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DIAMOND RADIATION DETECTORS FOR FUEL DEBRIS CHARACTERISATION BY HIGH DOSE RATE GAMMA MEASUREMENT

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ABSTRACT

A novel radiation detection instrument using diamond for measurement of high gamma dose rates is introduced. Diamond has many important benefits for high flux measurement compared to other techniques, including high rate measurement and radiation tolerance. Collaborative work with Kyoto University has shown these detectors can be calibrated and used on nuclear sites for characterisation. Demonstrated at Sellafield, the diamond detector system will be useful inside the FDNPP Primary Containment Vessel (PCV) for mapping high dose rates and protecting robots.

1. INTRODUCTION

Diamond is an ideal semiconductor material for detection of ionising radiation: sensitive to gamma yet radiation-tolerant. An ultra-pure synthetic diamond crystal measuring 4.5mm x 4.5mm has been used to remotely measure very high dose rates inside legacy nuclear reprocessing facilities.

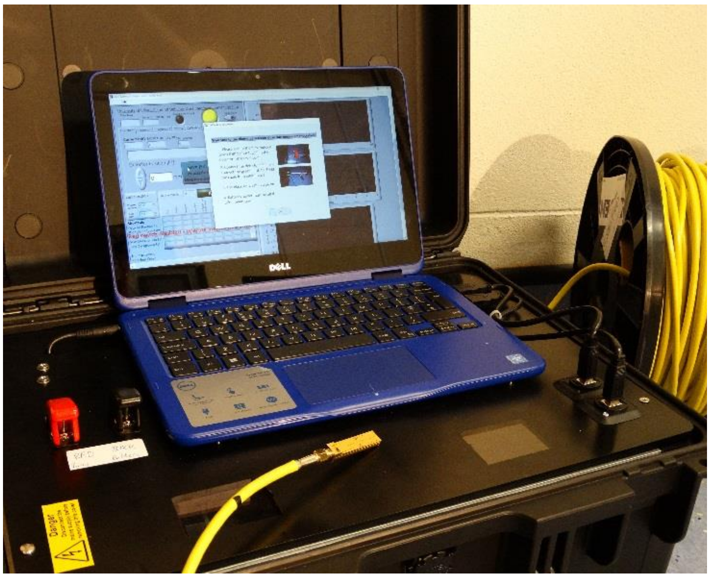

Figure 1: The diamond detector system measures high dose rates and consists of the control unit, 150m cable and detector head. The detector head's width is 10mm.

2. STATE OF THE ART

The diamond detector system is particularly well-suited to dose rate measurement within extremely radioactive environments, having been extensively tested at Sellafield, UK and KURNS, Japan (Payne et al, 2017).

Dosimetry in highly active (HA) cells had previously been carried out using thermoluminescent dosimeters (TLDs) or in special cases, Alanine. These are passive techniques requiring a timed exposure and subsequent processing for read-out. Diamond radiation detectors offer a new technique for dose rate measurement inside HA cells, taking advantage of:

- Real time measurement – detector can be moved during deployment to map a whole cell in a single pass.
- Radiation tolerance – during prototype testing, exposure beyond ~70,000 Gy caused no performance degradation.
- Miniature size – detectors can be placed inside small-bore pipework down to ½ inch diameter.
- Wide sensitivity range – stable operation calibrated from 80 mGy/hr to 24,000 Gy/hr.

2.1 Current Mode method of detection

Most radiation detectors operate in "pulse mode" meaning that the highest measurement possible is dictated by the rate at which the pulses can be counted. In HA cells detectors usually saturate because the photon flux is too high for the detector's maximum count rate, necessitating bulky shielding around the detector. In the diamond detector system, current mode is used instead of pulse mode, meaning that there is no upper limit for the flux that can be measured. This has proven to be very useful in situations where the detector cannot be shielded and the dose rates are unknown and high, shown in (Hutson 2018).

	Diamond	Gallium Arsenide	Alanine	TLD*	Ion Chamber
Type	Semi-conductor	Semi-conductor	Passive EPR	Passive	Gas-filled
Detection mode	Current	Pulse	Passive	Passive	Current
Measurement type	Dose rate	Spectrum	Integrated dose	Integrated dose	Dose rate
Measurement frequency	20 Hz	MHz	Single	Single	Hz
Processing time	Real time (instant)	Real time (instant)	Weeks	Days	Real time (instant)
Dose rate range	0.05 – 24,000 Gy/hr	< 0.01 Gy/hr	< 70 Gy/hr	<20 Gy/hr	< 1 Gy/hr
Detector size	4.5mm crystal (Total 1 x 1 x 2.5 cm)	35 cm	5 mm	5 mm	1 x 1 x 4 cm
Cooling	None	Liquid nitrogen	None	None	None
Radiation damage	None	Detector and counting electronics	n/a	n/a	Yes

Table 1 Comparison between diamond and other radiation detectors

3. CALIBRATION

The signal from the diamond crystal has been calibrated using collimated cobalt-60 and caesium-137 sources and has been shown to be independent of isotope. Diamond's resistance to electrical current varies predictably with dose rate, and this special property is the basis of radiation measurements. During calibration experiments, diamond detectors were exposed to a series of known dose rates and the flowing current response measured. Incident radiation generates current in the crystal, the magnitude of which allows dose rate determination. Example calibration data is shown in Figure 2a and 2b for medium and high dose rates.

Once these calibration curves are obtained, the fitting coefficients are used by custom control software to automatically convert measured current into dose rate. Therefore any unknown dose rate may now be measured.

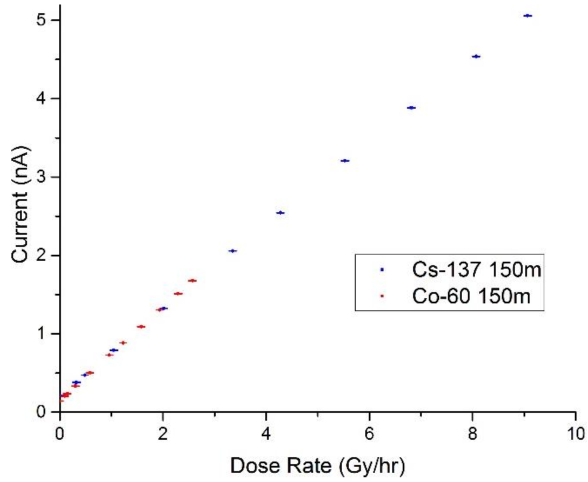

Figure 2a: Medium dose rate calibration with Cs-137 and Co-60 up to 9 Gy/hr air kerma.

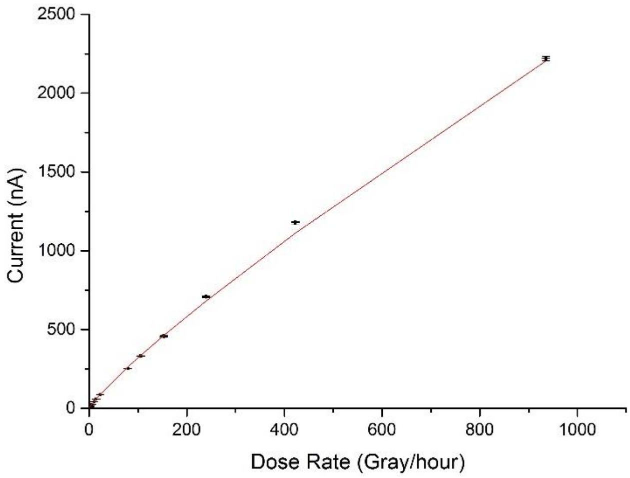

Figure 2b: High dose rate calibration using Co-60, data collected using the KURNS Co-60 irradiator.

4. EXPERIENCE AT SELLAFIELD

Sellafield is the UK's most complex nuclear site, and is currently embarking on a complex decommissioning programme. As reprocessing activities end, it is beginning post-operational clean out. Dose rate characterisation is needed inside highly active facilities previously used in reprocessing. Following a series of prototype deployments, the system is now regularly used on plant. The diamond detector produces dose rate measurements in real time, and therefore replaces the use of TLDs and Alanine, which required two weeks for processing. The dose rate measurements are of improved quality and are instantly available to operators on plant, reducing operational delays. Obtaining a dose rate profile typically takes a few minutes; essentially this is the time it takes to lower the detector in a controlled manner to defined cell heights.

The custom-built control software is used to make operation by personnel straightforward and automatic. During deployments, the data is visualised on-screen as it is recorded, and at the end of the measurement, a graph showing the cell dose rate profile and simple spreadsheet files are produced attributing measurements to their locations. Dose rate data collected using the diamond detector system from within a highly active cell at Sellafield may be found in (Hutson et al, 2017).

5. IMPORTANCE FOR FDNPP PCV CHARACTERISATION

Inside the PCVs at FDNPP the dose rates are upwards of 100 Gy/hr due to the presence of nuclear fuel debris, thought to be at the bottom of the vessel. To remove the fuel debris, it is important to measure dose rates within the vessel to understand where the debris is, so that access for cutting tools can be made safe.

The diamond detector would be ideal for any remote system aiming to characterise the inside of the PCVs, allowing real-time mapping of dose rates. This would allow high-resolution mapping of the hazards contained within the vessels, precisely locating the fuel debris. This information would be crucial to inform the clean-up strategy.

Experience at Sellafield in highly active facilities has shown the diamond detector very capable of accurate remote measurement in real time.

6. PREVENTION OF RADIATION DAMAGE TO ROBOTS EXPLORING THE PCV

Several robotic systems have been introduced into the reactors to learn more about their condition since the accident in 2011. Examples include the TEPCO robot designed to withstand 100 Gy/hr for 10 hours (TEPCO, 2017), and swimming robots (e.g. Sunfish).

However, many of these moving robots have stopped working due to radiation damage caused by intense exposure. It is well-known that electronic components containing silicon are susceptible to gamma radiation: initially this consists simply of bit-flips, but as accrued dose increases the sensitive integrated circuits become damaged beyond repair, and the robot is unable to measure parameters, or move itself to safety.

A diamond radiation detector mounted on a robot entering the PCV would provide real time dose rates, mapping the PCV as the robot moved around. Indeed, the robot could be used as a platform to lower the diamond detector into a more hazardous area using a telescopic pole mechanism, thereby reducing harmful exposure to the robot.

In addition, when placed on the robot itself, the measured accrued dose to the robot could be used as an alarm so the robot can be safely returned home once its permitted dose was reached. This alert system would reduce the amount of robot debris left inside the PCV by allowing recovery and replacement of the robots.

4. CONCLUSIONS

Diamond radiation detectors are advantageous in any highly radioactive environment in which high radiation levels must be remotely and accurately measured without man-entry. Cells previously used for reprocessing, containing nuclear fuel or at risk of criticality are typically congested with restricted physical access making the characterisation task very challenging. Miniature radiation-tolerant diamond detectors are the only available technology suitable to carry out surveys in these harsh environments, and their routine use at Sellafield continues to demonstrate value.

Diamond detectors will be an important radiometric instrument to understand the distribution of highly radioactive material inside the Fukushima Daiichi NPP primary containment vessel.

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