LONG-COoled Spent FUEL VERIFICATION USING A DIGITAL CERENKOV VIEWING DEVICE

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Abstract

The Swedish and Canadian safeguards support programs to the IAEA have developed a Digital Cerenkov Viewing Device that is a non-intrusive, non-destructive analytical instrument to verify long-cooled fuel in storage ponds. The instrument was developed with specific imaging software to assist in the operation and verification of the spent fuel. This instrument was successfully tested at the Central Interim Storage Facility for Spent Nuclear Fuel on PWR non-fuel and spent fuel, long-cooled BWR spent fuel and very long-cooled, low-burnup Ågesta fuel.

1 INTRODUCTION

The Swedish and Canadian Safeguards Support Programs in 1993 began a joint program to develop a high sensitivity Cerenkov Viewing Device (CVD) to meet the International Atomic Energy Agency (IAEA) need to verify 40-year-cooled spent fuel with a burnup of 10 000 MWd/t U. A commercial charge-coupled device (CCD) instrument was subsequently purchased and tested at Swedish nuclear facilities. The detector had an ultraviolet light (UV) quantum efficiency of 8%. Initial studies \cite{1, 2, 3, 4, 5} showed that new Cerenkov characteristics were observed because of the low noise and high resolving power of the instrument. The instrument had the ability to store Cerenkov images in a digital format and the potential to perform image processing to assist the operator in fuel verification. However, the study indicated that a detector with a UV quantum efficiency of 40% was required to meet the IAEA requirement.

A new improved camera was recently purchased and called a prototype Digital Cerenkov Viewing Device (DCVD). It was subsequently tested at the Swedish Central Interim Storage for Spent Fuel (CLAB) on pressurized-water reactor (PWR) spent fuel and non-fuel, long-cooled boiling-water reactor (BWR) spent fuel, and Ågesta pressurized-heavy-water reactor (PHWR) fuel assemblies.

2 INSTRUMENTATION

The prototype DCVD system consisted of a CCD camera system purchased from Andor Technology (Belfast, Ireland) along with the camera’s PCI interface controller card, which was used in a custom-built computer. A program was written to operate the camera and present the Cerenkov images on a liquid crystal display (LCD). The schematic of the equipment is shown in Figure 1. Cerenkov light passes through the objective lens and a UV-pass filter to produce an image on the CCD located in the detector vacuum housing. The camera head contains a three-stage thermal electric cooler, the pre-amplifier, and control electronics for the detector. The custom-designed computer system contains the Andor controller card, a solid-state hard drive, a removable memory storage card and a number of interface boards. Attached to the computer are the LCD and heads-up display systems. Both 250-mm and 105-mm UV-transmitting lenses were used with the camera system. The detector was a Marconi CCD47-20, 1024 \times 1024 pixel frame-transfer chip with 13 \times 13 \mu \text{m} square pixels and a quantum efficiency of 52\% at 300 nm. Cerenkov images were taken at a detector temperature of -20° C.
The computer is based on the PC/104-PLUS modules. It consists of a core module (Ampro) 266 MHz Pentium processor (Tillamook) with MMX technology, 64 MB of memory, and a Scandisk 440 MB solid-state hard drive. The other modules are an Ethernet card, video card, PC card interface and a PCI adapter board for the PCI controller card. The low power consumption of the computer permitted battery operation for up to 2 h using 2 re-chargeable lithium-ion batteries. A 12 V to 5 V DC-DC power supply located in the computer box provides power for the computer and the camera head.

Figure 2 shows the DCVD camera head mounted on a railing bracket along with the computer system and a Phillips LCD 15-cm screen (640 x 480 pixels). The railing bracket was designed to accommodate square, round and L-shaped railings using adjustable rollers and spring clamps. The railing bracket, when installed, can be moved along the entire length of the bridge and the camera head can be moved small distances in both x and y directions for fine adjustments. A gimbals mount for the camera head permits tilting of the camera head to obtain precise alignment with the fuel assembly. The second part of the figure shows an operator using the DCVD system with the heads-up display. The image quality from this display (Olympus, 800 x 600 pixel) was excellent.
3 EXPERIMENTAL RESULTS

3.1 Influence of binning

The DCVD camera has the capability of grouping an array of pixels together as a single super pixel in a process called binning. This results, effectively, in an instrument with the same detector area but fewer detector elements. Binning increases the photon count recorded per super pixel but reduces the image resolution. For example, at $2 \times 2$ binning (4 pixels are combined into a single pixel) the number of image points (pixels) is reduced by a factor of 4 while the signal-to-noise ratio increases by a similar factor. Noise was found to be insignificant in the binning tests because of the extremely low dark current and the relatively short exposure times needed. The binned PWR images shown in Figure 4 indicate that $4 \times 4$ binning still shows excellent resolution. A decrease in resolution becomes pronounced in the $6 \times 6$-binned image.

3.2 Cerenkov characteristics of PWR spent fuel assemblies

A DCVD image of a $15 \times 15$ PWR fuel assembly is shown in Figure 5a. The fuel has a burnup of 50 000 MWd/t U and cooling time of 2 years. The exposure time was 10 s. The fuel rods can be seen as dark round circles; bright Cerenkov light is produced in the water surrounding the fuel rods. The main Cerenkov characteristic of this assembly is the pattern of 20 bright guide tubes. Eight of these
guide tubes are arranged in an inner circle with 12 on the outside edge. In an operating reactor, these guide tube holes may contain a control rod assembly, which reduces the reactivity of the fuel, or a flow restrictor to control water flow. Also evident is the very small instrument hole (1 to 2 mm) at the centre of the assembly. The Cerenkov images clearly shows that this assembly is brighter in the centre than at the edges. This can be seen from the Cerenkov light from between the fuel rods and is more obvious from the brighter inner guide tubes compared to the outer guide tubes. This is a new Cerenkov characteristic that is difficult to detect using the Mark IVe Cerenkov viewing device.

The false-colour image, Figure 5b, emphasizes the fact that the inner guide-tube holes are brighter than the outer ones. Additionally, the Cerenkov light from between the fuel rods in the centre of the assembly is brighter than the outer part of the fuel assembly.

3.3 Cerenkov characteristics of the helium PWR non-fuel assembly

Three types of PWR non-fuel assemblies were studied at the CLAB facility: a skeleton assembly (no rods), a helium-filled rod assembly, and a high-density assembly (steel rods). These non-fuel assemblies were surrounded by relatively short-cooled fuel (1 to 5 years) to produce a near-neighbour effect. This effect is observed when gamma rays from surrounding assemblies (near neighbours) pass through the non-fuel storage volume and produce Cerenkov light via the Compton process. This paper discusses the results obtained for the helium PWR non-fuel assembly. The positive results obtained for the other two non-fuel assemblies are given in an internal report [6].

The helium non-fuel assembly (Figure 6a) is a 17 × 17 array of rods constructed like a spent fuel assembly, except that the fuel rods contain the inert gas helium. The shiny surfaces seen with the unaided eye and to some degree in the visible light pictures indicate that the assembly has not been irradiated. The helium-filled rods can be seen under the top nozzle. The DCVD image, Figure 6b, shows dark rods and the Cerenkov light from between them. The guide-tube holes are relatively bright and they all appear to have the same light intensity, which is not characteristic of spent fuel. In spent fuel, the central guide-tube holes are brighter than the outer guide-tube holes. This non-fuel assembly is difficult to verify. (The alignment in Figure 6b is not exact; the camera is aligned slightly towards the top left of the assembly.)
3.3.1 Use of light collimation to detect the helium non-fuel assembly

Figure 7a shows a DCVD image of a PWR spent fuel assembly with the DCVD instrument that is well aligned. Figure 7b shows the result when the DCVD instrument is moved 10 cm to the left. The same procedure was used for the helium non-fuel assembly shown in Figure 7c. The spent fuel assembly shows that in the off-alignment image the light from the guide tubes on the right is relatively dark, compared with the light in a similar image of the helium non-fuel assembly. This is an indication of

![FIG. 7. PWR fuel and non-fuel light collimation effect](image)

the high degree of light collimation from the guide tubes in normal spent fuel. In the helium non-fuel assembly, the light from the guide-tube holes is less collimated. This may be due to the guide tubes’ bright, shiny inner surfaces reflecting much of the light to the top of the assembly. In normal spent fuel, the inner surfaces are oxidized, and only the vertical component of the Cerenkov light exits the top of the guide tube. This is a subtle but distinct difference in Cerenkov characteristics between fuel and unirradiated non-fuel assemblies.

3.3.2 Digital Analyses of Spent Fuel and Helium Non-Fuel Assemblies

Digital data in the form of pixel intensity values can be easily obtained from the DCVD images. Images from the PWR helium non-fuel and a spent fuel were examined for quantitative information. Pixel intensities were obtained for several inner and outer guide tubes in each assembly. The ratio of the inner to outer values for the fuel and non-fuel assemblies were 1.24 and 1.05 respectively. As expected for the spent fuel where the Cerenkov light is being generated from within the assembly, the inner guide tubes are substantially brighter than the outer tubes. For the He non-fuel assembly, the intensities are not significantly different, as expected because of the near-neighbour effect.

Additional measurements were made on the light intensity in the water spaces between the fuel rods. The ratios of the inner guide-tube intensity to the intensity in these water spaces were calculated to be 3.5 and 2.7 for the He non-fuel and spent-fuel assemblies respectively. These values are consistent with the observed CVD characteristic of very bright guide tubes in the He non-fuel assembly that are due to multiple reflections of the light along the length of the very shiny (unirradiated) guide-tube surfaces. These quantitative measurements show conclusively that spent fuel has different Cerenkov characteristics than non-fuel assemblies. This type of analysis illustrates the potential for using numerical techniques, perhaps some form of artificial intelligence, to detect spent fuel and non-fuel assemblies.

![FIG. 8. Missing fuel rods](image)
3.4 Fuel assembly with missing fuel rods

A DCVD image of a BWR fuel assembly (16 000 MWd/t U, 21-year cooled) with missing fuel rods is shown in Figure 8a. The missing fuel rods can be detected because the regular pattern of the fuel rods \((8 \times 8)\) changes. The high resolution and high contrast digital image readily shows that there are five missing fuel rods: one from the top right-hand corner, one on the left side and three in the bottom row. The false-colour image, Figure 8b more clearly shows the missing fuel rods even though the four missing pins on the outer edges do not show significantly higher intensities. The empty fuel rod position on the left side of the assembly surrounded by adjacent fuel rods is very bright compared to the outer vacant fuel rod sites in the assembly.

3.5 DCVD measurements of long-cooled fuel assemblies

A primary objective of the field test was to assess the sensitivity of the DCVD instrument. The measurement goal was to determine the ability of the DCVD to verify fuel with a burnup of 10 000 MWd/t U with a cooling time of 40 years. The low-burnup criterion was selected because the first charges of fuel in reactors are not normally taken to the design burnup. The cooling time criterion was set by the lifetime of operating reactors, approximately 40 years. There are currently no known power reactor fuel assemblies with cooling times greater than this. There are, however, fuel assemblies with burnups less than the specified 10 000 MWd/t U with long cooling times. To obtain fuel that could be tested to meet the measurement criteria, we needed to have fuel with low burnups and the longest cooling times available. Figure 9 shows a plot of photon flux as a function of cooling time for a range of burnups. These theoretical curves have been confirmed by field measurements at the CLAB facility [7].

3.5.1 Long-cooled BWR fuel assembly

The longest-cooled BWR fuel assembly stored at the CLAB facility has a burnup of 5400 MWd/t U and a cooling time of 24 years. Images obtained using the Mark IVe CVD and the DCVD are shown in Figure 9. The CVD image (a) shows a medium-to-low contrast image with well-resolved fuel rods. The small bright spots seen in the centre of the inter-rod gap of the DCVD image (c) are difficult to detect with the CVD. These bright spots result from the geometry of a number of spacer grids that are located along the length of the fuel assembly. This light is highly collimated. This fuel assembly appears to be at the detection limit of the CVD. In fuel bays with lower water quality, it may not be possible to detect this assembly using the CVD. The DCVD image (b) shows a high contrast image with much higher resolution than the CVD image.

![FIG. 9. Photon flux versus cooling time for BWR fuel with different burnups](image)

3.5.2 Long-cooled Ågesta fuel assemblies

The longest-cooled spent fuel stored in the CLAB facility is from the Ågesta PHWR. A number of these fuel assemblies have cooling times of 29 years and burnups as low as 1130 MWd/t U. Figure 11a shows a visible light picture of a basket containing 31 Ågesta fuel assemblies. A normal camera image of a long-cooled fuel assembly (1200 MWd/t U, 29-year cooled) is shown in Figure 11b. This assembly could not be verified using the Mark IVe CVD (Figure 11c); Cerenkov light could be detected between the assemblies but Cerenkov characteristics from the fuel could not be observed.
The DCVD image, Figure 11d, shows a relatively high contrast image of the fuel assembly. When the DCVD is moved from a non-aligned to an aligned position over the fuel assembly, the Cerenkov glow pattern changes from an asymmetric to a symmetric pattern (higher light intensity). The pattern and the relative rate of intensity change during this transition, the collimation effect, is characteristic of spent fuel. The exposure time for this image was 10 s.

Figure 11e shows a $4 \times 4$-binned image with an exposure time of 5 s. This image is almost identical to the non-binned image (Figure 11d), and it appears that $4 \times 4$ binning does not significantly degrade the DCVD image. We estimate from the total counts in the pixels that at $4 \times 4$ binning, this long-cooled fuel assembly could be verified with an exposure time of less than 1 s.

### 3.6 DCVD measurements of Ågesta fresh-fuel assembly

Figure 12a shows a DCVD image of an Ågesta assembly with a burnup of 1130 MWd/t U and a cooling time of 29 years. The assembly on the right (Figure 12b) is fresh fuel (unirradiated). During the DCVD alignment procedure over the spent fuel (non-aligned to aligned), the characteristic collimation effect was observed. When moving to an aligned position over the fresh fuel, the glow from the fresh-fuel assembly did increase. However, the characteristic collimation effect (rapid increase and decrease in glow intensity) was not observed. Additionally, the light pattern was asymmetric even when well aligned over the assembly. These characteristics are indicative of a non-fuel assembly and that the observed glow is produced by the near-neighbour effect.
4 DISCUSSION

Laboratory measurements indicated that the DCVD instrument was over 100 times more sensitive than the Mark IVe CVD. Although the quantum efficiency of the CCD is not 100 times higher than that of the Mark IVe CVD, its very low noise and high resolution permit the detection of extremely dim images. The DCVD instrument was able to verify the Ågesta fuel assembly with a burnup of 1200 MWd/t U and a cooling time of 29 years. This long-cooled Ågesta fuel assembly has a photon flux about 6 times lower in intensity than the target fuel (Figure 8). However, these measurements were all achieved at the CLAB facility, where the water quality is extremely high and may not be representative of some power-reactor storage bays. The effects of water quality remain to be assessed at other facilities. It is expected that most spent fuel storage facilities have good water quality and that the measurement targets can be met.

5 FUTURE CAMERA DEVELOPMENT

Several improvements can be made to the camera system, but we are dependent on manufacturers for these improvements. Andor Technology plans to have a 5 MHz analogue-to-digital converter system incorporated into a digital camera head. They expect frame rates of 15 frames per second with a new high-gain chip manufactured by Marconi. This chip, called an electron-multiplied charge-coupled device (EMCCD), has a gain of ~100 applied to the pixel signal after the readout register and before the output amplifier. A significant increase in sensitivity is obtained because this amplified signal has the normal dark current and the read-out noise of a non-amplified signal. This new EMCCD back-thinned chip with high UV quantum efficiency and low noise is expected in the spring of 2002.

6 CONCLUSIONS

The prototype DCVD instrument was successfully developed and tested for verifying spent-fuel and non-fuel assemblies. The portability of the instrument was adequate and future improvements look promising. The digital images provided by this technology permitted better discrimination of spent fuel and non-fuel assemblies, along with an improved ability to detect missing fuel rods (partial defect). The high quantum efficiency, low noise, and high resolution permitted the verification of Ågesta fuel with a burnup of 1200 MW/t U and a cooling time of 29 years, well below the target of 10 000 MWd/t U burnup and 40-year-cooled fuel.

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