Deployment of Diamond-Based Radiation Detector for Very High Dose Rate Measurements – 17042

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ABSTRACT

The diamond-based radiation detector system has been developed at the University of Bristol to measure radiation within nuclear facilities known to exhibit high dose rates. The challenge at Sellafield site in the UK, described herein also applies to many other nuclear operators worldwide, making the transfer of diamond detector technology to other applications feasible. Development of an operator-friendly system, extensive detector testing and controlled calibrations have led to several successful deployments of the device at Sellafield site, providing them with valuable data about the radiological contamination within their highly active plants. Designed for measurements of intense radiation fields, this new tool for characterisation of radiologically hazardous environments is a game-changer, improving the availability and quality of dose rate data used in safety case justifications. Compared with conventional technology diamond detectors are radiation tolerant, miniature, and can measure an extraordinary range of dose rates.

INTRODUCTION

The decommissioning of high activity and high hazard facilities requires characterisation data to be collected, informing models and allowing strategic decisions based on real data, rather than pessimistic assumptions and predictions. It is necessary to understand the plant state in terms of the quantification and distribution of radiological hazard, and for this task specialised detector systems are required.

Innovative characterisation technologies are required due to extreme levels of radioactive hazard, which destroys or saturates conventional detectors. First in use at CERN's ATLAS experiment, diamond based radiation detectors offer a novel technology allowing the non-destructive assay of highly radioactive environments in the civil nuclear sector. The miniature diamond detector system developed at the University of Bristol, UK, allows real time dose rate measurements to be made remotely from within difficult to access areas, creating maps of radioactivity in facilities via small access ports, through complex networks of pipes and vessels, with a high radiation hazard. Compared with conventional technology diamond detectors are radiation tolerant [1], [2], miniature, and can measure an extraordinary range of dose rates.

Controlled testing of the device's response to radiation has allowed detector calibration, as previously described at Waste Management Symposia 2016 [3]. This understanding of detector behaviour has led to deployment inside active cells on the Sellafield site providing quantified high dose rate measurements. This new tool for characterisation of radiologically hazardous environments is a game-changer, improving the availability and quality of dose rate data used for strategic and tactical decision-making.

This paper describes the challenges seen at the Sellafield site which led to them initiating the partnership with the University of Bristol [4], [5]. Based on their requirements and feedback, the diamond detector system may be fitted to existing manipulation systems to provide dose rate measurements inside any facility where radiation levels may be from 0.5 to 3,600 Gy/hr.

POST OPERATIONAL CLEANOUT AT SELLAFIELD

Post operational clean-out (POCO) of facilities at the Sellafield site poses many characterisation challenges due to residual radionuclide contamination and radiation hence only remote methods of characterisation are possible. The activity of the liquor handled by the Highly Active Liquor Evaporation and Storage plant is thought to be $>10^8$ Bq/mL, so the dose rates inside the plant are sufficient to quickly damage most instrumentation systems that might be deployed. Improved characterisation information is required to define more realistic and pragmatic approaches for POCO and decommissioning, particularly for older facilities. Improved characterisation of facilities is required to define the exact nature of the hazard pre and post POCO.

Pre POCO characterisation is required to inform the process by which these facilities will be POCO'd and the ultimate plant End State. Certainty provided by real measurements will be used to support models, and alongside existing detailed plant knowledge will produce an understanding of the processes and waste types/volumes. This improved understanding will be used with a view to reducing overall cost of any decommissioning project, removing conservatisms whilst safety is maintained.

The small size and low mass of the system allows it to be readily deployed on simple tools remotely into highly active nuclear environments to measure radiation dose rates. The measurements are possible by use of bespoke software and hardware customised for the application.

DIAMOND AS A RADIATION DETECTOR

The device uses a diamond-based radiation detector to make dose rate measurements. These semiconductor particle detectors are made of electronic-grade single crystal diamond material, and are sensitive to ionising radiation. Diamond detectors are currently in use at CERN's ATLAS Beam Conditions Monitor [6], [7], and their development is continued by CERN's RD42 collaboration. For the past three years, researchers at the University of Bristol in partnership with Sellafield Ltd have been studying the feasibility of adapting diamond-based radiation detectors for civil nuclear applications, specifically on the Sellafield Site. Sellafield have recognised there are significant benefits to using diamond detectors due to their radiation tolerance for use within high dose rate areas, as an alternative to silicon-based or GaAs equivalents. Furthermore, diamond is more efficient and therefore sensitive per unit volume detector material.

BENEFITS OF THE DIAMOND RADIATION DETECTOR SYSTEM

The following principle benefits of the diamond radiation detector system have been identified:

1. Extraordinary calibrated range (0.5 Gy/hr to 3600 Gy/hr) using high activity controlled radioactive sources
2. Radiation tolerant; not susceptible to radiation damage like other semiconductors.
3. No requirement for cooling or temperature correction due to wide band gap semiconductor material.
4. Miniature to overcome physical access limitations common in high hazard plant.
5. Real-time measurements and analysis using bespoke software and hardware.
6. Wide range of applications in decommissioning and operational plants.

CALIBRATION

The response of the diamond detector as a function of radiation dose rate has been measured using high activity Co-60 and Cs-137 sources at two national facilities, the National Physical Laboratory, UK and the Dalton Cumbrian Facility, UK. The continuous generation of charge carriers within the diamond crystal leads to a small but measureable current, and this signal is proportional to the dose rate experienced by the detector, hence can be calibrated.

These test results showed linearity between dose rate and measured response with no known upper limit in terms of dose rate and accrued dose to the detector. These devices are capable of measuring an extraordinary dose rate range and were tested from 0.5 Gy/hr up to 3,600 Gy/hr with no decrease in performance. The detector's calibrated range is thought to exceed the dose rates experienced inside the world's most radioactive facilities.

DEPLOYMENT

Successful detector response calibrations using Co-60 and Cs-137 gave rise to a deployment of the detector into an active cell on Sellafield Site. In Fig. 1 the data collected during detector deployment in May 2016 is presented. This figure shows the dose rates measured as a function of depth within an active cell using the diamond radiation detector system. The most radioactive material was located towards the bottom of the vessels, showing the presence of highly radioactive material yet to be removed from the bottom of the cell's tanks. The profile of dose rates was as expected, with a peak of 76 Gy/hr, proving the instrument's capability.

The deployment highlights further applications within the nuclear industry: the technology will allow nuclear operators worldwide to make dose rate measurements inside their most radioactive plant: a task other detectors are unsuitable for.

The diamond detector was lowered into an active cell on Sellafield Site, and its calibrated response plotted in real time, showing how radiological contamination was concentrated toward the bottom of the cell. Further deployments are planned to characterise other highly radioactive cells where data collection using other instruments has thus far been previously impossible.

To avoid contamination of the detector, the diamond detector was lowered through the inside of a series of steel pipes, joined and overlapping at 1.5m intervals. The joined pipe overlaps provide additional shielding to the diamond detector from the radioactive material, and is manifest as a reduction in dose rate from the increasing trend shown in Fig. 1.

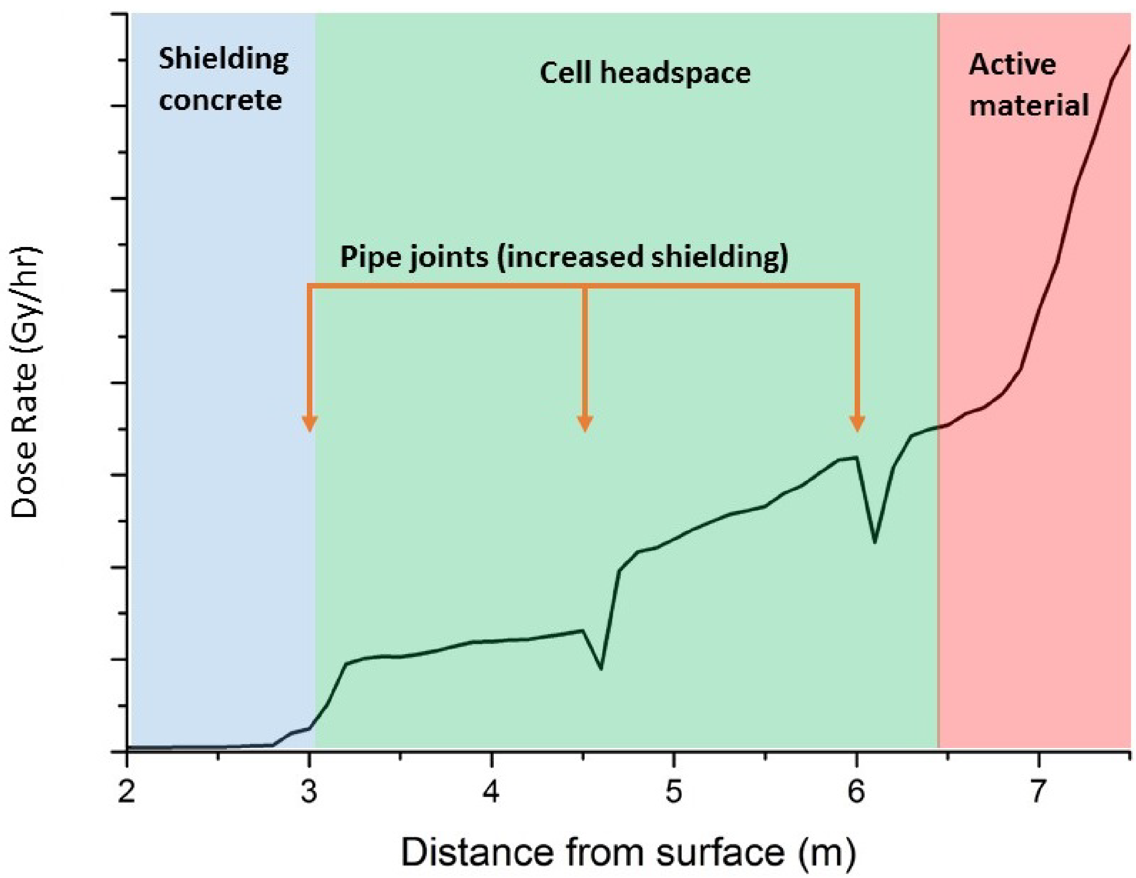

Fig. 1. Detector response as a function of distance into an active cell at the Sellafield Site

APPLICATIONS

Testing in controlled environments, coupled with successful deployment at Sellafield has demonstrated the effectiveness of the diamond detector system. The system's ease of use was commended and the real-time display allowed the operators to maximise data collection in areas of interest. Custom-built software ensured the data and statistics collected from the device during deployment was output in a form suitable for the intended purpose. In combination with position information, automatic analysis is able to produce instant and self-updating plots of dose rate measurements with position as the detector is moved within the facility. Data can be output in graphical or text-based format, ensuring plant radiological information is available as appropriate for decision makers.

Many other nuclear facilities worldwide may benefit from an improved understanding of the radiological state of their plant, especially the high dose rate environments which are often the most difficult to characterise. Facilities previously used in the handling and reprocessing of fuel would particularly benefit from the insight diamond detector high dose rate measurements can provide.

Though calibrated up to 3,600 Gy/hr, the detector has been exposed above 24 kGy/hr, and continued to operate normally. The upper limit of the detector's range is yet to be found, but it is judged that very few real applications will encounter dose rates as high as the highest calibrated dose rate.

A useful application for the system would be mapping the distribution of melted fuel material in the stricken Fukushima Daiichi Nuclear Power Plant, and this will be investigated in partnership with our collaborators from Kyoto University.

AN EFFECTIVE PARTNERSHIP BETWEEN INDUSTRY AND ACADEMIA

The challenges posed by POCO at the Sellafield site can be significant, requiring input and innovation from external stakeholders with problem-solving capabilities. Experts at Sellafield Ltd identified diamond detectors as part of the solution to their characterisation challenges, and sought to combine their plant and process knowledge as nuclear industrialists with the innovators at the University of Bristol. The project team at Bristol draws on expertise from the largest diamond research group in the UK; the materials analysis and thin film growth group; electronic systems and particle physics, and so together with Sellafield Ltd the solution to some of the most complex decommissioning problems in the nuclear industry is being developed.

Highly trained operators at Sellafield Ltd routinely deploy inspection equipment to ensure the structural integrity of hazardous plant, using remote deployment techniques, making them ideally placed to safely deploy the new diamond detector technology.

The development of the technology has benefitted from support in-kind from Sellafield Ltd, who have provided plant access, health physics support, and highly skilled plant operators ensuring the device was safely exposed inside the cell and was returned to the operator surface free of contamination.

The project has been a prime example where engagement with end users has been used to full effect to allow Sellafield Ltd to realise the benefits of diamond detector technology. Quarterly update seminars have been held, allowing the Bristol team to report on project progress, and Sellafield Ltd to explain the customer requirements. The Bristol team have been quick to respond to operator feedback, making changes to the software and hardware to take account of human factors to ensure data is collected efficiently in the safest manner possible.

To bring the technology into routine use, the project will integrate the detector system with existing remote deployment equipment already in use on plant, including both robotic systems and manual manipulators. This will allow further instances where the diamond detector system can be deployed through existing cell penetrations, provided much-needed dose rate data.

Japanese stakeholders

We have established a successful partnership with Kyoto University Research Reactor Institute (KURRI) with whom we have also carried out calibration tests of detectors at their irradiation facility. The project's association with Japan is set to increase with more collaborative development planned with KURRI, which is planned to lead to the use of diamond detectors at the stricken Fukushima Daiichi Nuclear Power Plant. The diamond dose rate system makes it possible for the high dose rates in the reactor cores to be measured, characterising the cores and providing the ability to locate the corium. This is discussed in further detail at the Waste Management Symposia 2017 [8].

CONCLUSION

Diamond based radiation detectors have been calibrated and then deployed at Sellafield, UK to measure high dose rates within highly active cells. Data collected using the system developed by the University of Bristol is presented and demonstrates the viability of this detector technology.

Application examples include monitoring active facilities, disaster response and use in decommissioning and dismantling. This work will enable a range of operators worldwide to gain a more comprehensive understanding of their plant's condition, providing significant advantages in terms of safety and cost-saving.

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