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CSSP Report 2004-01-02 **SKI Report ISRN SKI-R-03/46**

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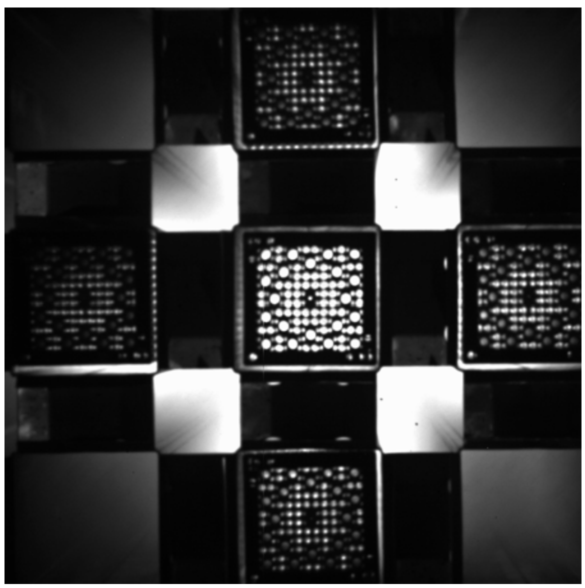

Canadian and Swedish Safeguards Support Programs

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CERENKOV CHARACTERISTICS OF PWR ASSEMBLIES USING A PROTOTYPE DCVD WITH A BACK-ILLUMINATED CCD

Prepared for the Canadian Safeguards Support Program
and the Swedish Support Program

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ABSTRACT

The Canadian and Swedish Safeguards Support Programs have developed a prototype Digital Cerenkov Viewing Device (DCVD) to verify spent fuel. Field measurements were conducted in January 2003 at the Swedish facilities CLAB and Ringhals Unit 2 on PWR fuel and non-fuel assemblies. The images obtained are documented and the Cerenkov characteristics observed are discussed. New Cerenkov information obtained offers the possibility of computer assisted verification of spent fuel and non-fuel assemblies. Quantitative analysis for parameters such as cooling time, alignment and Cerenkov glow as a function of distance are discussed.

Document Revision History

Revision 0 2003 November 12

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1 INTRODUCTION

In 1993 the Swedish and Canadian Safeguards Support Programs began a joint program to develop a high sensitivity Cerenkov viewing device. A commercial instrument was purchased from AstroCam (Cambridge, UK) and subsequently tested at Swedish nuclear facilities. The results of these tests have been documented[1, 2, 3]. More recently, a new charge-coupled-device (CCD) camera system was purchased from Andor Technology (Belfast). It was tested at Central Interim Storage for Spent Fuel (CLAB) in Sweden on pressurized-water reactor (PWR) fuel and non-fuel, long-cooled boiling-water reactor (BWR) fuel, and Ågesta test reactor fuel assemblies[4]. This instrument is called the prototype digital Cerenkov viewing device (DCVD). It incorporates a Marconi back-thinned, UV-enhanced, 1024 × 1024 frame-transfer CCD with an ultraviolet light (300 nm) quantum efficiency of 52%. The Andor camera was connected to a portable computer system based upon the PC/104-*plus* format, the Cerenkov images were viewed on a liquid crystal display (LCD), and a railing bracket held the camera steady to obtain the Cerenkov images of the spent fuel. The prototype DCVD instrument was successful in meeting the measurement objective of verification of fuel with a burnup of 10 000 Wd/t U and cooling time of 40 years.

This report discusses studies carried out in Sweden at the Ringhals Nuclear Power Plant Unit 2 and CLAB during the period January 14-24, 2002. It focuses on the Cerenkov characteristics of a variety of PWR spent-fuel and a non-fuel assembly using the prototype DCVD. The prototype DCVD instrument study on BWR fuel and non-fuel assemblies is published in a separate report[5].

2 INSTRUMENTATION

The prototype DCVD was slightly modified as a result of the first field test of the instrument[4]. New ergonomic handles were installed and the railing bracket was modified to hold the new handles on the camera. A detailed description of the instrumentation can be found in the first field test report. The DCVD system mounted on Ringhals Unit 2 walking bridge is shown in Figure 1.

3 EXPERIMENTAL RESULTS

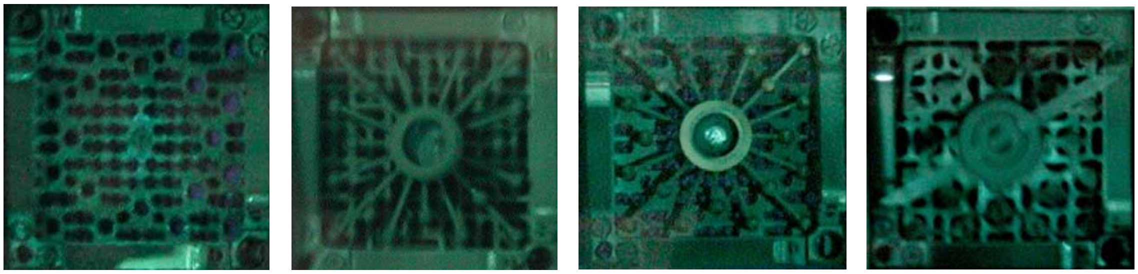
This report normally shows images of the fuel or non-fuel assembly from a normal camera, a Mark IVe Cerenkov viewing device (CVD) and from the prototype DCVD instrument. The camera pictures were taken with a Nikon COOLPIX 990 digital camera, often with a 3X tele-extender. To obtain the CVD images, the Nikon camera was attached to the Mark IVe CVD. Most of the measurements with the prototype DCVD instrument were taken using the 105-mm lens rather than the 250-mm lens because of the small field of view (one fuel assembly) with this longer lens.

Because of the digital nature of the data, the brightness and contrast of images reproduced in this report have been scaled to produce good images. It is difficult to directly compare image intensities in this report without examining the un-scaled, original data. For example, an assembly image that has only a few counts in each pixel (a long-cooled fuel or a short exposure time) can be scaled to look as bright as one that has many counts.

Figure 1: The prototype DCVD mounted on the Ringhals Unit 2 bridge

3.1 Cerenkov characteristics of PWR spent fuel

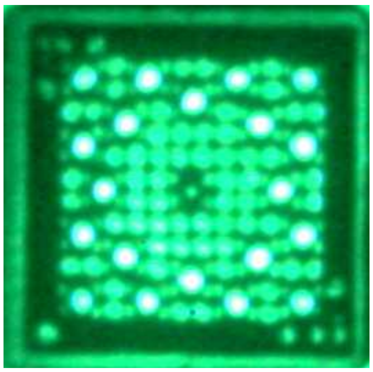
A number of different fuel assemblies with the 15 × 15 array of fuel rods were examined. These assemblies are identified as Siemens, Siemens FOCUS and Westinghouse Performance+ assemblies. In addition, these assemblies can have control rods (commonly called a spider) or a flow restrictor (stopper) inserted into the guide tubes. Figure 2 shows normal, visible-light images.



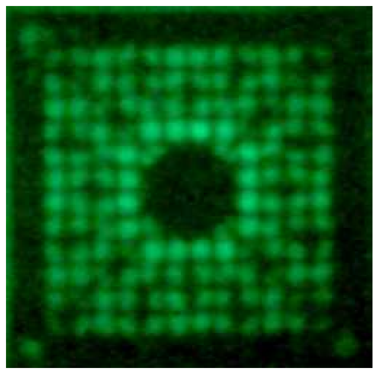
Spent fuel	Spider	Spider	Stopper
Westinghouse Performance+	Westinghouse Performance+	Siemens	Siemens

Figure 2: Normal camera images of PWR spent fuel and fuel with inserts

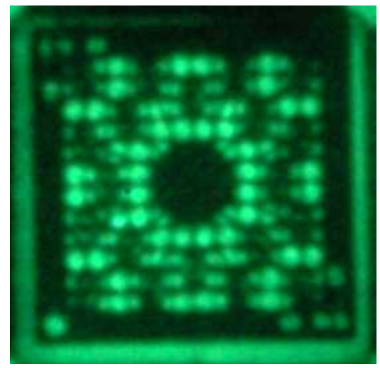
Figure 3 shows the CVD images of the above fuel assemblies. The image of the fuel assembly is overexposed, but the bright guide tubes and dark fuel rods are obvious. The next two CVD images show control rods inserted into the guide tubes of the two types of fuel assemblies. These images show the characteristic radiating arms from the central hub of the assemblies. Additionally, there is a bright area around the central hub of the assembly. Fuel rods can be resolved, but the bright guide tube holes cannot be detected because of the inserted control rods, or spider. The CVD images of the Siemens and Westinghouse Performance+ assemblies with spider inserts are very different. The last two images show stoppers inserted into the guide tubes of Siemens and Siemens FOCUS fuel assemblies. The CVD images show the dark diagonal handle (more difficult to detect in the Siemens FOCUS fuel assembly), which is used to install and remove the insert. The Siemens assembly shows a dark outline of the stopper and the dark fuel rods. It is difficult to resolve the fuel rods and the structure of the stopper in the Siemens FOCUS fuel assembly.



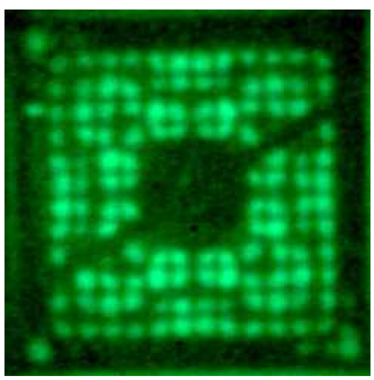
Spent fuel
Siemens



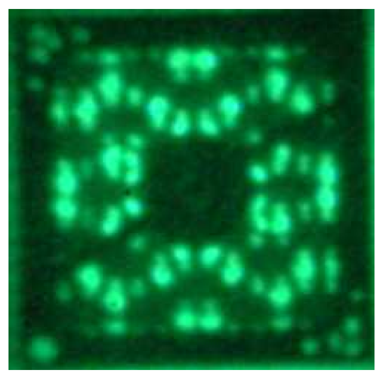
Spider
Siemens



Spider
Westinghouse Performance+



Stopper
Siemens



Stopper
Siemens FOCUS

Figure 3: CVD images of PWR fuel assemblies with and without inserts

The DCVD images of these fuel assemblies are shown in Figure 4. They are higher in resolution compared to the CVD images and details, such as spacer grids, can be easily detected. The spent-fuel assembly shows well-defined dark fuel rods, spacer grids below the top nozzle, the very bright guide tubes and the brighter central region of the assembly. The second image shows the spider inserted into a Siemens spent-fuel assembly. The radiating arms of the spider can be clearly seen; no light can be detected from the filled guide tubes and there is a bright area surrounding the central hub of the spider. The third image is a Westinghouse Performance+ fuel assembly with a spider insert. The dark fuel rods can be detected, the spider's radiating arms from the central hub are just detectable and light from the guide tubes is absent. The first image in the second row shows a Siemens assembly with a stopper. The dominant feature is the apparent large central hub, which is in fact round but looks square because it is superimposed on the top nozzle of the fuel assembly. The dark outline of the stopper can be detected along with the diagonal handle of the stopper. The next image in the row is a Siemens FOCUS assembly with a stopper. Its appearance is very different than the Siemens assembly with a stopper. It is difficult to resolve the normal Cerenkov characteristics of spent fuel. The dark fuel rods are difficult to detect, there are no bright guide tubes and the handle of the stopper is also difficult to detect. The last image in the second row is the same image except it is scaled higher (brighter). The image shows the characteristic round central hub of the stopper and the diagonal handle.

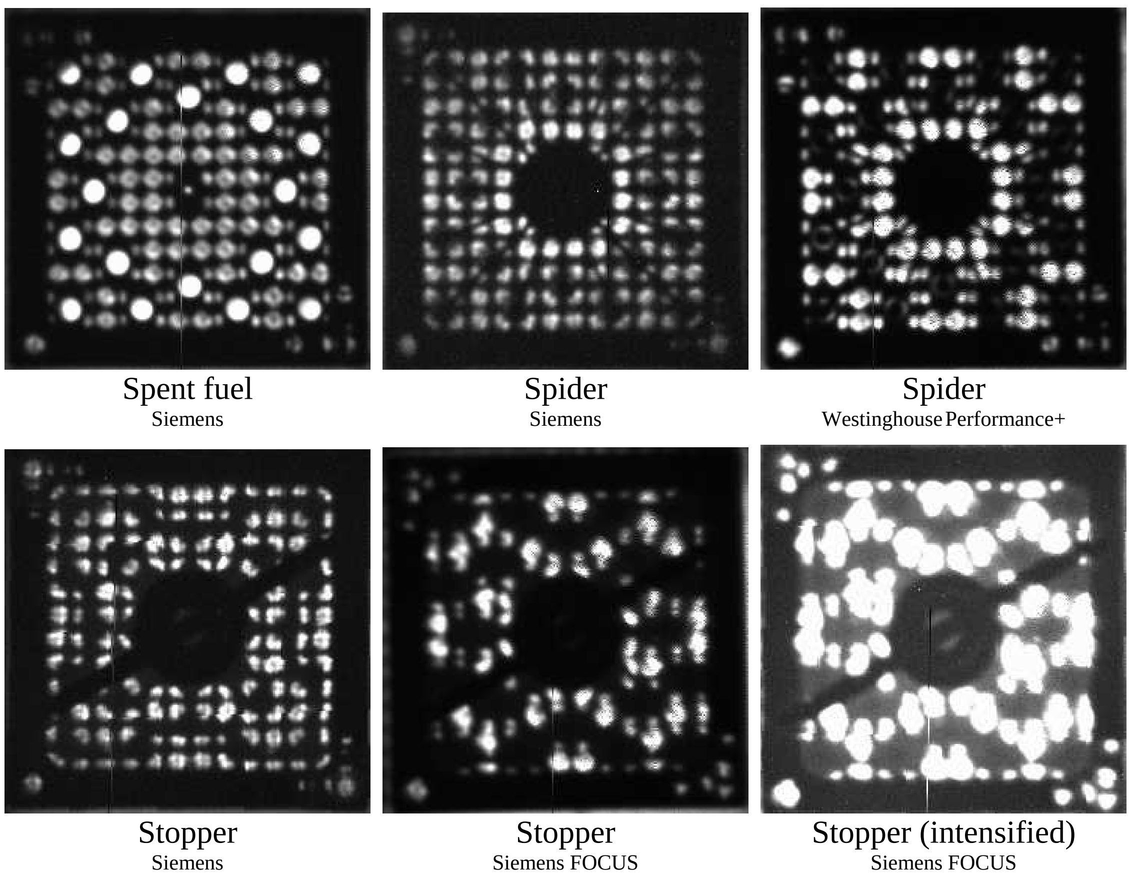


Figure 4: DCVD images of PWR fuel assemblies with and without inserts

3.2 Intensity measurements of spent fuel with different cooling times

Six fuel assemblies were measured to determine their Cerenkov intensity as a function of cooling time. The burnups and cooling times of six fuel assemblies are shown in Table 1. The assemblies were selected from various positions within the pond. W05 and Y26 were corner neighbours; Z04 had three near neighbours (all longer-cooled) and the remaining three had no near neighbours.

Intensities were measured by selecting the brightest pixels (less the brightest 1% of intensities to reduce the effects of noise). The procedure is described in detail in (5).

Table 1: Intensity measurement of six fuel assemblies

Fuel ID	Burnup (MWd/t U)	Cooling time (years)	Intensity (counts)
Z04	44	1	17101
Y26	43	2	8113
W05	42	4	4053
T12	56	6	2891
R26	41	9	1047
K30	32	14	462

A plot of the measured intensity versus the cooling time is shown in Figure 5. Theoretical calculations of photon intensities as a function of burnup and cooling times for PWR fuel are not available; therefore corrections to normalize the higher burnup and somewhat lower burnup for the assemblies identified as T12 and K30 respectively could not be made. An approximate linear correction for these two values yields the data points shown as circles in Figure 5. Corrections for the other data points would not alter the curve's shape since the burnups of the remaining assemblies are similar.

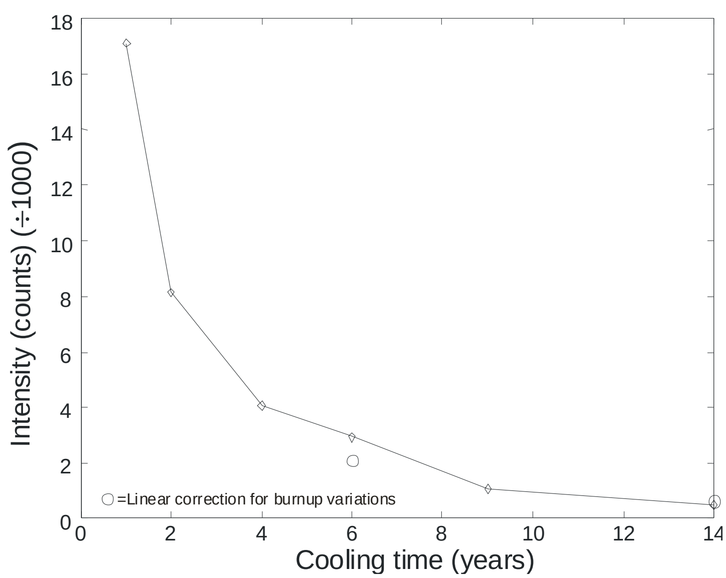


Figure 5: Decreasing light intensity with cooling time for several PWR assemblies

This curve is very similar to the Cerenkov intensity decay curve calculated for BWR fuels[6]. On the basis of these few results, it seems possible to determine the cooling time of an assembly knowing its burnup and DCVD Cerenkov intensity. Considerable effort remains to be done in this area, specifically with respect to the precision of readings and the stability of the CCD detector. Water quality in fuel bays will also be an important factor, although it should be constant in any one facility over a short time period.

3.3 Near-neighbour effect on Cerenkov light intensity

A fuel arrangement with assemblies with one-year cooling time and similar burnups was set up to assess the near-neighbour effect. The arrangement of the individual fuel assemblies is show in Figure 6. The central assembly (49/1) and the assembly to the right of it (47/1) were measured.

	47/1		
42/1	49/1	47/1	
	49/1		43/1

Figure 6: Fuel arrangement to assess the near-neighbour effect

The centre assembly has four adjacent near neighbours and the assembly on the right has one near neighbour and three diagonal neighbours. The near-neighbour effect occurs when gamma rays from neighbouring fuel assemblies travel into the adjacent assembly and generate Cerenkov light in the water spaces.

The intensities measured in the cross arrangement are shown in Figure 7. In the BWR case (5), the quantitative data showed a clear near-neighbour effect. In this case, the data shows an effect opposite to what is expected; i.e. the assembly that should have a lower intensity shows a higher intensity. The diagonal near neighbour in the lower right portion of the assembly is a complicating factor but should not affect the results to the degree observed.

Data is not available for the left-hand fuel in the arrangement.

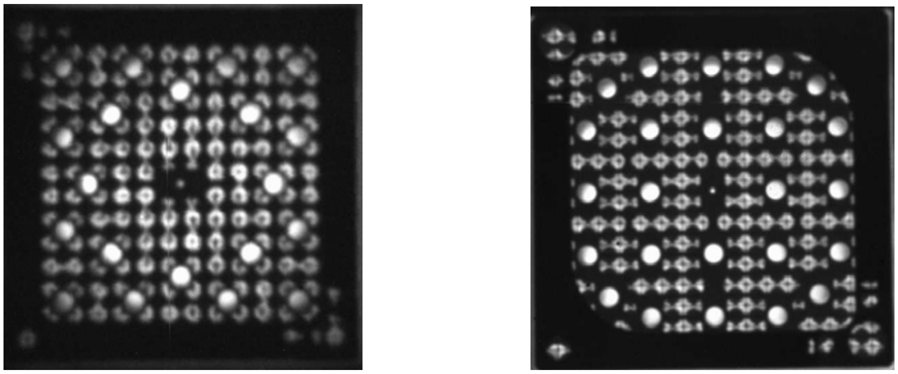
	SF		
SF	17289	21120	
	SF		SF

Figure 7: Intensities of fuel assemblies with similar burnups and cooling times

With the mixed results for the BWR and PWR data, we can claim only modest success. The proper procedure for this experiment would be to image the fuel assemblies in an isolated position and then move them into the appropriate position within a cross or square arrangement. We have not been able to move fuel during recent field tests, but this will be suggested for further tests.

3.4 Relative DCVD sensitivity at Ringhals Unit 2 and CLAB

A significant amount of data was obtained at the CLAB storage facility using the DCVD instrument. The water quality at CLAB is very high compared to fuel storage bays located at nuclear power stations. At Ringhals Unit 2, the fuel pond contains about 2000 µg/g boron to absorb neutrons emitted by the spent fuel. Fuel assemblies with similar burnup and cooling time were measured at both facilities to assess the relative absorption of Cerenkov light. The results given in Figure 8 show that the measured Cerenkov light intensity at Ringhals Unit 2 fuel bay could be about half the light intensity of a similar fuel in CLAB. However, the neighbouring assemblies were not the same. At CLAB, the fuel assembly was surrounded by short-cooled fuel while at Ringhals it was isolated. More studies are required to assess the effect of water quality at these and other fuel bays.



Ringhals Unit 2, (32/14)
75 counts/s

CLAB (34/14)
160 counts/s

Figure 8: Relative intensities for similar fuels from Ringhals Unit 2 and CLAB

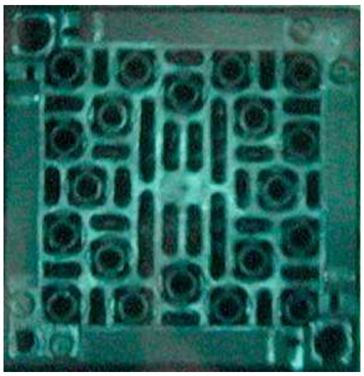
3.5 Cerenkov characteristics of an irradiated skeleton assembly

Isolated non-fuel assemblies do not emit Cerenkov glow. They are dark to the eye, to a CVD or DCVD. However, when they are surrounded by short-cooled near neighbours they appear to glow. This is due to the near-neighbour effect where the high-intensity gamma rays from the near neighbours travel into the non-fuel-assembly storage site and generate Cerenkov glow in the water.

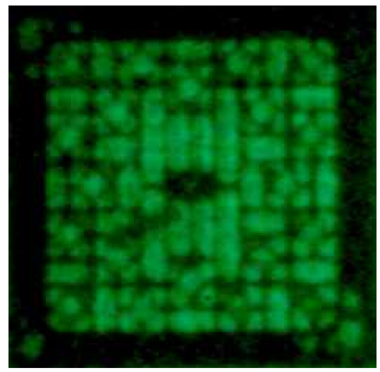
An irradiated skeleton assembly fuel assembly containing 20 guide tubes, spacer grids, top and bottom nozzles but no fuel rods was examined. This non-fuel assembly was surrounded by spent fuel with burnups ranging from 43 000 to 49 000 MWd/t U and cooling times from 1 to 4 years. This arrangement is shown schematically in Figure 9. The normal camera and CVD image of this non-fuel assembly are shown in Figure 10 for this non-fuel assembly. The normal camera image shows the top nozzle, the guide tubes and the spacer grids can be just detected below the top nozzle. The view of this assembly through the eyepiece of the CVD is sharper than the picture shown in Figure 10. The CVD image shows the presence of spacer grids, guide tubes, no fuel rods and the light from the guide tubes is similar in intensity to the light from the water volume below the top nozzle. This is a low contrast image and is unlike spent fuel (Figure 4), which shows very bright guide tubes compared to light from between the dark fuel rod.

44/1	43/2	47/1
43/4	Irradiated skeleton	47/1
43/1	43/2	49/1

Figure 9: Irradiated skeleton surrounded by short-cooled fuel



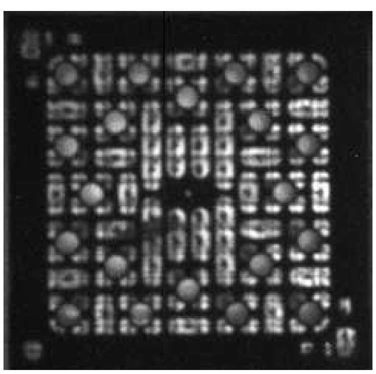
Normal camera image



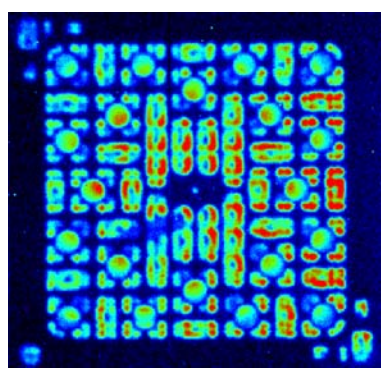
CVD image

Figure 10: Normal camera and CVD image of an irradiated skeleton

The DCVD image, Figure 11, has much higher resolution. The guide tubes, spacer grids can be clearly seen and there is no evidence of fuel rods. This is a low contrast image compared to spent fuel (Figure 4). The light from the guide tubes appears to be lower than the light in the water volume below the top nozzle. This is opposite to spent fuel where the light from the guide tubes is significantly brighter than the light from between the fuel rods.



Grey-scale image



False-colour image

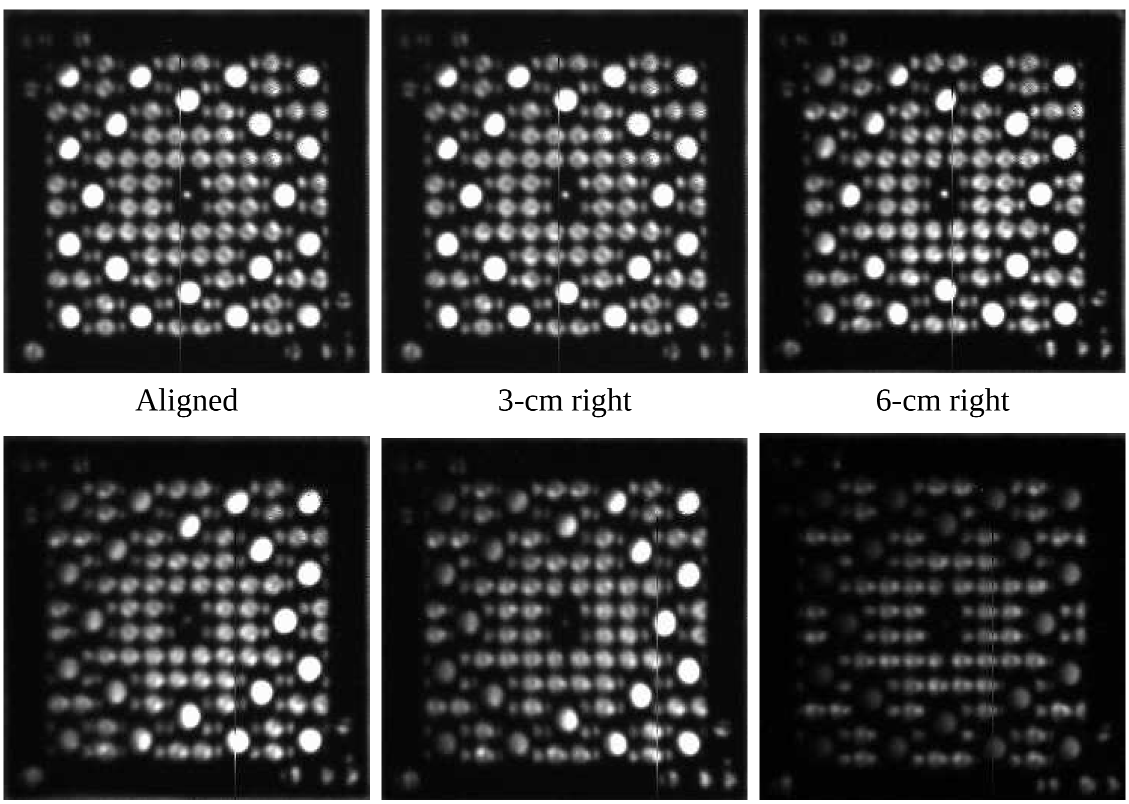
Figure 11: DCVD grey-scale and false-colour image of an irradiated skeleton

The false-colour image in Figure 11 provides added colour contrast between intensity levels in the digital image. The right-hand side is brighter indicating that the camera is not properly aligned with the assembly.

3.6 Cerenkov collimation characteristics of spent-fuel and non-fuel assemblies

The Cerenkov light emitted by spent-fuel assemblies is highly collimated. For PWR spent fuel, this is particularly true of the light from the guide tube holes and to a lesser degree the light from between the fuel rods. This light is highly collimated because the Cerenkov light originates from the entire length of the assembly. The Cerenkov light, when it is generated in the water, is emitted in all directions. Only the vertical component of this light reaches the top of the fuel assembly. The off-axis light is absorbed by the dark oxidized surfaces of the fuel rods and the guide tubes. To study this effect, an experiment was set up to measure the degree of collimation in spent fuel and in an irradiated skeleton assembly. Measurements were taken from an aligned and a number of distances from the aligned position. The width of the fuel assembly is 21.4 cm.

In the spent-fuel assembly (49 000 MWd/t U, 1-year cooled), Figure 12, the high contrast DCVD aligned image shows the 20 guide-tube holes with uniform brightness, the dark fuel rods and the spacer grids below the top nozzle. In the 6-cm image, the light from the left-side guide tube holes is starting to decrease in light intensity. In the 9-cm image, the intensity of the guide tubes on the left side of the assembly has decreased significantly. Additionally, the light from between the fuel rods shows a slight decrease in light intensity. The 12-cm position shows that about half of the guide tubes have decreased in light intensity and there is also a decrease in light intensity between the fuel rods on the left side of the assembly. At the 25-cm position, only a faint image of the assembly can be detected.



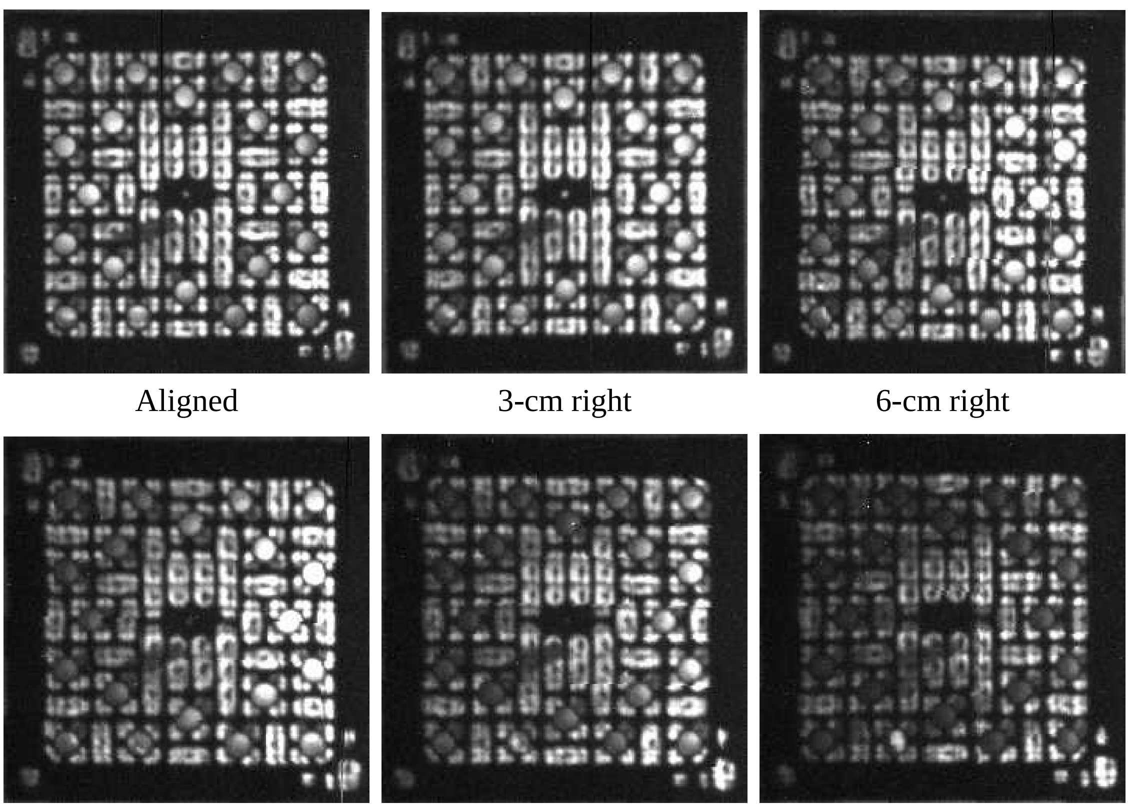
Aligned 3-cm right 6-cm right

9-cm right 12-cm right 25-cm right

Figure 12: Collimation characteristics of a PWR spent-fuel assembly

Figure 13 (aligned) shows a low contrast DCVD image of an irradiated skeleton. This assembly appears to be emitting light because is it surrounded by short-cooled near neighbours. The intensity of light from this assembly is considerably lower than the above short-cooled spent-fuel assembly. Unlike the spent-fuel assembly the Cerenkov light is fairly uniform across the assembly. The spacer grids below the top nozzle can be detected and there are no fuel rods. Unlike the spent-fuel assembly the light from the guide tubes is not uniform in intensity and is lower or the same intensity as the light below the top nozzle.

Further images were recorded as the DCVD was moved off-alignment to the right in 3-cm increments. The images at 3 to 12 cm show an increase in light intensity and a more uniform light distribution in the guide tubes on the right side of the assembly. In the 12-cm image, only the guide tubes on extreme right and close to the middle of the assembly have uniform and higher light intensity. The light from these guide tubes is relatively low compared to a spent-fuel assembly. A possible explanation for the brighter guide tubes is that this light is extremely collimated but low in intensity, and to be able to measure the maximum light intensity, the DCVD instrument must be directly over and aligned with the guide tubes. The 25-cm position image is very dark and it is difficult to detect any Cerenkov characteristics.



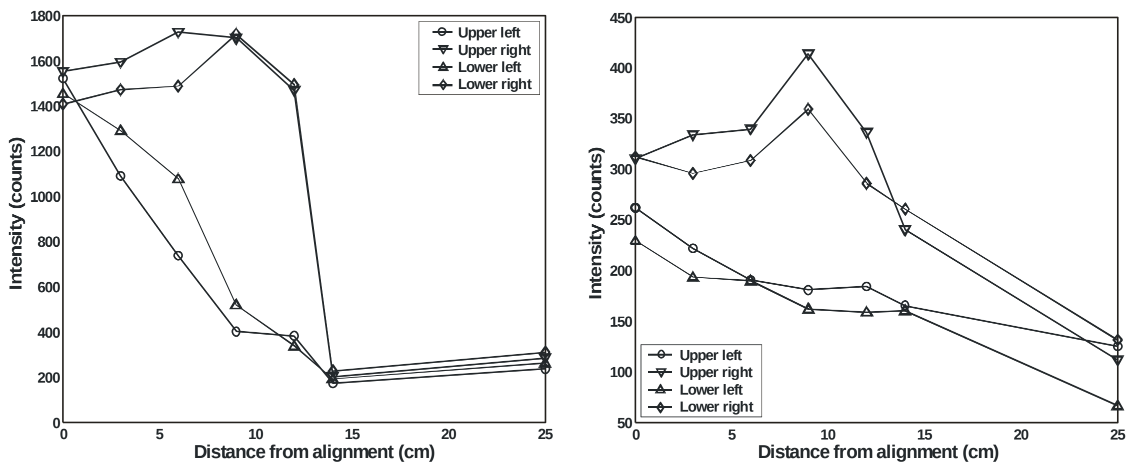
Aligned 3-cm right 6-cm right

9-cm right 12-cm right 25-cm right

Figure 13: Collimation characteristics of an irradiated skeleton assembly

The light intensity was measured in four quadrants of the fuel and non-fuel assemblies imaged in Figure 12 and Figure 13. These intensities were plotted against distance from alignment; the plot is showed in Figure 14. The plots demonstrate several features of alignment that are not perhaps immediately intuitive. The spent fuel plot shows the left left-hand side of the image decreasing more gradually than the right-hand side. In fact, it appears that the alignment is not absolutely correct since the right-hand side increases slightly in intensity as the DCVD is moved to the right. The relatively flat part of the curve for the right-hand side is expected as the DCVD is still moving over alignment for those right-hand guide tubes and water gaps. Once alignment is lost, however, there is a rapid drop in intensity. This alignment feature of Cerenkov light with spent fuel has been documented repeatedly in a qualitative way for the CVD system[7]. For the skeleton assembly case, there is an increase in brightness as the DCVD is moved to the right, again because that side of the assembly is moving directly into alignment. The falloff though with alignment is much more gradual than for spent fuel; this feature has also been documented qualitatively.

Calculating intensities in a live image for each quadrant in an assembly may provide the inspector with an automated, or at least assisted, method of determining alignment. It may also be possible using the fall-off pattern calculated from a series of images to provide assistance in the detection of non-fuel assemblies.



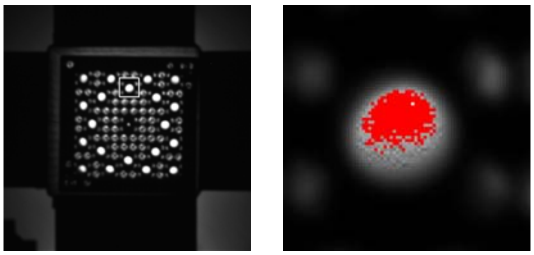
Spent fuel Skeleton

Figure 14: Fuel alignment characteristics for PWR spent-fuel and skeleton assemblies

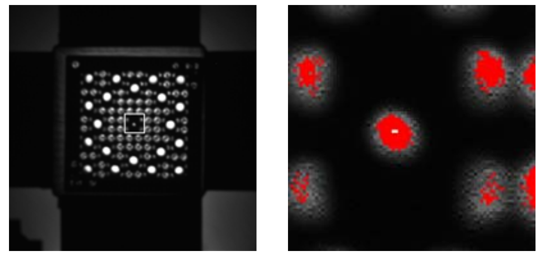
3.7 Cerenkov intensity in adjacent storage cells

It may be possible to perform off-line corrections for near-neighbour effects, thereby improving the detection of non-fuels in the presence of spent fuels. This technique would require some knowledge of the fall-off characteristics of spent fuel Cerenkov intensities as the DCVD is moved away from the fuel of interest. Moreover, it is expected that the glow pattern surrounding a spent fuel could vary with the cooling time (and perhaps burnup) of the fuel. This effect is expected as the source of the γ-rays causing the Cerenkov effect changes from the predominately high-energy γ-rays of short-cooled spent fuel to the lower energy γ-rays (mainly Cs^{137}) of long-cooled spent fuels.

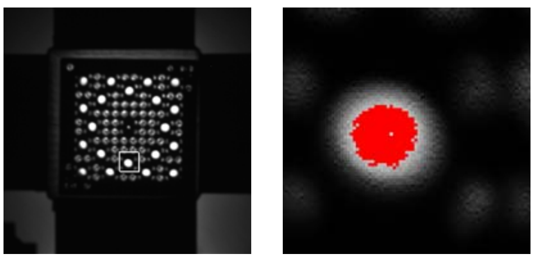
Data was obtained on the intensity of the Cerenkov radiation in adjacent storage cells caused by one isolated spent-fuel assembly. A small region was selected in the upper, middle and lower region of the spent-fuel assembly itself and the intensity measured in that region. The DCVD was then moved one storage cell to the right (the storage pitch is 35 cm) and an image taken of the empty cell. Regions of interest were defined in the empty cell that matched the position of the same region in the fuel assembly image. Figure 15 shows the images taken of the fuel assembly and one empty location to its right. The region of interest is indicated in the left–hand image of each pair of images and the pixel data selected for the intensity measurement is shown in the right-hand image of each pair. In the empty cell image there are of course no features present and the intensity is obtained from a scattering of pixels.



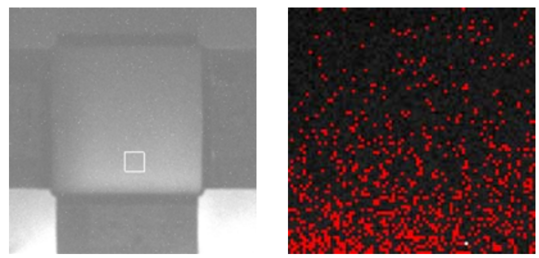
(a) Upper region



(b) Central region



(c) Lower region



(d) Typical empty location

Figure 15: Cerenkov intensities in adjacent storage cells

The first three data points for each region of interest follow a fairly good logarithmic decay with distance (see Figure 16). The last point is so low in intensity that the dark current and other camera-related parameters begin to predominate. These results indicate that it may be possible to determine the Cerenkov light intensity contribution from one assembly in the water spaces of adjacent assemblies. The known intensity curve could allow a form of background subtraction, or, more appropriately in this case, a near-neighbour correction. Additional factors such as self-shielding within the assembly of interest would have to be quantified to make this technique feasible.

4 CONCLUSION

The prototype DCVD instrument with the Marconi CCD47-20 back-illuminated chip was successfully tested at Ringhals Unit 2 on PWR fuel and non-fuel assemblies. A good relationship was obtained between measured intensities of fuel assemblies with similar burnups but different cooling times. The application of quantitative analysis on images shows promise for near-neighbour correction and is recommended for analysis in greater detail in future studies. Further work is suggested to develop an indicator of alignment and perhaps even notification of low collimation that can be an indicator of a non-fuel assembly.

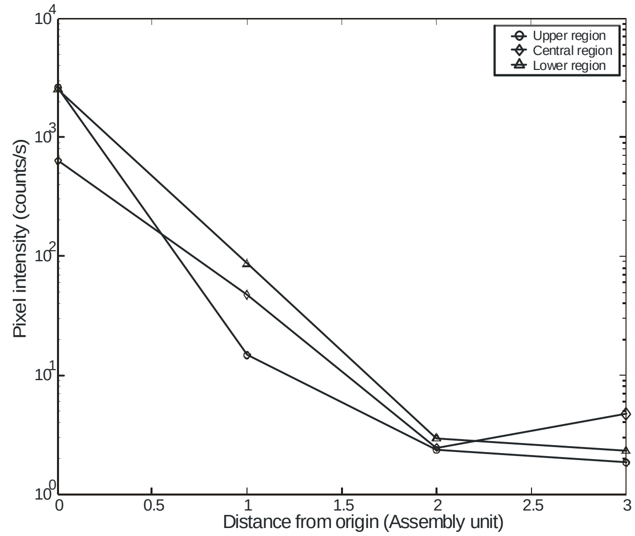


Figure 16: Intensity fall-off with distance from assembly

5 ACKNOWLEDGEMENTS

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6 REFERENCES

1 J.D. Chen, L. Hildingsson, O. Trepte, E.M. Attas, G.R. Burton and G.J. Young; "Development of a high sensitivity Cerenkov viewing device: Concept SCCD field tests in Sweden"; CSSP Report 88, May 1996.

2 O. Trepte, L. Hildingsson, J.D. Chen, G.R. Burton, G.J. Young and E.M. Attas; "Development of a high sensitivity Cerenkov viewing device: Field test at Ringhals 2 PWR facility, Sweden"; SKI Report 94:45, October 1996.

3 J.D. Chen, E.M. Attas, G.R. Burton, G.J. Young, L. Hildingsson and O. Trepte; "Development of a high sensitivity Cerenkov viewing device: Concept SCCD CVD summary report"; CSSP Report 91, October 1996.

4 J.D. Chen, A.F. Gerwing, P.D. Lewis, M. Larsson, K. Jansson, B. Lindberg, E. Sundkvist, M. Ohlsson; "Development of a high sensitivity digital Cerenkov viewing device: Prototype digital Cerenkov viewing device field test in Sweden"; CSSP Report 123, SKI Report 01:8, July 2002.

5 J. D. Chen, A.F. Gerwing, R. Maxwell, M. Larsson, K. Axell, L. Hildingsson, B. Lindberg and E. Sundkvist; "Cerenkov characteristics of BWR assemblies using a DCVD with a back-illuminated CCD"; CSSP Report 2004-01-01, SKI Report ISRN SKI-R0-03/45, November 2003.

6 S. Rolandson; "Determination of Cerenkov light intensities from irradiated BWR fuel"; SKI Report SE 1-94, January 1994.

7 "Cerenkov Viewing Devices for Spent Fuel Verification at Light Water Reactors"; IAEA inspector training textbook.