Institution: University of Surrey

Unit of Assessment: UOA 9 Physics

Title of case study: 3D radiation dosimetry for remote scanning of hazardous environments

1. Summary of the impact (indicative maximum 100 words)

The University of Surrey's Radiation and Medical Physics Group developed a technique used in radiotherapy applications in medicine and have played a significant role in extending its application to environmental nuclear decontamination. The key concept is to use polymeric gels as direct detectors of radiation to show visually the regions where radiation is being concentrated and the direction from which it comes. Two Surrey research contracts with the National Nuclear Laboratory (NNL) culminated in the creation of a commercial radiation dosimeter known as the RadBall,® which offers the advantages of being portable, non-electrical, simple to use, and able to be remotely operated. Surrey's research is having an impact by shaping industrial practice in the decommissioning of radioactive waste in the UK and in the USA. The use of the RadBall® to detect radiation ensures the safety of workers and protects the general public. RadBall® has been used at the Sellafield nuclear processing facility, and licensing agreements and developments are underway with US government laboratories.

2. Underpinning research (indicative maximum 500 words)

Starting in 1996, University of Surrey researchers pioneered the development of three-dimensional (3-D) radiation dosimetry using polymer gels, and they have been among the world leaders in this area since then. Initial work was performed by Dr Simon Doran (Surrey lecturer from 1995–2006, now at the Institute of Cancer Research and Visiting Senior Fellow at the University), with two PhD students and an Erasmus student (Hepworth, Bero and Koerkamp). This research led to well-cited outputs on the characterisation of so-called "gel dosimeters" [1] and to one of the seminal papers on optical computed tomography (CT) scanning of gel dosimeters [2]. Simply stated, the optical properties of a gel dosimeter change as a result of irradiation. Optical scanning of irradiated gels is then used to determine the radiation dose as a function of position in 3D space. Doran followed these initial investigations by a research programme that developed the methodology of optical CT gel dosimetry [3] through the PhD research of Nikola Krstajić. They successfully patented the design of scanners used in the research [4]. They employed these scanners to characterise polymer gel samples in the later research activities that resulted directly in the impact.

The direct origin of the main impact was an experimental project, undertaken by an MSc physics student (Prott) with Dr Doran as supervisor. The subject for the dissertation had been suggested by Dr Paul Jenneson (Surrey lecturer in Physics) after discussions with Dr Steven Stanley (Nexia Solutions). The idea for the project was to surround a sample of a newly-developed radiochromic polymer, known commercially as PRESAGE®, with a lead sheath containing an array of holes. This object was then placed in a radiation field, which would lead to a set of "rays" being transmitted through the holes. Exposure of the polymer to radiation changes its colour in a way that could be scanned in 3-D, using the optical tomography apparatus previously developed by Doran's group. They envisaged that inverse ray tracing could be used to calculate the position of the radiation sources to which the sample had been exposed, whereas the extent of the colour change could be used to determine the dose-rate of the source, given a suitable calibration. The Surrey team carried out the world's first optical CT scan of the radiochromic polymer PRESAGE®. This material is a key component of RADBALL®, the commercial product that has produced the main impact. The successful research results were first published in an MSc dissertation in 2007 and presented at the DOSGEL 2008 conference, before appearing in a journal [5].

The original intended target of this research was in the field of medical physics, where 3-D radiation dosimetry is used for the verification of complex radiotherapy treatments. Doran has led a programme of applications of 3-D gel dosimetry in medicine [6]. Surrey contributions to the field are outlined in two major and heavily-cited reviews [7,8] charting the developments over more than a decade.

3. References to the research (indicative maximum of six references)

[1] Dynamics of polymerization in polyacrylamide gel (PAG) dosimeters: (II) modelling oxygen diffusion, S J Hepworth et al 1999 Phys. Med. Biol. 44 1875 doi:10.1088/0031-9155/44/8/302

[2] A CCD-based optical CT scanner for high-resolution 3D imaging of radiation dose distributions: equipment specifications, optical simulations and preliminary results, Simon J Doran *et al* 2001 *Phys. Med. Biol.* 46, 3191 doi:10.1088/0031-9155/46/12/309 (93 citations)

[3] Focusing optics of a parallel beam CCD optical tomography apparatus for 3D radiation gel dosimetry, Nikola Krstajić and Simon J Doran 2006 Phys. Med. Biol. 51, 2055 (44 citations)

[4] Fast laser scanning optical CT apparatus, Doran and Krstajić, US patent 7,633,048 2009

[5] RadBall™: A new departure for 3-D dosimetry, Simon J Doran et al 2009 J. Phys.: Conf. Ser. 164 012042 doi:10.1088/1742-6596/164/1/012042

[6] A preliminary analysis of LET effects in the dosimetry of proton beams using PRESAGE™ and optical CT, S. Al-Nowais, S. Doran, A. Kacperek, N. Krstajic, J. Adamovics, D. Bradley, *Applied Radiation and Isotopes*, Volume 67, Issue 3, March 2009, Pages 415–418, http://dx.doi.org/10.1016/j.apradiso.2008.06.032

[7] Radiation dosimetry using polymer gels: methods and applications, M McJury et al. British Journal of Radiology (2000) 73, 919-929 (92 citations)

[8] Polymer gel dosimetry, C Baldock *et al* 2010 *Phys. Med. Biol.* 55, R1-R63 doi:10.1088/0031-9155/55/5/R01 (165 citations)

Funding for this research included Doran's contract with the National Nuclear Laboratory (NNL) (formerly Nexia) starting in 2009. Prior to then, research was carried out by self-funded PhD and MSc students.

4. Details of the impact (indicative maximum 750 words)

The impact came about via an existing collaboration between Dr Doran and two colleagues in the Radiation Physics Group, Dr. Walter Gilboy (Senior Lecturer, now retired) and Dr. Paul Jenneson (Lecturer), both of whom were long-standing supporters of the optical CT programme. Both had industrial contacts through previous collaborations with Nexia Solutions (which later became the NNL). The team envisaged the application of gel dosimetry in the area of remote monitoring of radiation levels in hazardous environments, rather than its original application in medical physics. Encouraging research results at Surrey were the basis for a patent application for a radiation detector [Corroboration reference C1], with Stanley at NNL and Doran and Jenneson at Surrey being the named inventors.

The initial shape of the dosimeter was cylindrical, and Nexia wished to optimise this configuration. To achieve the optimisation, in 2007 Doran carried out computer simulations and explained the implications of using different materials and collimator thicknesses on the contrast achieved in the detector gel. Encouraged by developments, Nexia developed a revised polymer shape and surrounding collimator, in collaboration with dosimeter manufacturer Heuris Pharma

LLC. In collaboration with NNL in 2009, Doran evaluated the first incarnation of the new RadBall® design [C2]. The green spherical sample created by Dr Doran in this phase of development has proved iconic: it was used widely by NNL in its publicity (e.g., slides 13 and 14 of reference [C3]) and on the polymer manufacturer's homepage (www.presage3d.com), where the Surrey laboratory and key researchers also feature prominently. The results from this phase supplemented the original Surrey research and resulted in a second patent application [C4].

The research undertaken at Surrey has led to NNL's development of a commercial dosimeter, known as RadBall®, which has a clear advantage in being portable, non-electrical, simple to use, and able to be remotely operated. Prior to radiation exposure, the ball of polymer initially is translucent, and it becomes increasingly opaque upon exposure to radiation, in proportion to the dose. The direction of the opaque tracks in the ball shows the position of the source, and the change in the tracks' opacity indicates the source's activity. The polymer sphere is then imaged in an optical-CT scanner to relate the opacity to the received radiation dose.

A key impact of the research is the change in practice in nuclear decommissioning brought about by adoption of the RadBall® technology. RadBall® is being used by NNL at Sellafield in the former reprocessing building, where radioactive waste is contained in cells, which are small solidly-constructed rooms. Decommissioners are clearing out the so-called "legacy waste" accumulated from years of nuclear energy and weapons production. The RadBall® dosimeters are placed within radioactive cells either directly by workers or remotely through robots and cranes. The radiation levels can be mapped out, and sources of radiation can be identified, so as to facilitate the decommissioning process.

The technology thus has an impact on the safety of radiation workers, and it provides protection to the general public in the decommissioning of nuclear facilities. A nuclear engineer at Sellafield explains the benefits of RadBall's portability [C5]: *"You can use it in hard-to-reach areas in the plant and in areas where electric devices struggle with high radiation levels. It tells us where the hazards are and how severe they are."*

Linking the impact of RadBall® to the Surrey research, a Business Manager (Instrumentation and In-situ Analysis) and Intellectual Property Manager from NNL [C6] says: *"Working with the University of Surrey provided the National Nuclear Laboratory with access to valuable and essential expertise which proved to be a critical factor with regards to the development of the technology."*

From 2010 onwards, impact from the research *continued* when NNL established a strategic collaboration with the USA Department of Energy. They tested RadBall first at the Savannah River National Laboratory and then at the Oak Ridge National Laboratory. A large team, supported through significant investment, has been developing a robotic solution for deployment of the device. A first set of tests at Savannah River's Health Physics Instrument Calibration Laboratory used gamma-ray and X-ray sources to identify the optimal dose and collimator thickness. Then, tests at the Shielded Cells facility employed RadBall® to characterise cells containing contamination from unknown radiation sources. In this milestone development, a 3D visualisation of the radiation within the cell was obtained.

Numerous reports on the outcomes that have flowed from this research at Savannah River have appeared, and plans have been articulated for testing a robot for remote RadBall® deployment into highly contaminated facilities [C7]. The University of Surrey's vital research contribution to the origin of the RadBall® technology is spelled out in a recently-published history in an NNL technical report [C8].

In the past few years, there has been an increasingly high public profile for the project, with stories run in both the popular press (*e.g*. the BBC) [C5] and in U.S. governmental reports [C9]. As a testimony to the significance of the technology, it has been awarded the IChemE Award for Innovation and Excellence in Health and Safety.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[C1] Patent application WO/2009/063246, Radiation detector with polymeric core, inventors: Stanley, Doran, Jenneson, Filing date: 14.11.2008

[C2] Information on RadBall® on NNL website: http://www.nnl.co.uk/radball/

[C3] NNL presentation at http://ripassetseu.s3.amazonaws.com/www.nnl.co.uk/_files/documents/aug_11/NNL__1314362301_NNL_RadBall_Presentation.pdf

[C4] Family of patent applications (20110017924, CA 2705365, JP 2011503602) entitled "Novel radiation detector", inventors: Stanley, Doran, Jenneson

[C5] BBC news article: http://news.bbc.co.uk/1/hi/business/7754355.stm

[C6] Business Manager (Instrumentation and In-situ Analysis) and Intellectual Property Manager, NNL. Contact details provided.

[C7] Testing of the RadBall technology at Savannah River National Laboratory, Farfán *et al*., http://sti.srs.gov/fulltext/SRNL-STI-2009-00808.pdf

[C8] RadBall®: technical development report published by NNL http://ripassetseu.s3.amazonaws.com/www.nnl.co.uk/_files/documents/aug_11/NNL__1314363747_RadBall_-_Technical_Developmen.pdf

[C9] http://www.ornl.gov/info/news/pulse/no326/feature.shtml

[C10] Founder and president, Heuris Pharma LLC. Contact details provided.