Some Recent Technology Developments From The UK's National Nuclear Laboratory To Enable Hazard Characterisation For Nuclear Decommissioning Applications - 10317

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ABSTRACT

Under its programme of self investment Internal Research and Development (IR&D), the UK's National Nuclear Laboratory (NNL) is addressing the requirement for development in technology to enable hazard characterisation for nuclear decommissioning applications. Three such examples are described here:

RadBall developed by the NNL (patent pending) is a deployable baseball-sized radiation mapping device which can, from a single location, locate and quantify radiation hazards. RadBall offers a means to collect information regarding the magnitude and distribution of radiation in a given cell, glovebox or room to support the development of a safe, cost effective decontamination strategy. RadBall requires no electrical supplies and is relatively small, making it easy to be deployed and used to map radiation hazards in hard to reach areas. Recent work conducted in partnership with the Savannah River National Laboratory (SRNL) is presented.

HiRAD (patent pending) has been developed by the NNL in partnership with Tracerco Ltd (UK). HiRAD is a real-time, remotely deployed, radiation detection device designed to operate in elevated levels of radiation (i.e. thousands and tens of thousands of Gray) as seen in parts of the nuclear industry. Like the RadBall technology, the HiRAD system does not require any electrical components, the small dimensions and flexibility of the device allow it to be positioned in difficult to access areas (such as pipe work). HiRAD can be deployed as a single detector, a chain, or as an array giving the ability to monitor large process areas. Results during the development and deployment of the technology are presented.

Wireless Sensor Network is a NNL supported development project led by the University of Manchester (UK) in partnership with Oxford University (UK). The project is concerned with the development of wireless sensor network technology to enable the underwater deployment and communication of miniaturised probes allowing pond monitoring and mapping. The potential uses, within the nuclear sector alone, are both numerous and significant in terms of the proceeding effort to clean up the UK's nuclear waste legacy.

INTRODUCTION

The challenges of deactivating, decontaminating, demolition and decommissioning of nuclear facilities in the UK and USA demands the development of new technologies to enable the detection and characterisation of radiation hazards in a wide variety of scenarios. Presented in this paper are some recent technology developments to enable hazard characterisation for nuclear decommissioning applications. Each of the three example technologies selected have been developed by the NNL under its self investment Internal Research Development (IR&D) Programme. The NNL IR&D programme has the following goals:

1. To build R&D capacity (skilled staff, modern facilities and one-of-a-kind equipment) in a select number of "signature research" areas that will form robust technology platforms, which uniquely position the laboratory both as a supplier of unique services and an authority on nuclear issues.

2. To leverage these technology platforms and other sources to grow an Intellectual Property (IP) portfolio of products and know how for commercial application in nuclear and related markets.

NNL IR&D TECHNOLOGIES

TECHNOLOGY 1: RadBall

The NNL has developed a remote, non-electrical, radiation-mapping device, known as RadBall, which offers a means to locate and quantify radiation hazards and sources within contaminated areas of the nuclear industry. The positive results from initial deployment trials on the Sellafield Site in the UK and the anticipated future potential of RadBall have led to the NNL partnering with the Savannah River National Laboratory (SRNL) to further underpin and strengthen the technical performance of the technology.

RadBall consists of a colander-like outer shell that houses a radiation-sensitive polymer sphere. It has no power requirements and can be positioned in tight or hard-to reach places. The outer shell works to collimate radiation sources and those areas of the polymer sphere that are exposed react, becoming increasingly less transparent, in proportion to the absorbed dose. The polymer sphere is imaged in an optical-CT scanner which produces a high resolution 3D map of optical attenuation coefficients. The orientation of the opacity track provides the positional information regarding the source (achieved by using a reverse ray tracing technique) and the activity of the detected source is assessed by quantifying the magnitude of the opacity change (which follows a linear relationship with respect to absorbed dose).

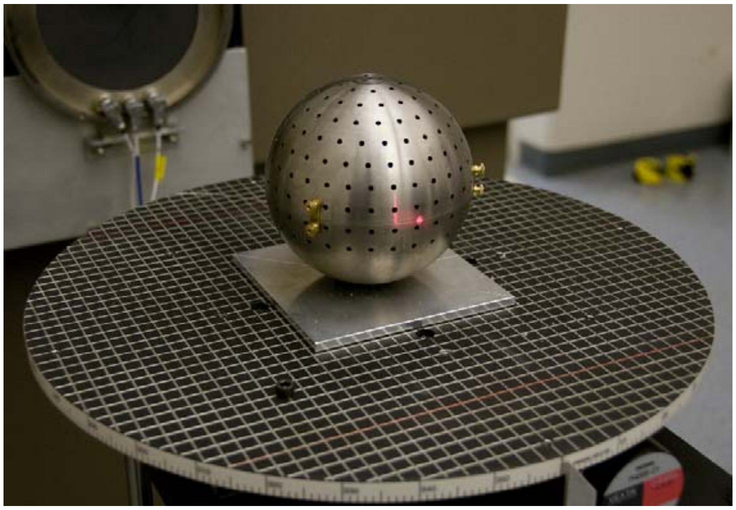


Figure 1: Photograph of RadBall.

The study completed at SRNL addressed key aspects of the testing of the RadBall technology. The first set of tests was performed at Savannah River Nuclear Solutions' Health Physics Instrument Calibration Laboratory (HPICL) using various gamma-ray sources and an x-ray machine with known radiological characteristics. The objective of these preliminary tests was to identify the optimal dose and thickness of collimator shell. The second set of tests involved a highly contaminated hot cell. The objective of this part of the testing was to characterise a hot cell with unknown sources.

Three experimental phases were completed at the HPICL which included the exposure of forty-five RadBalls. The majority were completed with ^{137}Cs and ^{60}Co sources.

- Phase 1 experiments were primarily used to obtain information on the target dose for RadBall. Experiments were completed with a ^{137}Cs source with irradiations from 0.5 to 5 Gy and with a ^{60}Co source also with irradiations over the range of 0.5 to 5 Gy.
- Phase 2 experiments investigated the RadBall performance with different radiation sources and different collimator thicknesses.
- Phase 3 experiments investigated the ability of the RadBall technology to perform with high background levels of radiation. Un-collimated RadBall polymers were given a background radiation dose and then a 2nd irradiation was performed with the collimator fitted.

After irradiation at the HPICL, the RadBall polymers were sent to Duke University Medical Center for optical CT scanning. The data results from the optical CT scan were subsequently analysed using Image Processing and Analysis, Java (ImageJ) software. All 45 RadBall irradiations completed at the HPICL resulted in radiation tracks that were visible in the optical CT scans and have demonstrated the effective performance of the RadBall against the selected radiation sources and doses. Analysis of the RadBall optical CT scans from the HPICL experiments has indicated that for optimum contrast, and thus ability to accurately locate radiation tracks in the PRESAGE^{TM} polymer, a target dose of between 3 – 5 Gy is required. At these target doses, the contrast of optical CT scans is improved by increasing the collimator thickness. Experiments completed with the 10mm collimator provided the optimum contrast for data analysis. The ability of the RadBall technology to characterise the different radiation sources is currently being investigated.

A Selection of RadBall Irradiations from HPICL

Figure 2(a) & (b) show optical-CT scan images of a RadBall N-2-2 irradiated with a 1.0 Gy ^{60}Co radiation source with a 5 mm collimator. Figure 2(c) is a plot profile taken from across the radiation tracks shown in Figure 2(b) and highlights the ability to be able to pick out the radiation tracks from against areas of the un-irradiated polymer. Six tracks are visible in the plot profile. There is a wider diameter radiation track in the middle of the RadBall due to the middle collimation hole being slighter larger than the other holes on the collimation device. The diminishing intensity of the peaks to the left and right of the middle peak is due to the curvature of the collimator geometry.

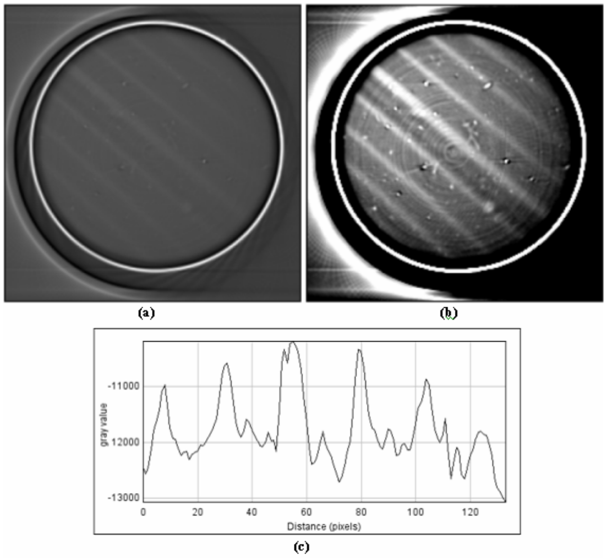


Figure 2: RadBall N-2-2 (a) Pre (b) Post Enhanced Contrast Optical CT Scan Images (c) Plot Profile.

Locating Radiation Sources

Based on a reverse ray tracing technique, the NNL have developed in-house software to enable the RadBall technology to accurately locate radiation sources. This was tested on the data from the calibration experiments, for a RadBall to radiation source distance of 100 cm, the RadBall predicts the position of the radiation source to within 10 mm (I.e. to within 1% accuracy).

Hot Cell Deployment

The second set of tests involved the deployment of RadBall in a highly contaminated hot cell in the Savannah River National Laboratory’s Shielded Cells Facility. The objective of this part of the testing was to characterize a hot cell with unknown sources.

Figure 3 is a photograph of the Hot Cell in the SRNL Shielded Cells Facility in which RadBall was deployed.

Figure 3: Photograph of SRNL Shielded Cell Facility Hot Cell.

Figure 4(a) is a 3D visualisation of the chosen hot cell in SRNL's Shielded Cells Facility created in Autodesk Inventor^{TM} and is used in conjunction with the radiation results from the deployed RadBall to visualise the origins of the detected radiation.

The RadBall testing in the hot cell involved the characterisation of the hot cell by using common methods such as teledetectors and smears to determine the dose rates and radionuclides present in the hot cell. Swipes were taken in the selected shielded cell and ^{60}Co, ^{137}Cs, ^{154}Eu, and ^{241}Am were found on the floor and walls. RadBall was deployed in the hot cell at a raised height of 42 inches above the floor and left for a 72 hour time period with a 10 mm collimator. The optical CT scans of RadBall N-7-5 showed 21 faint radiation tracks in the RadBall polymer. The co-ordinates of these tracks were imported into the NNL's in-house software along with the geometry of the hot cell. These combined data sets predicted the location of the radiation sources in the hot cell. The majority of the radiation was deemed to be originating from the floor. RadBall located 12 closely distributed radiation sources originating from the floor which are pointed towards the bottom of the equipment tray and the bottles located on the right hand side of the tray. These predicted radiation location results are overlaid on a floor view from the 3D visualisation of the hot cell in Figure 4(b). This analysis is consistent with the RadBall pre-deployment radiation dose investigations which confirmed that the highest radiation doses were on the floor of the hot cell.

(a) **(b)**

Figure 4: (a) 3D Visualisation of Hot Cell in SRNL Shielded Cells Facility (b) RadBall Predicted Radiation Results Overlaid on Hot Cell Floor.

TECHNOLOGY 2: HiRAD

HiRAD has been developed by the NNL in partnership with Tracerco Ltd (UK). The HiRAD is a real-time, remotely deployed, radiation detection device developed to operate in elevated levels of radiation (i.e. thousands and tens of thousands of Gray) as seen in parts of the nuclear industry. Like the RadBall technology, the HiRAD system does not require any electrical components, which was a major driver during the development due to the very high radiation levels seen in some nuclear facilities. The NNL believe that the HiRAD's resistance to radiation makes it a unique technology for radiation based plant monitoring on highly active waste processing and storage facilities.

The device consists of a small scintillating crystal coupled to a variable length fibre optic cable. Scintillation light produced from the crystal in a radiation field is transmitted down the fibre optic cable, detected by a suitable photon detection device which is then recorded on PC software and used to infer the radiation levels of the environment. The small dimensions and flexibility of the device allow it to be deployed down small, difficult to access areas (such as pipe work). HiRAD can be deployed as a single detector, a chain, or as an array giving the ability to monitor large process areas.

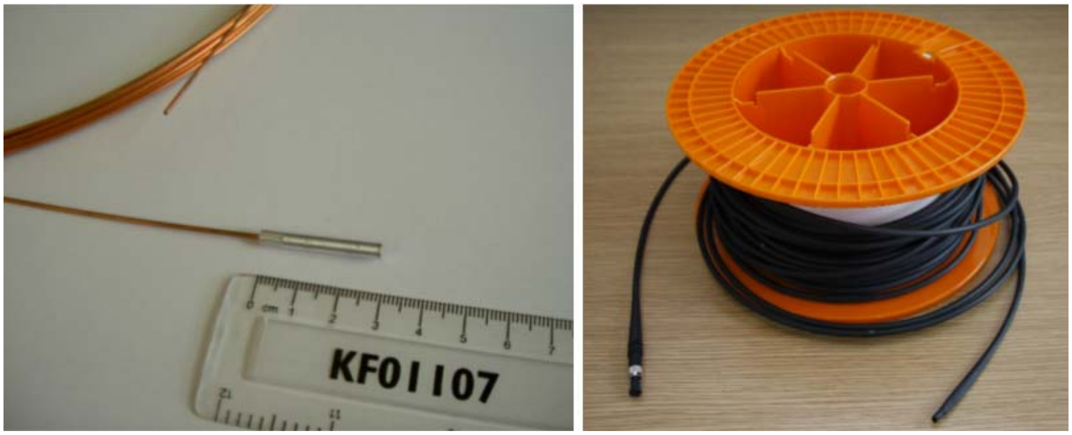


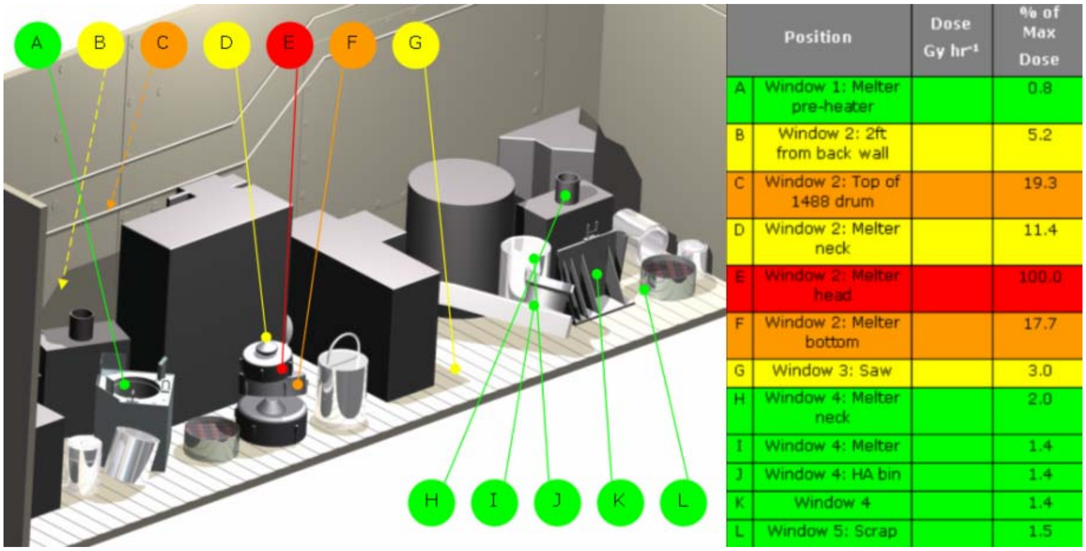
Figure 5: Photographs of HiRAD Deployed in WVP Breakdown Cell.

Prior to deployment in the Waste Vitrification Plant (WVP) breakdown cell, the HiRAD device was calibrated with low and high level radiation sources at Tracerco Ltd (UK) laboratories and the National Physical Laboratory respectively. During this calibration, the HiRAD technology was shown to be sensitive over the radiation range of 0.01 to 8,580 Gy hr^{-1} (currently the highest dose-calibration facility in which HiRAD has been tested). Although un-tested, the HiRADs upper radiation limit is estimated at 100,000 Gy hr^{-1}.

Recent development of the HiRAD by the NNL has seen the technology deployed on the Highly Active Waste Vitrification Plant (WVP) on the Sellafield Site in the UK. This represented the first deployment of the HiRAD technology in an actual facility on a nuclear site. A single HiRAD device was used to map the radiation intensities over a given volume within the breakdown cell of line 1 in the WVP. The HiRAD was posted through a traverse (normally used for posting electrical cables from the cell face into the cell) and moved around by Master Slave Manipulators (MSMs) to provide multiple point measurements of radiation intensity. At the end of the technology trial, the fibre optic cable was cut and the cable sacrificed in the breakdown cell. Figure 6 is a photograph taken from an operating window on the breakdown cell and shows the deployed HiRAD (enlarged image on bottom right) in location.

Figure 6: Photograph of HiRAD Deployed in the Breakdown Cell.

HiRAD responded well to the radiation levels in the breakdown cell and a 3D visualisation was created to display the results recorded. The HiRAD radiation results from the deployment trial have been presented on a 3D visualisation of the breakdown cell as shown in Figure 7.



Position		Dose Gy hr^{-1}	% of Max Dose
A	Window 1: Melter pre-heater		0.8
B	Window 2: 2ft from back wall		5.2
C	Window 2: Top of 1488 drum		19.3
D	Window 2: Melter neck		11.4
E	Window 2: Melter head		100.0
F	Window 2: Melter bottom		17.7
G	Window 3: Saw		3.0
H	Window 4: Melter neck		2.0
I	Window 4: Melter		1.4
J	Window 4: HA bin		1.4
K	Window 4		1.4
L	Window 5: Scrap		1.5

Figure 7: 3D Visualisation of the WVP Breakdown Cell with Overlaid HiRAD Radiation Results.

The actual recorded dose rates for the equipment items monitored during the trial are classified as restricted information; however, for the purposes of this publication the radiation doses have been illustrated in the above figures as percentages of the maximum recorded dose: The colour: Red = 100%, Orange = 15 – 25%, Yellow = 2 – 15%, Green = 0 – 2% of the maximum recorded dose.

For guidance, the customer provided an estimation of the dose within the line 1 breakdown cell well in excess of 1000 Gy hr^{-1}. The HiRAD deployment trial identified that the radiation levels in the breakdown cell were of lower magnitude than previously estimated by the customer and it is concluded that the dose rate estimates were too conservative and pessimistically evaluated cell conditions.

TECHNOLOGY 3: Wireless Sensor Network

The NNL has supported the project led by the University of Manchester (UK) in partnership with Oxford University (UK) into the development of a wireless sensor network technology to enable the underwater deployment and communication of miniaturised probes allowing nuclear pond monitoring and mapping. The technical issues addressed in the project have significant applications within the nuclear industry with regards to underwater baseline and dynamic property monitoring in ponds containing, for example, legacy waste sludge, submerged objects, skips and spent fuel flasks. The network platform, when combined with existing and future sensing technologies, will enable the quick and representative mapping of the given pond through the collation of various physical and chemical properties.

To date, there has not been an effective strategy for monitoring of such radiation environments:

- Remotely Operated Vehicle (ROV) technology has been used in the past; however, this has often failed due to umbilical entanglement. The size associated with current ROV technology also means significantly reduced access in certain areas as well issues with ROV recoverability. Due to the sheer size of the ponds an accurate and meaningful survey using a single and moveable point measurement simply requires too much time which also means it is unsuitable for dynamic process monitoring.
- Dip-stick technology has similar deployment issues as with ROV’s with regards to access in hard to reach areas (such as beneath and in between containers). Using a single and moveable point measurement to obtain a reasonable survey requires long time periods and is unsuitable for dynamic process monitoring.
- Sensing nodes deployed on the end of a gantry has also been attempted in the past. For many of the older ponds on the Sellafield site this is not an option as the mechanical integrity of the pond can not be risked.
- For newer storage ponds the risk of impact from a gantry extension with stacked spent fuel flasks needs to be mitigated.

Figure 8 shows a 3D visualisation of a nuclear storage pond environment in which the wireless sensor network technology could be deployed. Figure 9 is a 3D visualisation of a wireless sensor.

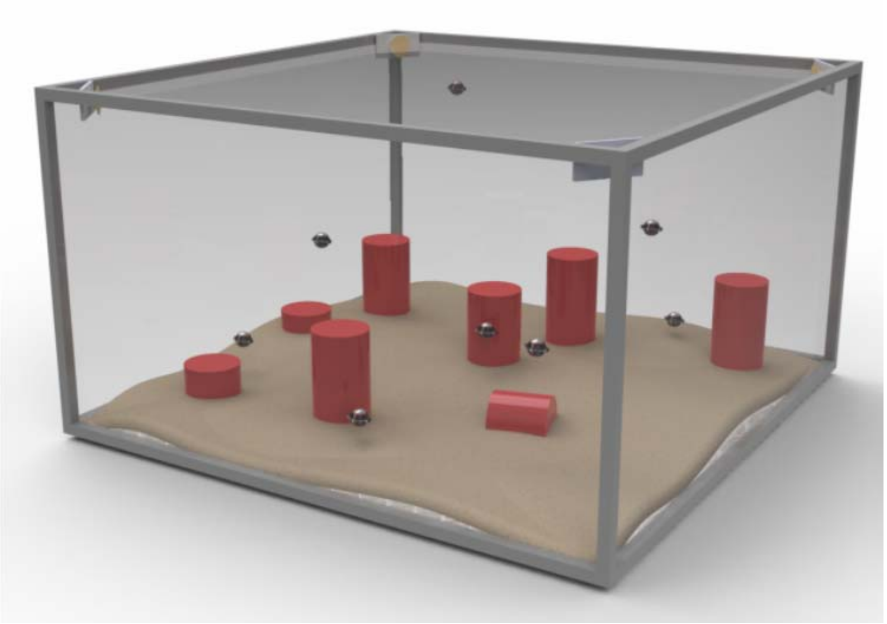


Figure 8: 3D Visualisation of a Nuclear Storage Pond.

Figure 9: 3D Visualisation of Underwater Robot.

The proposed technology offers a means to perform networked monitoring in a number of instances:

- Safety monitoring during sludge mobilisation and recovery: This is an important requirement as monitoring the sludge height in the pond during mobilisation and recovery enables the workers to remain unexposed to radiation. Monitoring may enable a more controlled sludge mobilisation therefore reducing the need to stop work due to radiation exposure caused by surfaced sludge material. Therefore, this may offer a means to improve the sludge recovery and treatment rate which has significant associated cost benefits.
- Full pond mapping to enable a more strategic material recovery approach: The technology will offer a means to map the pond sludge with regards to types or local variations in sludge composition which may have originally been down to different types of material being introduced in the pond at different times. Therefore, this will allow operators to make special provisions for specific materials as well as a methodology for targeting certain regions which would suit a specific recovery and treatment route (whether dependant on physical or chemical characteristics). This will offer a means to improve the overall efficiency of the recovery and treatment strategy.
- Locating large partially or fully submerged objects: Large objects are to be removed from the sludge before the sludge itself. Therefore, the proposed technology could offer a means to locate such objects which may be partially or fully hidden.
- Yield stress measurements on the pond surface: Mapping the yield stress on the pond surface may also provide a means to highlight regions of the pond surface which are easily mobilised. The sludge present in these ponds is in some instances extremely difficult to mobilise due its high yield stress. However, locating the ‘weak points’ or the ‘Achilles heel’ in the sludge/fluid interface may provide a means to easily achieve the initial disturbance/suspension.
- Monitoring containment on the Fuel Handling Plant: The networked probes could be used to monitor local radiation levels around the numerous spent fuel containers. This may offer a means to detect local radiation build up which potentially could pre-empt seal failure which often leads significant remedial action.

Work in the project to date has focused on four areas: communications and ranging, sensing, mechanical design and control, and exploration and localisation. The main challenge in terms of communications and ranging is achieving adequate transmission rates in a confined, cluttered underwater environment, with power and size constraints, using off-the-shelf transducers. Results from small-scale tests indicate that multipath propagation can be mitigated and that reliable communication can be achieved at 3.3kbps using low order modulation, low complexity communications algorithms and a transmission frequency of 50kHz. Future research will seek to enhance transmission rates, and investigate multiple access capabilities to enable multiple minnows to communicate. Finally, waveform and modulation schemes will be designed to support both communications and ranging.

Efforts in terms of sensing have focused on low cost, low power, compact sensors for turbidity and surface hardness, since commercial devices cannot be used. An experimental ultrasound probe that is able to distinguish between 5 different levels of hardness is under development, and a turbidity probe based on optical sensors will be investigated. Studies of the options for buoyancy and propulsion systems, control, and hull design, in terms of power and size have indicated that to ensure a manoeuvrable system with an adequate lifetime, minnows should be spherical (diameter 130mm - 200mm), velocity should be < 1ms-1 and the power supply should be a Li-Ion battery pack. A further study of buoyancy/propulsion systems indicated that propellers should be used for both vertical and horizontal manoeuvring. A prototype vertical displacement system and its PD- controller have been successfully demonstrated. The next stage prototype, allowing both horizontal and vertical movement is currently being designed, and motion control strategies will be investigated.

In the exploration and localisation work, factors influencing the accuracy of minnow position estimates have been identified, and a study of how errors propagate when minnows are used to localise minnows in an iterative manner has been completed. Error propagation will be controlled by defining a reliable error metric. Optimal placement of reference nodes will also be investigated. A simulation environment has been developed, and traditional localisation and mapping algorithms have been implemented. Preliminary results indicate that inaccuracies in robot position introduce errors into maps, which in turn present difficulties for exploration. A single hop localisation algorithm has been developed that can accurately localise minnows in cluttered environments in the presence of large positional errors. This will be used to compare the simulated performance of mapping algorithms.

CONCLUSIONS

The NNLs IR&D programme is funding and developing a wide variety of innovative technologies to enable radiation hazard characterisation for nuclear decommissioning applications:

The RadBall and HiRAD technologies offer the ability for nuclear plants to collect information regarding the severity and distribution of radiation in a given cell, glovebox or room to ensure that the safest and most cost effective decontamination strategy can be determined and executed. Both technologies do not require electrical supplies and can be easily deployed in hard to reach areas of plants to map radiation hazards.

The RadBall technology has recently undergone a phase of control testing at SRNL. The RadBall calibration experiments and hot cell deployment completed at SRNL were successful in that for each trial, the technology was able to locate the radiation sources. Results from the RadBall trials have also enabled optimisation of the parameters for RadBall deployment. The deployment of RadBall in the SRNL Shielded Cells Facility represents the first successful hot cell deployment of the technology. RadBall was able to locate the strongest radiation doses originating from the floor of the hot cell and the predicted position of these radiation sources has been displayed on a 3D visualisation of the hot cell.

The HiRAD technology has a calibrated range of between 0 to 8580 Gy hr^{-1} and an estimated working range of between 0 to 100,000 Gy hr^{-1}. A recent HiRAD technology trial has successfully demonstrated the ability of HiRAD to be easily and effectively be deployed and provide dose mapping of the breakdown cell of line 1 in the Sellafield Waste Vitrification Plant. Due to difficult access and expected high radiation doses the customer had never had the opportunity to dose map their facility. The HiRAD technology was able to obtain radiation results within 30 minutes of the deployment team arriving at the operating face of the breakdown cell and the recorded radiation results have been overlaid on a 3D visualisation of the breakdown cell.

The Wireless Sensor Network is an exciting new platform to enable a networked and integrated approach to the science of process monitoring and measurement. The potential uses, within the nuclear sector alone, are both numerous and significant in terms of the proceeding effort to clean up the UK's nuclear waste legacy.

FUTURE WORK

RadBall: Future milestones involve the development of a robot for remote RadBall deployment into highly contaminated facilities, portable optical CT scanner development, and RadBall deployment at another DOE facility using the robot and portable scanner to promptly obtain visualizations of the contaminated hot cell or glove box. Further software and visualisation development will also take place to provide an enhanced, texturized output image to better define the sources of radiation in the deployed environment (e.g. similar to map contours).

HiRAD: The NNL have recommended that Sellafield Ltd consider a number of further HiRAD deployments including: the Waste Vitrification Line (to provide real time process measurements), Further breakdown cell deployments (to enable further radiation level estimation of the remaining breakdown cells) and other as of yet un-identified scenarios on the Sellafield site.

Wireless Sensor Network: The next step for the project is concerned with the integration of different sub-systems into a fully operational prototype, a ‘shoal’ of which will be tested in storage pond-like environment.

ACKNOWLEDGMENTS

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