Detection of Partial Defects using a Digital Cerenkov Viewing Device

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Abstract. The International Atomic Energy Agency (IAEA) is using the digital Cerenkov viewing device (DCVD) to verify Light Water Reactor (LWR) spent fuel assemblies with cooling times as low as 40 years cooled and with burnups of less than 10,000 MWd/t U. The Swedish and Canadian support programs have investigated the ability of the non-intrusive DCVD to detect partial defects. The IAEA defines a partial defect as a fuel assembly with 50 percent or more of the fuel rods missing/substituted. This detection requirement presents a difficult challenge due to the complex structure of the fuel assembly and the environment in the storage pond. Previous studies have indicated that the quantitative nature of the DCVD permits the detection of missing/substituted fuel rods at the IAEA's definition of a partial defect. This ability assumes that the substituted rods are not radioactive. Preliminary tests on Pressurized Water Reactor (PWR) spent fuel indicate that it is possible to detect partial defects using the DCVD. Further tests were carried out to assess factors that affect the DCVD measurement ability to detect partial defects. The results from the measurement of 156 PWR fuel assemblies shows that it should be possible to detect a 50 percent partial defect in spent fuel. The results of this investigation are summarized in this paper.

1. Introduction

The reliable detection of partial defects in spent fuel using the DCVD requires an understanding of the environmental effects of the fuel pond, the operation of the instrument and the characteristics of the instrument. Field studies have been carried out to examine these factors and determine how they would affect the measurement of Cerenkov light. The studies include the attenuation effect of pond water, tested using a calibrated light source, the effect of focus on the measurement and linearity of the instrument response. These studies were carried out at Forsmark Sweden. In addition, a study was also performed in Ascó Spain to obtain a statistically significant sample of PWR fuel assembly measurements for partial defect studies. The results of these studies are discussed.

2. Attenuation effect of pond water

A calibration light source (CLS) was developed to examine the attenuation caused by the water in spent fuel storage ponds. Ultraviolet (UV) light emitted by spent fuel is strongly absorbed by organic compounds and scattered by microscopic particles. This absorption/scattering can be so severe that the Cerenkov light emitted by spent fuel cannot be detected by the DCVD. Tests were carried out at the Forsmark nuclear power plant to determine the absorption of UV light in what is considered to be a facility with high water quality.

The DCVD was used to measure the light intensity from the CLS. The CLS is shown in Fig. 1. It consists of four very stable ultraviolet light emitting diodes.

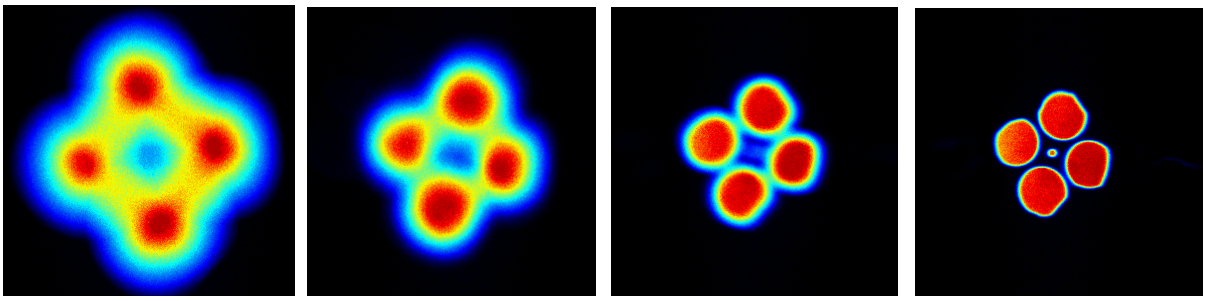
Fig. 1. Calibration light source

The CLS was positioned directly below the DCVD using two support cables. One cable supplies power and the second, a measuring tape or rope, provides a distance measurement from the DCVD to the top of the CLS. The two cables can be seen on either side of the DCVD that are held by two operators in Fig. 2.

Fig. 2. DCVD measurement setup at Forsmark bridge

The distance from the DCVD to the water surface is 4.48 meters and the top of the fuel assembly is 7 meters below the surface. The total distance from the DCVD to the top of a fuel assembly is 11.48 meters.

DCVD images of the CLS at a range of distances are shown in Fig. 3. The DCVD focus was set at 11.48 meters (the top of a fuel assembly) making the first three images out of focus.



5.48 meters | 7.48 meters | 9.48 meters | 11.48 meters (top of fuel, focussed)

Fig. 3. UV light images of CLS as a function of distance from DCVD in a fuel bay

The large measurement distances between the DCVD and the CLS allow the CLS to be considered a point source. Its intensity at different distances follows an inverse square law, given by the equation:

$$B = \frac{I}{r^2} \qquad (1)$$

where B is the measured flux, I is the flux of the light source at a reference position and r is the distance of the CLS to the DCVD. The readings at the DCVD must also account for refraction caused by the surface of the water. The inverse square law then becomes:

$$B = \frac{I}{r_c^{\ 2}} \qquad (2)$$

The corrected distance is:

$$r_c = r_{water} + nr_{air} \qquad (3)$$

Where r_{water} is the distance of the CLS to the water surface, r_{air} is the distance of the DCVD to the water surface (4.48 meters) and n (1.36) is the refractive index of the water. The first measurement taken at 5.48 meters (one meter below the surface of the water), was used as the initial value for the inverse law calculation to normalize the data. This is a good assumption because there should be minimal to no absorption of UV light from one meter of water. Both the measured and the inverse square law results (expected) are plotted in Fig. 4. The photon flux of the CLS is 1.65 x 10^{12} photons per square centimetre per second (measured using a calibrated radiometer).

Fig. 4 shows that the measured values are almost identical to the inverse square law values down to a distance of 8.48 meters. Then the measured intensities are less than the inverse square law values down to the bottom of the pond showing increasing UV light absorption likely due to impurities in the pond. This change in intensity is less than expected, indicating that the water contains very little ultraviolet light absorbing impurities. At the distance of 11.48 meters (top of fuel assembly) the difference in light intensity is 10 percent. This attenuation is attributed to absorption or scattering of the UV light by impurities in the water. The data show increasing absorption beyond a depth of 12 meters.

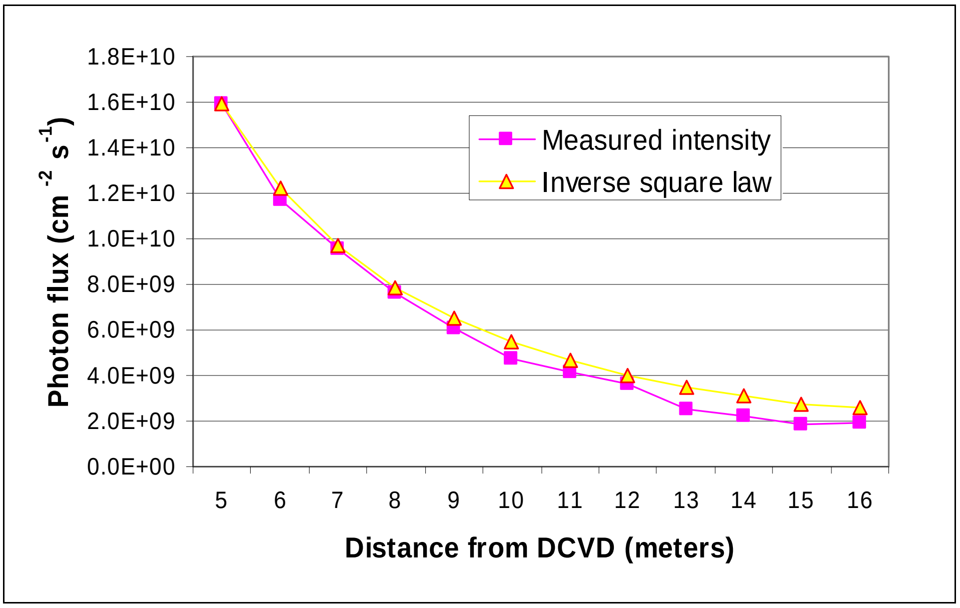
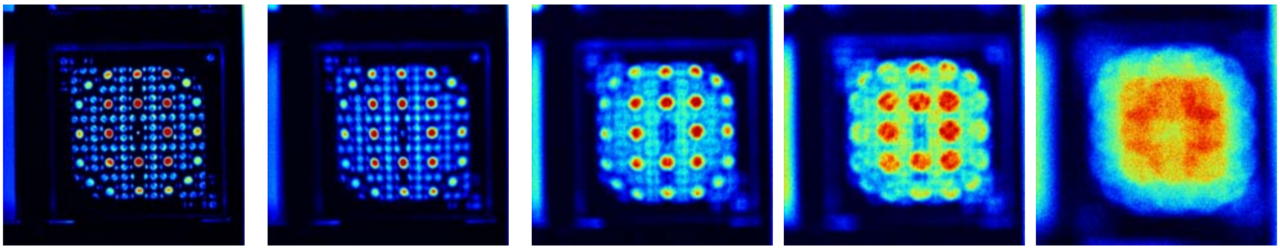


Fig. 4: Calibration light source intensity as a function of distance from DCVD

3. Effect of focus on measured intensity

Different measurements using the DCVD can potentially use different degrees of focus. The objective of this test was to determine what happens to the measured photon flux when an image is out of focus. This test shows the effect that focus has on the overall photon flux measurement.



1 2 3 4 5

Fig. 5: Progressively defocused images of a PWR fuel

A series of Cerenkov images of a fuel assembly were taken from a fixed position. Each image is defocused to a degree from the initial focused image. The photon flux for the fuel assembly is then calculated using an algorithm that calculates the Cerenkov intensity of the fuel assembly [1] from the DCVD image. The images can be seen in Fig. 5.The left most image (image 1) is sharply focussed. In the subsequent images (2 to 5 left to right), the focus quality decreases to the last image where the image is not recognizable as a fuel assembly.

Table 1: Effect of focus on integrated intensity

Image	Photon flux (counts)	Percent change
1	18,273,317	0.0%
2	18,318,570	0.2%
3	18,605,757	1.8%
4	18,787,876	2.8%
5	18,990,757	3.9%

Table 1 summarizes the results for the defocused images. The effect of focus on the photon flux is minor. The difference in the gross intensity value between the first two images is less than 0.25 percent although the image is noticeably out of focus. The difference between the first and third image is surprisingly small given the degree of defocus.

These results show that a minor change in focus of the instrument will not have a significant effect on the photon flux value and will have little if any effect on the ability to detect partial defects.

4. Instrument linearity tests

A fuel pond will have fuel assemblies with a range of burnups and cooling times and it may be necessary to increase the integration time to obtain sufficient intensity from some assemblies and reduce the integration time for assemblies with high Cerenkov light emission. The objective of this test is to determine if the measured intensity value of a fuel assembly increases linearly with an increase in integration time.

To perform this test, a series of measurements of a spent fuel assembly with a burnup of 28 MWd/kg U and a cooling time of 2.3 years were captured at increasing integration times. Integration times ranged from 1/30th of a second to 4 seconds. Two measurements were acquired at each integration time. All other DCView settings were held constant.

The resulting measurements were then processed to determine the integrated intensity at each of the integration times. The results are shown in Fig. 6

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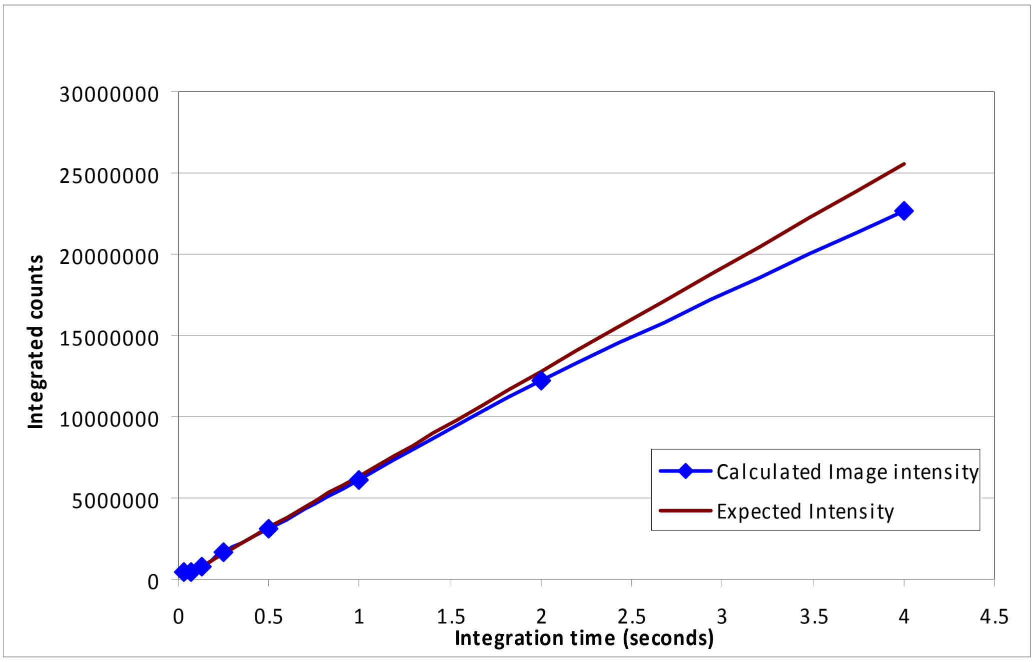

Fig. 6. Integrated intensity as a function of integration time

The response shown in Fig. 6 was unexpected because the integrated intensity should increase proportionally with integration time. Further examination of the data showed that the maximum pixel intensities in the images were not increasing proportionally with the integration time. This has been attributed to saturation in the gain register of the detector when the integration time was greater than 0.5 seconds. In the range from 0.067 to 0.5 seconds the response is linear as expected (Fig. 7). This means that for this study and the subsequent studies that saturation has likely occured where the maximum pixel intensity values exceed 4000 counts. For pixel intensity values below 4000 the response is predictable. The DCVD must be set up so that the gain register does not become saturated for the exposure times used.

The results of this test indicate that the integrated intensity of a measurement can be scaled based on integration time to allow comparison with images taken using a different integration time.

This is important for facilities that have fuel assemblies both with very long and very short cooling times. More study is required to determine if this scaling factor is specific for each detector.

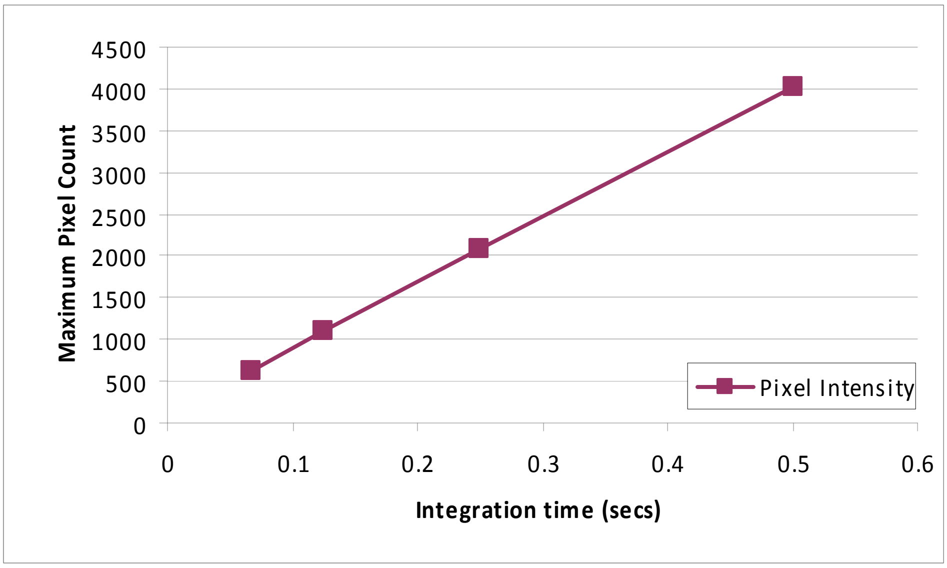

Fig. 7. Pixel intensity (0.067 to 0.5 seconds)

5. Measurement of PWR fuel assemblies for partial defects

A total of 156 PWR spent fuel assemblies were measured at the Ascó nuclear power plant to assess the capability of the DCVD to detect partial defects, defined by the IAEA as 50 percent missing or substituted fuel rods. Two or three measurements were taken of each fuel assembly and the intensity values were calculated as an average of the measurements. The expected intensity was interpolated from the theoretical data [3] using the cooling time and burnup of the assembly (Fig. 8).

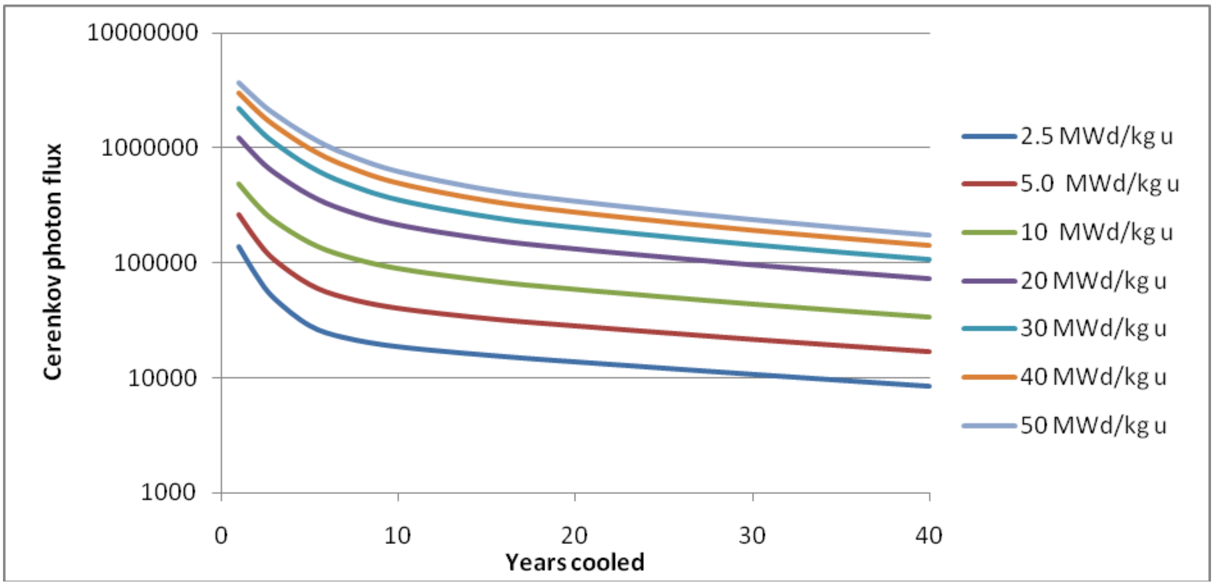

Fig. 8. Theoretical photon flux (intensity) for fuels of differing burnup and cooling time

The fuel assemblies measured had a wide range of burnups and cooling times. Since the exact integrated intensity reduction of a 50 percent partial defect is not known, a lower boundary of 30 percent less than the expected intensity is calculated, simulating the intensity level of a partial defect. (If 50 percent of the fuel rods are substituted with steel rods, it is assumed that the intensity of the fuel assembly will be reduced by at least 30 percent). An upper boundary was also plotted by adding 30 percent to the expected intensity. The results of this test are shown in Fig. 9.

Fifty-six of the fuel assemblies measured had inserts; control rods, burnable poisons and thimble plugs, which reduced the measured intensity. This provided an opportunity to study the effect of inserts on the measured intensity and also gives an indication on the overall contribution of Cerenkov light by the guide tubes to the total intensity of the fuel assembly. Comparing the integrated intensity of these assemblies to fuel assemblies without inserts with similar burnup and cooling times indicates that the inserts reduce the integrated intensity by 30 percent. The measured intensity values, also plotted in Fig. 9, are consistent with this observation.

Several assemblies showed measured intensities significantly higher than expected. This could be caused by the non-linearity (saturation) phenomenon described earlier or could be a result of a design change or position difference in the spacer grid configuration which allows more Cerenkov light to be emitted from the fuel assembly. Further investigation is required to confirm the cause of this anomaly.

The plot shows that the measured intensity values are generally within ±30 percent of the expected value. The results indicate that these assemblies do not have a partial defect as defined by the IAEA.

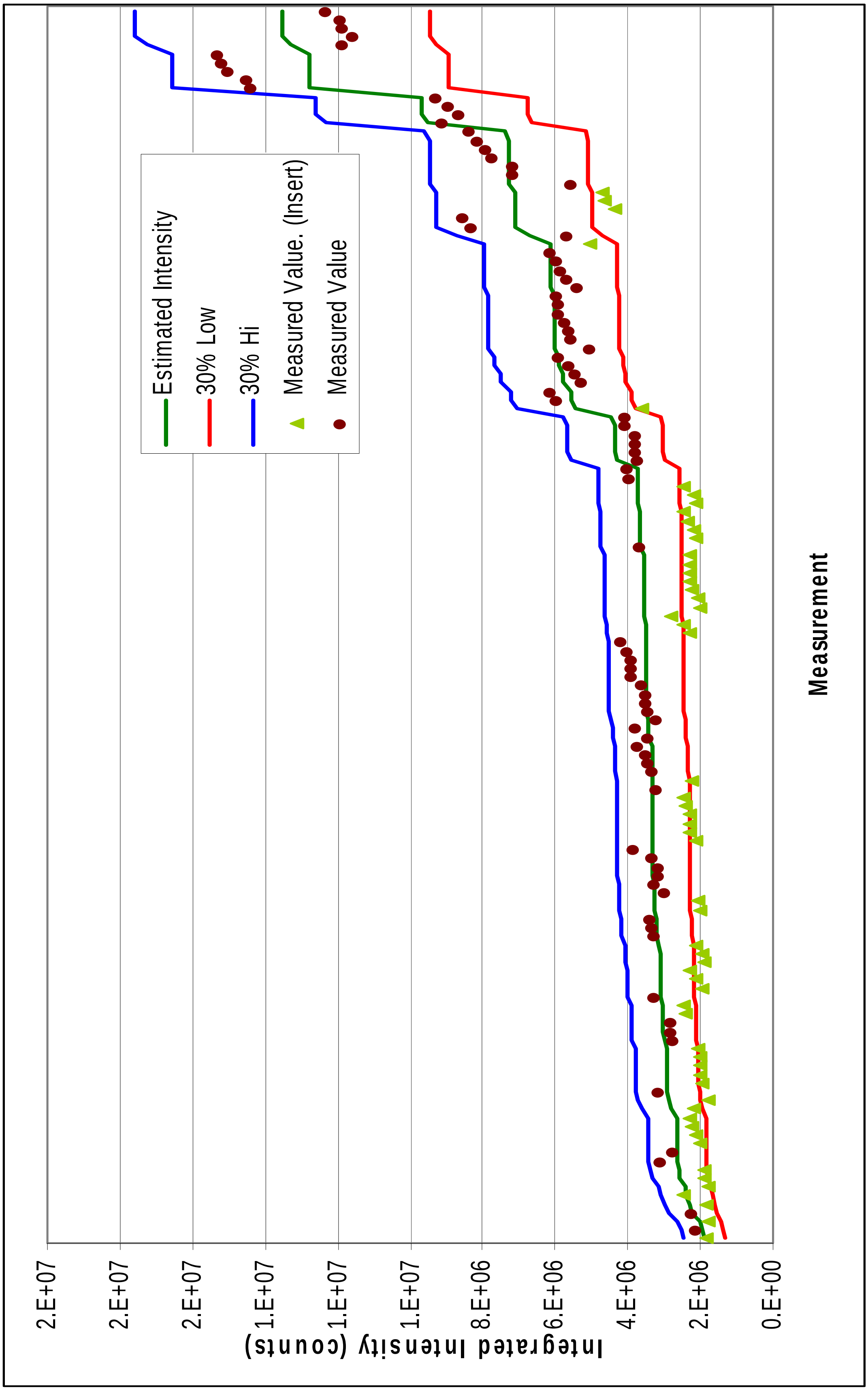

Fig. 9. Integrated intensity of surveyed fuel assemblies

6. Conclusions

Field tests to assess the impact of water quality on DCVD measurements showed that the water quality in the Forsmark fuel ponds is quite high resulting in a UV light attenuation of less than 10 percent. Cerenkov light attenuation in this facility is likely to have little impact on a DCVD measurement.

Small changes in focus of the DCVD which are likely as the instrument is used by different operators will not have a significant effect on the accuracy of the measurements.

The DCVD responds predictably to increases in the measurement integration time. This means that measurements of fuel assemblies with lower Cerenkov light output (long cooled and/or low burnup) can be scaled so comparison to fuel assemblies with higher Cerenkov light output is possible.

The measurement results of PWR fuel assemblies at the Ascó NPP show that the measured Cerenkov light output falls within a reasonably tight tolerance of what is predicted by the burnup and cooling time declarations. Fuel assemblies measured showed results that were close to expected although some assemblies measured unexpectedly high. Cerenkov light output of PWR fuel assemblies with inserts is reduced by 30%. These results lead us to believe that a PWR spent fuel assembly that has a partial defect of 50% substituted fuel pins can be detected as an anomaly using the DCVD. If fuel assemblies with similar burnup and cooling time are grouped in the same area and evaluated as a group, the detection of even smaller defects may be possible if the DCVD operator was specifically looking for a defect.

7. Acknowledgements

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8. References

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