not be known sufficiently in advance by a diverter.

The DCVD has been used for sixteen years for partial defect verification either before a transfer or when a transfer is complete, just prior to the cask being closed underwater. The DCVD captures static images of each fuel assembly. Data are evaluated immediately in the DCView software, developed by the Swedish support program [2]. Within a region of interest (ROI) defined by the user, DCView averages the static images, performs background subtraction and calculates the total intensity value, which is then compared with the predicted value. The software also analyses each static image against a template indicating a known pattern of expected light emissions for each particular type of fuel. As the light is channeled in the spaces beside the pins, localized excesses of light would indicate pin removal.

Designed as a replacement for the ICVD, the neXt generation CVD (XCVD) was developed over the past five years and recently authorized for gross defect tests. The XCVD is compact and captures video at 30 frames per second. Its optical system is approximately eight times more sensitive than the ICVD, allowing the verification of low-burnup, long-cooled spent fuel [3]. As it is much more portable and requires less time to acquire a comparable number of still frames compared with the DCVD, the XCVD also makes it much easier and more efficient to conduct partial defect tests of spent fuel. Lab tests on a target image showed that the XCVD's sensitivity was higher than—but in a linear relationship to—the DCVD's, thus it should be possible to deploy the XCVD for the exact same methods as the DCVD [4]. New software (the XCVD Analysis Tool) was developed to process XCVD data offline, and the XCVD and DCVD were tested in the field by independently measuring the same populations of fuel.

# 2. Methodology

## 2.1 Analysis Algorithms

For qualitative gross defect attribute tests, XCVD data is processed by constructing a map from a continuous recording, as shown in Figure 1.

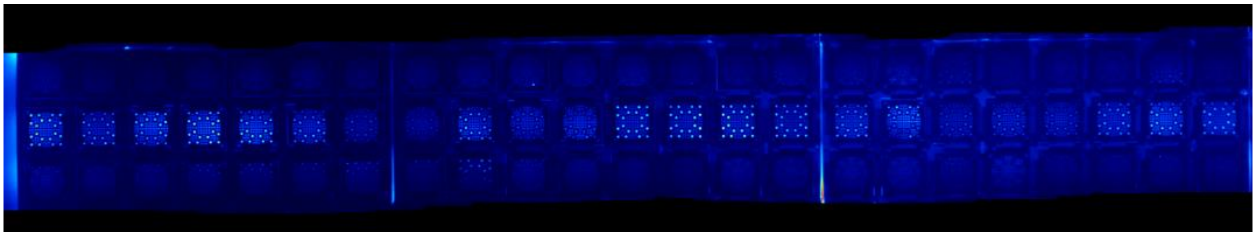

*Figure 1: Map constructed from XCVD data.*

The video recording and panoramic map are useful for qualitative review and reporting, but intensity measurements are necessary for the partial defect test. The intensity of a specific fuel can be measured by averaging the frames from the time when the XCVD was positioned directly over the fuel, selecting the ROI, subtracting the background, and calculating the total intensity in the

ROI. Using the same predicted values (based on the operator's declaration), the XCVD Analysis Tool and DCView compare the results of the XCVD and DCVD measurements, respectively.

To begin the intensity measurement, the user selects the number of frames (still images from the video taken by the XCVD as it was aligned over the fuel), which are then averaged. Since using more frames improves the signal-to-noise ratio, at least three frames should be selected, up to about twenty, after which the improvement is minimal [4]. Too many frames could increase blur, if the instrument was moving quickly while the recording was being acquired. Figure 2 shows the difference between a single frame, five frames and twenty frames.

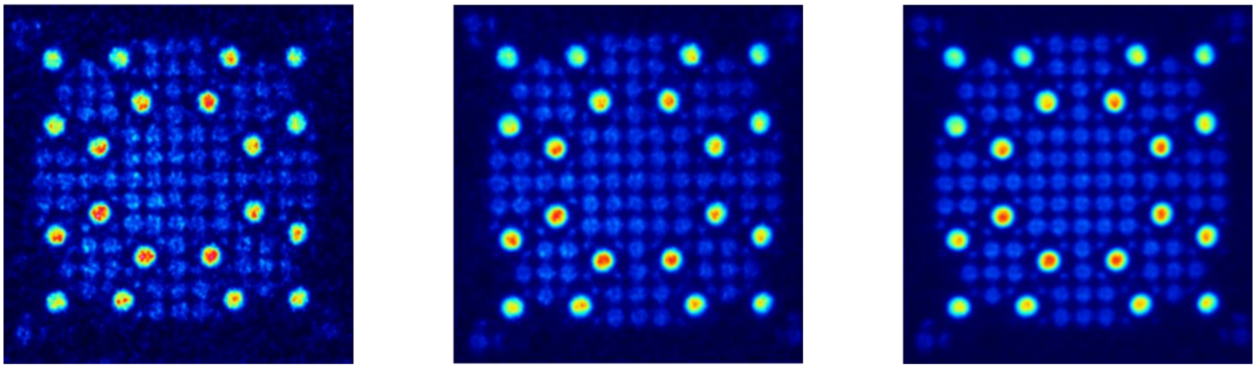

*Figure 2: A single XCVD frame, a stack of 5 frames and a stack of 20 frames.*

The rest of the analysis process is the same for both the DCVD and XCVD. First, the user selects the ROI around the fuel to be measured. The ROI must be the same for all fuel in the same group and should be positioned to include all the fuel pins and exclude nearby bright areas. See Figure 3 for an example.

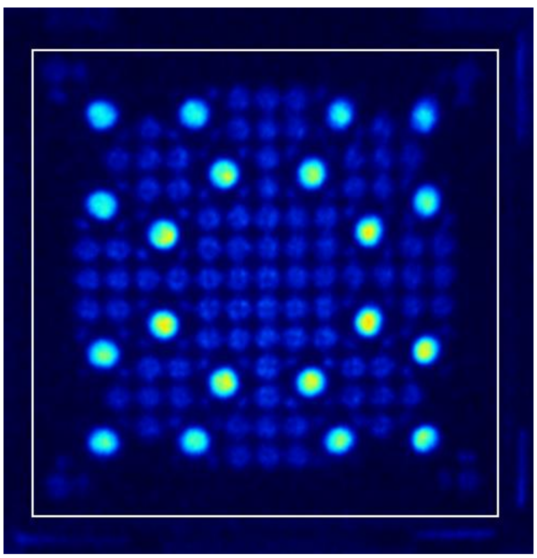

*Figure 3: Representative ROI for a single fuel assembly.*

Background subtraction is performed by taking the darkest pixel value from the ROI of the measurement and subtracting it from every other pixel from the ROI. The total intensity is the sum of all the pixels inside the ROI after the background subtraction.

For each group of a single type of fuel assembly, a simple linear regression model with ordinary least squares is fit to the measured and predicted intensities to determine the calibration factor for the group.

The simple linear regression model minimizes the sum of the squared residuals $\varepsilon_i$ according to the equations:

$$y_i = \alpha + \beta x_i + \varepsilon_i$$

$$\hat{\alpha} = \overline{y} - (\hat{\beta}\bar{x})$$

$$\hat{\beta} = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{n\sum x_i^2 - (\sum x_i)^2}$$

In the CVD analysis, the measured and predicted intensities are assumed to be proportional so the regression line should pass through the origin, so alpha equals zero and simplifies the beta equation to:

$$\hat{\beta} = \frac{\sum_{i=1}^{n} x_i y_i}{\sum_{i=1}^{n} x_i^2}$$

The measured intensity values are compared with the predicted values by calculating the relative error between the measured intensity values and the normalized predicted intensity values, that is:

$$\partial = \frac{v_A - \hat{\beta} v_E}{\hat{\beta} v_E}$$

where $v_A$ is the actual value measured, $v_E$ is the predicted value from simulation, and $\hat{\beta}$ is the normalization factor from the least squares fitting. A delta greater than 50% is considered an outlier.

## 2.2 Field Test Description

The XCVD and DCVD were used to measure two populations of fuel assemblies stored in two separate cooling ponds. The measurement conditions were kept constant for each population, in particular the cooling time of the fuel and the height of the instrument above the pond were the same for both the XCVD and the DCVD. In total (both populations), 274 fuel assemblies of nine types—including PWR and BWR; uranium and MOX; with and without inserts, with control rods and with flow restrictors—were measured once by each instrument.

There is a significant difference between the two instruments in terms of time spent acquiring data. The DCVD can acquire data for 40–60 fuel assemblies per hour, while the XCVD can acquire data for over 300 fuel assemblies per hour.

Since the CVD partial defect test is a relative measurement, the intensity values from the XCVD and DCVD are not expected to be exactly the same, but they should have a linear relationship. This linear relationship between the two instruments has been demonstrated in laboratory tests performed by the XCVD supplier, ASE Optics [4]. Therefore, when the analysis is performed group by group, the relative difference between the normalized predicted intensity values and the measured intensity values for each fuel should be similar.

## 3. Results

First, the intensity values measured by the XCVD and DCVD were compared to test if they had a linear relationship in the field, as they did in the lab. Figure 4 shows the intensity values measured by the XCVD versus the intensity values from the DCVD. A linear relationship between the two measurements was demonstrated, with an R-squared value of 0.987.

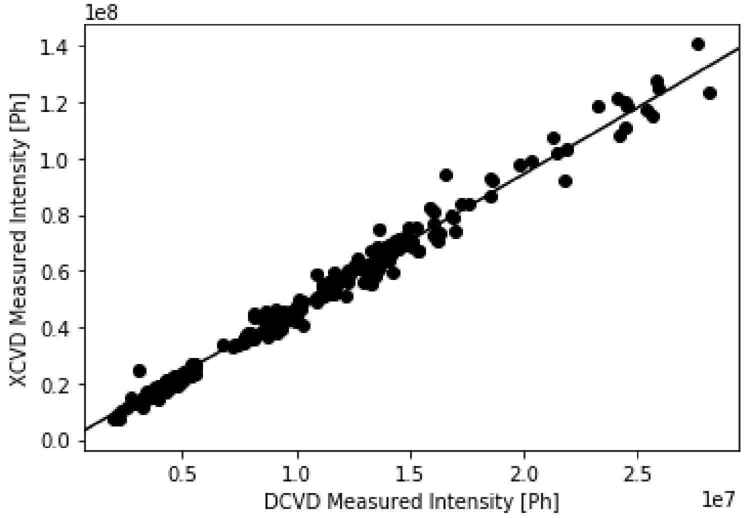


*Figure 4: DCVD vs. XCVD measured intensity for the first fuel population.*

The same was done for the second fuel population (Figure 5) and, again, a linear relationship between the two measurements was demonstrated, with an R-squared value of 0.939.

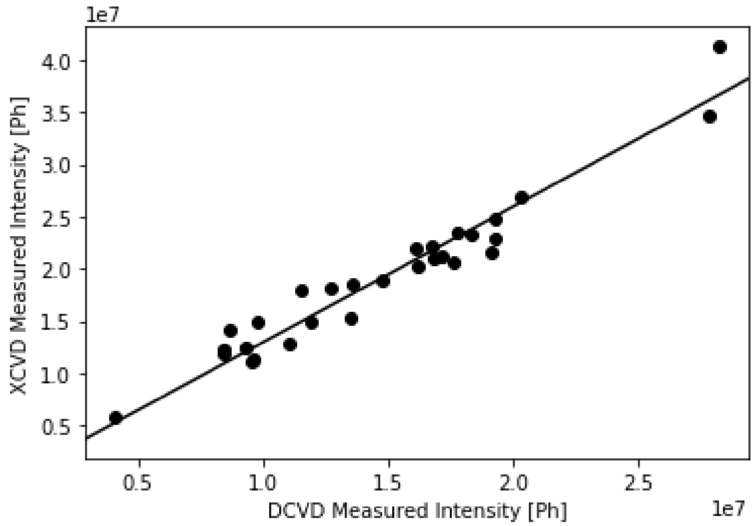


*Figure 5: DCVD vs. XCVD measured intensity for the second fuel population.*

Second, the distribution of the measured versus normalized predicted values was compared. For illustration, the typical output from a CVD for partial defect measurement plots the measured intensities versus the normalized predicted intensities. An example of this type of plot from XCVD and DCVD data for one type of fuel assembly is shown in Figure 6.

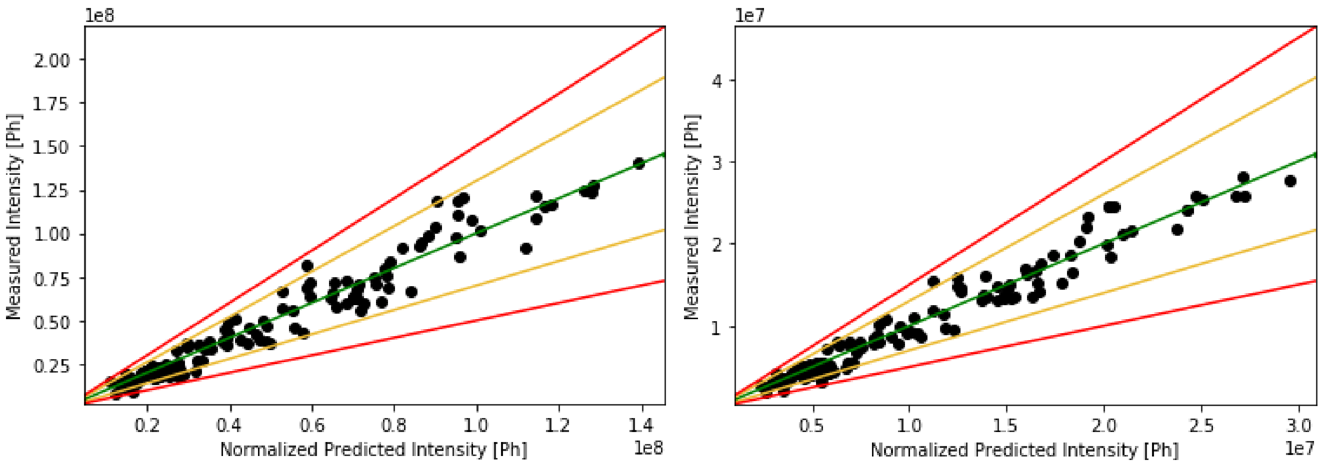


*Figure 6:Measured intensity from the XCVD versus normalized predicted intensity (left) and measured intensity from the DCVD versus normalized predicted intensity (right). Yellow lines indicate relative errors of ±30% and red lines indicate relative errors of ±50%.*

To compare the distribution, the relative errors were compared. In order to compare across the entire fuel population, the mean error of each group was subtracted from the individual error values so the distributions were centred at zero. Histograms of the zero-mean error values for the XCVD and DCVD are shown in Figure 7 for visual comparison.

To test whether the error distributions from the XCVD and DCVD differed significantly from one another, a Kolmogorov–Smirnov (KS) statistical test was performed on the entire fuel population and resulted in a KS value of 0.025 and a p-value of 0.999. This test demonstrated that the error distributions between the two instruments are not significantly different from each other and that the XCVD and DCVD produced comparable results.

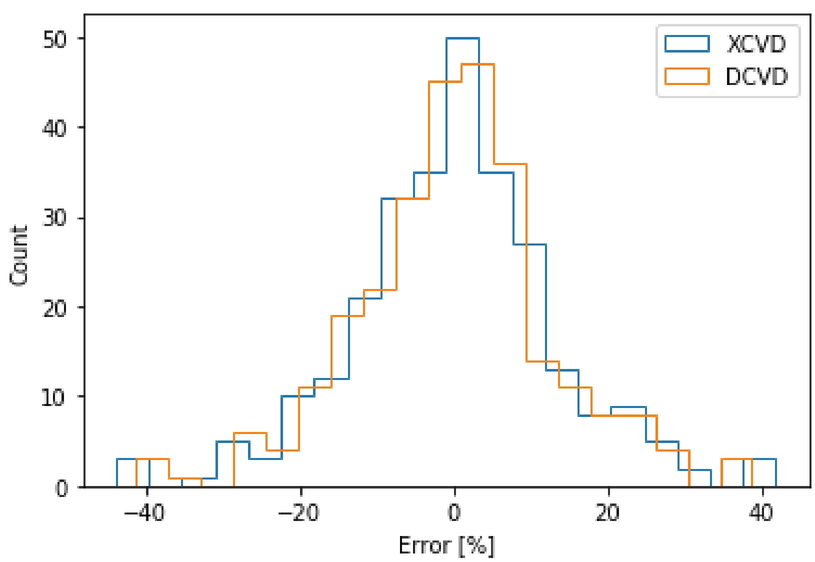


*Figure 7: Distribution of XCVD and DCVD zero-mean relative error values.*

# 4. Conclusions and Future Work

Based on the quantitative analysis of 274 fuel assemblies of nine types, the XCVD yields the same results as the DCVD when performing partial defect tests, but is five to ten times faster. The XCVD's much smaller size makes it much easier to carry and set up. This is a tremendous gain in efficiency and ease of use. Using the same measurement methodology for both instruments allowed the IAEA to quickly deploy the instrument in the field to perform verification. Based on the results presented in this paper, the IAEA has extended the authorization of the XCVD to include partial defect verification in addition to attribute testing (gross defect verification). The results from the first verification campaign with the XCVD demonstrated its highly consistent operation and functionality and highlighted the remarkable increase in efficiency.

There are several improvements planned for the analysis workflow, most importantly on the automation of the intensity calculation, as currently analysts must manually select the number of frames aligned over the fuel and set the ROI around each fuel. Both of these tasks could be done via automated algorithms. Further enhancements also may leverage different measurement methods, such as a maximum intensities map or quantification of the collimation effect. This would require further theoretical validation, work for which the IAEA would engage the research and development support of the Member State Support Programmes.

The RCVD, which contains the same optical hardware as the XCVD on a floating platform, is also slated to use this analysis workflow for partial defect verification. The RCVD can semi-autonomously scan a spent fuel pond while operators and inspectors stand off to the side (away from high dose areas instead of directly above the fuel), thus improving the instrument's efficiency and safety. Having the instrument float on top of the water mitigates one of the more problematic environmental conditions, in that it removes the effect of surface ripples which cause blurry images. Preliminary results from the RCVD demonstrated even higher gains in efficiency over the DCVD in challenging environmental conditions.

# References


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[4] ASE Optics. (2022) *XCVD F-method measurements feasibility study.* Internal report.