

PARTIAL DEFECT DETECTION IN LWR SPENT FUEL USING A DIGITAL CERENKOV VIEWING DEVICE

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ABSTRACT

Previous studies on the detection of partial defects focussed on the detection of a small number of missing or substituted fuel rods in a spent fuel assembly. Attention has now been directed to the diversion of fifty percent or more fuel rods, which is considered to be a more credible diversion scenario. The diversion of fifty percent of the fuel rods in a fuel assembly by rod substitution using stainless steel or zirconium rods should cause a decrease in the total Cerenkov light output from the fuel assembly. Studies were carried out in the laboratory and in the field to determine the ability of the digital Cerenkov viewing device (DCVD) to detect this expected decrease in Cerenkov light intensity. Because there are no real examples of LWR fuel with fifty percent rod substitution, a spent fuel assembly was modelled using ORIGEN-ARP, GEANT4 and ZEMAX to produce a Cerenkov light intensity at the detector of the DCVD. The preliminary laboratory, field and modelling results on the ability of the DCVD to detect partial defects will be given.

INTRODUCTION

Measurements of spent fuel using the digital Cerenkov viewing device (DCVD) produces a Cerenkov glow image of a spent fuel that is rich in features. The Cerenkov image is complex due to the number and arrangement of fuel rods, the top nozzle and lifting handle and the spacer grids within a fuel assembly. Initial DCVD development studies focussed on the high sensitivity of the instrument to detect low burnup and long-cooled spent fuel. The DCVD was able to detect fuel cooled for 40 years with a burnup of less than 10 000 MWd/t U [1]. More recently, development studies have focussed on the detection of partial defects. A partial defect is presently defined by the International Atomic Energy Agency (IAEA) as 50 percent missing or substituted fuel rods. Field studies have shown that the DCVD is capable of detecting a single missing fuel rod if it is not obscured by the top structure of the fuel assembly. Additionally, a single irradiated zircaloy rod located on the outside edge of a boiling water reactor fuel assembly can be detected [2]. Studies have turned to the ability to detect 50 percent substituted steel fuel rods in a fuel assembly.

The ability of the DCVD to detect fuel rod substitution is based upon the assumption that substituted rods are not radioactive and will not contribute to the overall Cerenkov glow intensity of the fuel assembly. If an assembly has 50 percent of its fuel rods replaced by steel rods, the overall light intensity should decrease and it should be possible to detect this lower light intensity from the fuel assembly using the DCVD.

Field studies were carried out to determine the degree of uncertainty caused by the precision of measurement, alignment of the DCVD over a fuel assembly, fuel design and near neighbours. The results of this study have been previously presented [3] and are briefly discussed.

To provide support for the field studies, modelling studies were carried out on fuel rod substitution for a PWR fuel assembly using ORIGEN-ARP, Geant4 and Zemax to produce a Cerenkov light flux at the detector of the DCVD.

QUANTITATIVE MEASUREMENTS

Quantitative measurements of light water reactor fuel were taken using the DCVD at the Ringhals nuclear power plant (Figure 1). The DCVD images were analyzed to obtain the total Cerenkov light emitted by the spent fuel assemblies. Precision measurement on a number of pressurized water reactor (PWR) and boiling water reactor (BWR) fuel assemblies gave 2 sigma precisions of less than ± 4 percent.



Figure 1. DCVD mounted on fuelling machine at Ringhals nuclear power plant fuel bay

Instrument alignment studies on PWR and BWR fuel showed that within ± 5 cm of the alignment point the difference in measured intensity is less than 5 percent of that obtained when the instrument is correctly aligned over the fuel assembly. Field measurements on fuel assemblies with 3 and 4 near neighbours showed no statistical difference in intensity with fuel with similar burnups and cooling times.

A 4x6 storage grid containing 16 fuel assemblies was measured to determine whether it is possible to detect a 50 percent fuel rod substitution. The degree of substitution should produce a corresponding decrease in Cerenkov light intensity because the substituted rods (stainless steel) are not radioactive and do not contribute to the Cerenkov light intensity of the fuel assembly. To determine whether it is possible to detect 50 percent fuel rod substitution, it is necessary to compare the measured results with the theoretical calculated results [4, 5]. If there is a 50 percent fuel rod substitution the measured light intensity is expected to be 50 percent lower than the theoretical calculated results. The results are summarized in Table 1. Not included in the table are 4 fuel

assemblies with 0.2 years-cool fuel because there are no theoretical calculations for fuel cooled less than one year. In the table, the heading “Expected intensity” is the theoretically calculated relative intensity and “Measured intensity” is the total number of counts obtained from the DCVD Cerenkov image.

Table 1: PWR spent fuel intensities and normalized data

PWR assembly information					2Y2, reference	
Fuel ID	Cooling time (years)	Bumup (MWd/ kg U)	Expected intensity (counts)	Measured intensity (counts $\pm 5\%$)	Expected difference	Measured difference
2Y2	1.3	46	3.38×10^6	8.14×10^7	0%	0%
1X2	2.3	46	2.24×10^6	6.10×10^7	34%	25%
1V4	3.3	45	1.68×10^6	3.73×10^7	50%	54%
1X3	3.3	44	1.64×10^6	4.25×10^7	52%	48%
1W2	3.3	47	1.75×10^6	4.07×10^7	48%	50%
1W7	3.3	48	1.79×10^6	4.04×10^7	47%	50%
03V	3.3	45	1.69×10^6	3.65×10^7	50%	55%
0V7	3.3	47	1.75×10^6	4.06×10^7	48%	50%
02V	3.3	45	1.68×10^6	3.80×10^7	50%	53%
1X6	3.3	44	1.64×10^6	4.58×10^7	52%	44%
3V6	4.3	45	1.35×10^6	2.49×10^7	60%	69%
5A0	14.3	23	1.98×10^5	5.48×10^6	94%	93%

Fuel assembly 2Y2 was arbitrarily used as a reference assembly to normalize the expected (calculated) and measured Cerenkov light intensities for all of the fuel assemblies. The expected and measured values show good agreement. This data indicates that there are no significant partial defects in this grid of fuel assemblies. Figure 2 shows the relationship of expected and measured intensities relative to assembly 2Y2.

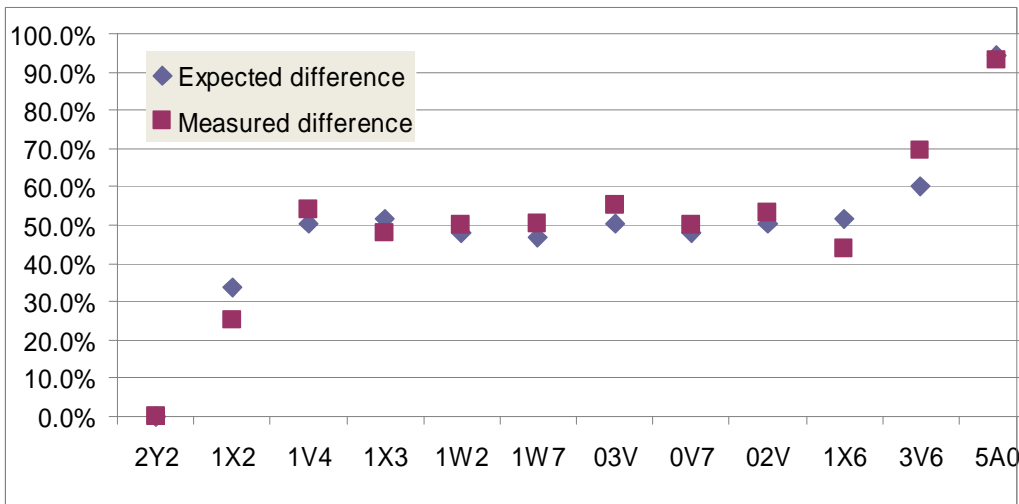


Figure 2. Expected and measured intensities relative to PWR assembly 2Y2

Fuel assembly 2Y2 has an expected intensity of 3.38×10^6 counts (no partial defect) and if we assume that this assembly has a 50 percent partial defect, this assembly should then produce a 50 percent lower light output. In the list of fuel assemblies, IV4 has an expected intensity of 1.68×10^6 counts which is about half of the expected light intensity of 2Y2. The measured light intensity is 54 percent of 2Y2 which is in excellent agreement with the expected value of 50 percent. These results indicate that that the DCVD should be able to detect a 50 percent decrease in light intensity and therefore a 50 percent partial defect.

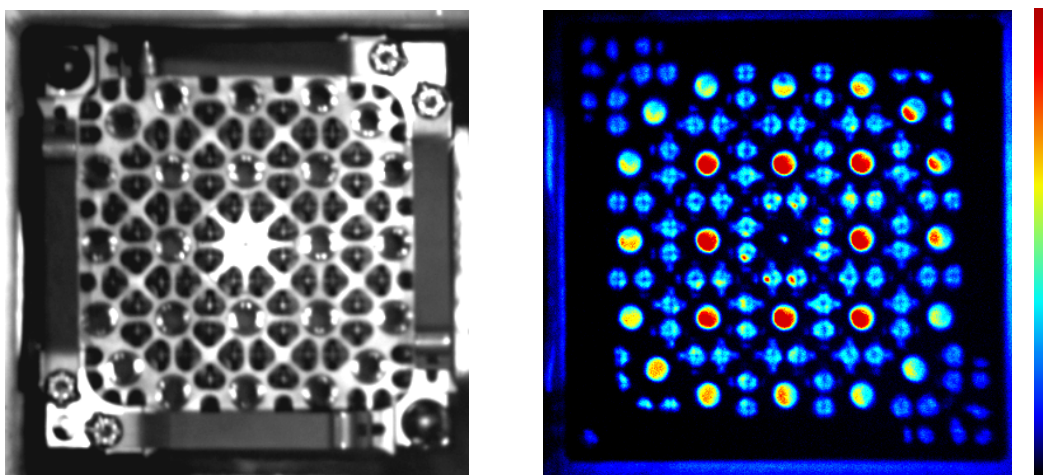
If we now assume that 2Y2 has a 30 percent partial defect, this assembly should produce 30 percent lower light intensity. In the list of fuel assemblies 1X2, has an expected intensity of 2.24×10^6 counts which is 34 percent lower in light intensity and the measured decrease in light intensity is 25 percent which is in fair agreement. This data indicates that it may be even possible to detect a 30 percent partial defect.

MODELLING

To provide support for the field study conclusions, modelling studies were carried out on a PWR fuel assembly. From Ringhals 3, a Framatome (Areva) 17x17 PWR fuel assembly 4X1, AFA-3GA, 44 931 MWd/t U burnup, cooled 2.3 years was modelled. The fuel depletion code ORIGEN-ARP [6] was used to calculate the gamma energy spectrum of the fuel assembly, Geant 4 ,version Geant 4.9.1.p03, [7, 8, 9] was used to calculate the Cerenkov light production and Zemax [10] was used to trace the Cerenkov photons from the fuel assembly to DCVD detector mounted on a bridge railing above the fuel assembly.

Fuel rod substitution scenarios

The fuel assembly to be modelled is shown in Figure 3. The visible light image shows the top nozzle of the fuel assembly and the lifting handle used to raise and lower the fuel assembly. The fuel rods are difficult to detect in this image. The DCVD Cerenkov image shows details of the structure of the fuel assembly. The dark blue colour is low light intensity and the red colour is high intensity. The fuel rods can be detected in this image by their dark round shapes. This AFA-3GA fuel assembly contains 264 fuel rods and 25 guide tubes.



Visible light image
Cerenkov light image
Figure 3. Framatome AFA-3GA, 4X1, 17x17 PWR fuel assembly

Rather than model 50 percent substitution it was decided to model a 30 percent fuel rod substitution. Substitution of 30 percent of the fuel rods represents about 80 fuel rods in the PWR fuel assembly. The substituted rods were to be blackened stainless steel rods. These stainless steel rods were to be substituted under the lifting handle of the fuel assembly, interspersed within the assembly but not under the handle and in one quadrant but not under the lifting handle. Only 40 stainless steel rods were substituted into one quadrant because 80 stainless steel rods would fill the entire half of the assembly. It was felt that this lower number could be easily detected.

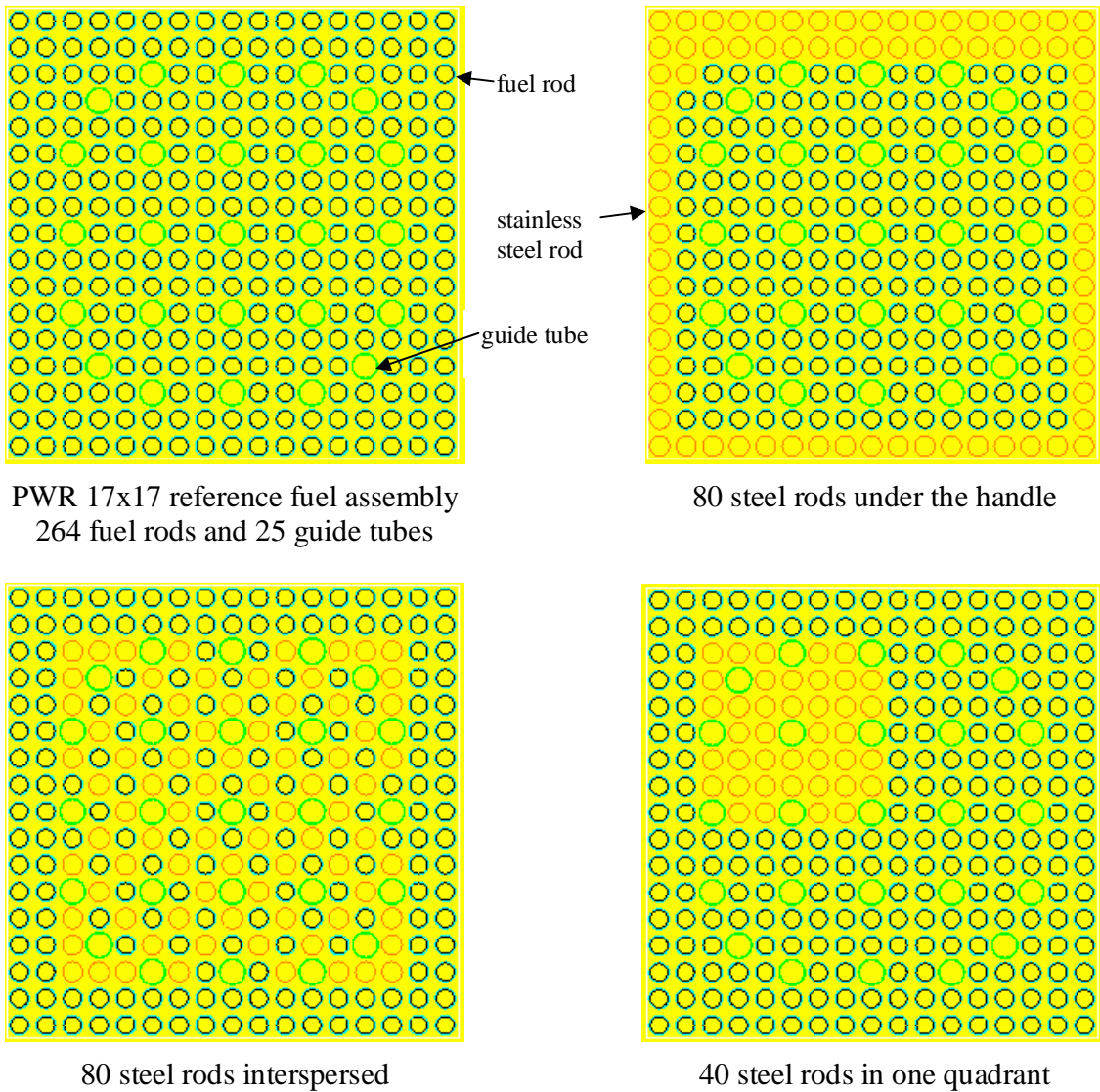
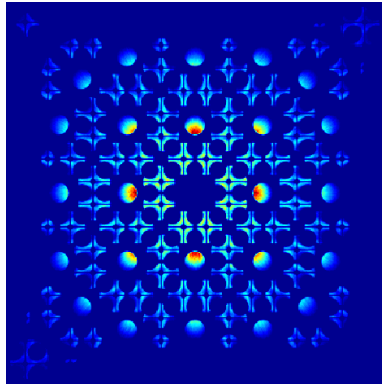


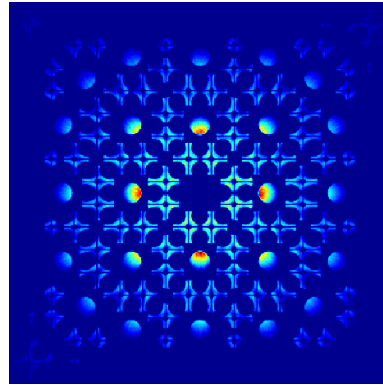
Figure 4. Four modelling cases for partial defect studies

Modelling results

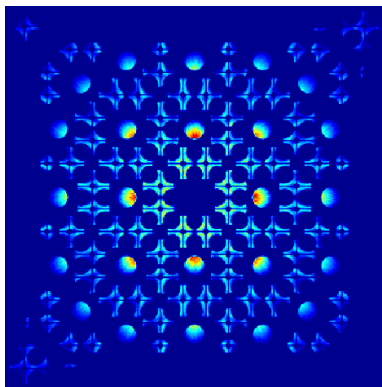
The Zemax results for the modelling are shown in Figure 5. The spacer grids and top nozzle structure are included in the model and all mechanical parts are assumed to be black and totally light absorbing. The DCVD is positioned directly above the centre of the fuel assembly.



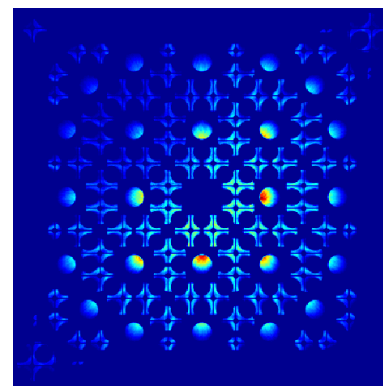
PWR 17x17 reference fuel assembly



80 steel rods under handle



80 steel rods interspersed



40 steel rods in one quadrant

Figure 6. Modelling results for partial defects

For the case of 80 steel rods under the handle, the outer guide tubes are noticeable darker than the reference PWR fuel assembly. Visually it is difficult to discern any difference between the reference fuel and the case with 80 interspersed steel rods. It is obvious that there are substituted rods (40 steel rods) in one quadrant because of the significantly lower light intensity.

The quantitative results for the four cases are given in Table 2. When the 80 steel rods are placed under the handle, the decrease in light intensity is only 15 percent. This smaller decrease was expected because the outer two rows of fuel rods are hidden under the lifting handle and do not contribute as much to the total light intensity compared to fuel rods located in the centre of the fuel assembly. The second case of 80 steel fuel rods interspersed in the fuel assembly shows that the Cerenkov light intensity decreases by 40 percent when compared to the reference PWR fuel assembly. This value is higher than expected for a 30 percent fuel rod substitution. Substitution of

40 steel rods (15 percent) in one quadrant of the fuel assembly results in a 22 percent drop in light intensity. Additionally, it is visually very noticeable in the modelled image (Figure 6) that fuel rod substitution has occurred because of the significantly reduced light intensity in the quadrant with the substituted rods.

Table 2. Quantitative modelling results

Modelled case	Calculated relative image intensities	Decrease in intensity
PWR 17x17 reference fuel assembly	4.57×10^7	
80 steel rods under handle (30%)	3.87×10^7	15%
80 steel rods interspersed (30%)	2.74×10^7	40%
40 steel rods in one quadrant (15%)	3.58×10^7	22%

DISCUSSION

For the case of 30 percent of the steel rods located under the handle, the decrease in total intensity is only 15 percent. The ability to detect this diversion using the DCVD may be possible but requires more experimental work to determine whether this difference can be reliably detected quantitatively. However, the modelled image indicates that there is lower light intensity in the guide tubes adjacent to the fuel rod substitution relative to the reference fuel assembly. It may be possible to detect this anomaly by taking an intensity profile across the fuel assembly. The visual difference between the modelled reference PWR fuel assembly and the case with 80 interspersed steel rods is indistinguishable. However, the modelled intensity shows a significant 40 percent decrease in light intensity. From the previous experimental field data, this indicates that 30 percent fuel rod substitution should be readily detected when the steel rods are interspersed in the assembly. The substitution of 40 steel rods (15 percent) in one quadrant was readily detected visually from the modelled image. The decrease in light intensity is 22 percent and should be detectable quantitatively using the DCVD but require further studies to confirm this ability.

CONCLUSION

Field measurements on PWR spent fuel assemblies have shown that it should be possible to detect 50 percent fuel rod substitution and perhaps even 30 percent. Modelling studies have shown that:

- 30 percent fuel rod substitution under the lifting handle may be detectable quantitatively and perhaps visually
- 30 percent fuel rod substitution interspersed in the fuel assembly can be detected quantitatively but not visually
- 15 percent fuel rod substitution in a quadrant can be detected quantitatively and can be easily detected visually

To confirm the ability of the DCVD to detect these types of fuel rod substitution, it is necessary to measure actual spent fuel assemblies with substituted rods.

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