Institution: Loughborough University

Unit of Assessment: B8 Chemistry

Title of case study: Radiochemistry at Loughborough: Safeguarding the Environment, Shaping Policy, Training the Next Generation of Nuclear Specialists

1. Summary of the impact

Research at Loughborough University during the REF period (and extending back at least three decades beyond that) has had a significant impact on national and international policy decisions governing the management of radioactive waste, one of the Grand Challenges facing society. The Unit's research ranges from deep geological disposal to abatement of marine discharges and remediation strategies for industrial radioactive waste, the latter safeguarding the competitiveness of the oil & gas and mineral processing sectors. This input has been crucial for revising the new Environmental Permitting Regulations and International Basic Safety Standards. Many of the Unit's doctoral graduates occupy important decision-making roles at key organisations such as the Nuclear Decommissioning Authority (NDA), Sellafield, Environment Agency, CEA (France) and the International Atomic Energy Agency (IAEA).

2. Underpinning research

The technical prowess and accumulated experience of the radiochemistry group at Loughborough University makes them one of the very few UK centres capable of addressing all aspects of the fundamental research required to direct policy on radioactive waste management. This high level of technical competence is crucial, as any safety case for the disposal of nuclear wastes must be supported by defensible scientific data and principles. In the context of a geological nuclear waste repository, essential components concern the solubility, speciation and retardation of key radionuclides in groundwaters and barrier materials (e.g. cement), since these affect their migration through the terrestrial environment. Loughborough University researchers have played a major role in carrying out research into these essential areas. Thus, following the failure of the nuclear industry body, Nirex, to gain approval for a deep facility at Sellafield, Loughborough University was entrusted with reducing the key uncertainties via a series of projects (2008 -2014) supported by the NDA, EPSRC and EU. The output from this ongoing work **[3.1, 3.2]** continues to determine whether porous cement could be a viable backfill material for this type of waste. Evidence to date has already underpinned policy changes and the reconsideration of current practices. Loughborough University researchers have made substantial contributions in formulating pan-European thermodynamic models of waste disposal systems. Building on the original CHEMVAL geochemical modelling projects, which set standards for numerical approaches, our most significant contribution has been the development of methods for radio-labelling natural organic matter (NOM) and associated thermodynamic models **[3.3].**

Until 2002, Sellafield discharged large volumes of technetium (as ^{99}Tc) into the Irish Sea, the isotope subsequently appearing in marine biota, notably Norwegian lobsters. Such was the environmental concern that an important contract to install a natural gas pipeline from Norway to the UK was placed in jeopardy. Loughborough University researchers played a crucial role in assessing the behaviour of the chosen Tc sequestrant, tetraphenylphosphonium bromide (TPPB), and its long-term stability when encapsulated in a cementitious waste form **[3.4, 3.5]**.

Large volumes of radioactive waste (NORM) are created each year by the use of fossil fuels and exploitation of industrial minerals. Original research at Loughborough University into scale formation coupled with strategies for inhibition and remediation **[3.6]** has been supplemented by high level advice to industry and Government.

The following members of staff directed the research during this period:

Peter Warwick (PE), Professor of Radiochemistry: 1981 - 2010
David Read (DR), Professor of Radiochemistry: 2010 - present. Visiting Professor 2008 - 2010
Dr. Nick Evans NE), Research Associate: 2003 – 2007, Lecturer: 2007 – 2011, Senior Lecturer: 2011 - present

3. References to the research

The following publications appear in peer reviewed journals; the journals in question are key international output mechanisms for the radiochemistry discipline in general, covering as they do a range of areas including geochemistry, nuclear science, environmental toxicology and radiological protection.

3.1. M. Felipe-Sotelo, J. Hinchliff, N. Evans , P. Warwick and D. Read. Sorption of radionuclides to a cementitious backfill under near-field conditions.” *Min Mag.* **501**: 3401-3410 (2012). http://dx.doi.org/10.1180/minmag.2012.076.8.53

3.2. A. Young, P. Warwick, A. Milodowski and D. Read. “Behaviour of radionuclides in the presence of superplasticiser.” *Adv. Cem. Res.* **25**: 32-43 (2013). http://dx.doi.org/10.1680/adcr.12.00032

3.3. N. Maes, L. Wang, T. Hicks, D. Bennett, P. Warwick, A. Hall, G. Walker and A. Dierckx 2006. The role of natural organic matter in the migration behaviour of americium in the Boom Clay - Part I: Migration experiments. *Physics and Chemistry of the Earth* 31, 541-547 (2006). http://dx.doi.org/10.1016/j.pce.2006.04.006

3.4. P. Warwick, S. Aldridge, N. Evans and S. Vines, The Solubility of Technetium(IV) at High pH. *Radiochim Acta* **95**, 709-716 (2007). DOI: 10.1524/ract.2007.95.12.709

3.5. S. Aldridge, P. Warwick, N**.**, Evans and S. Vines. Degradation of tetraphenylphosphonium bromide at high pH and its effect on radionuclide solubility. *Chemosphere*, **66**, 672-676 (2007). http://dx.doi.org/10.1016/j.chemosphere.2006.07.088

3.6. D Read, G.D. Read and M. Thorne. Background in the context of land contaminated with naturally occurring radioactive material. *J. Rad. Prot*. **33**: 367-380 (2013). Doi: 10.1088/0952-4746/33/2/367

Major grants supporting this work include (since 2000):

- Migration case study: Transport of radionuclides in a reducing clay sediment (EC ,2000, **PW**) £135,000
- Measurements of radionuclides in decommissioning wastes (Berkeley Tech Cent .2000, **PW**) R63,584
- Further development of STAB (NIREX, 2000, **PW**) £ 62,993; FUNMIG (EU, 2005, **PW**) £240,864
- Analytical development (Magnox, 2006, **PW**) £85,000
- The Chemistry of Technetium with Reference to Geological Disposal) (NNL, 2007, **PW**) £78,000
- Demonstration experiments for chemical containment (NDA, 2008, **DR**) £429,152
- Radionuclide Transport in the Environment (Sellafield, 2008, **PW**) - £51,000
- DIAMOND Superplasticiser Project (EPSRC, 2008 - **DR**) £78,429;
- Surface modified materials for radionuclide sequestration (NDA, 2011, **DR**) £80,000;
- Migration of radon, $^{14}CO_2$ and $^{14}CH_4$ through partially saturated media (MEC 2012, **DR**) £60,000;
- Radioactivity in the iron and steel industry (Tata Steel, 2012 **DR**) £35,000;
- NORM in onshore oil & gas production (Aurora Health Physics, 2011 **DR**) £42,000;
- Superplasticisers for applications in nuclear decommissioning and storage (NDA, 2012 **DR**)
- £78,998. Cooperation in education and training In Nuclear Chemistry (EU FP7, 2013 – **DR/NE**) £106,532.

- BIGRAD (NERC, 2009 - **NE**) £318,354 – 2009;
- SAMPL (NDA, 2010 - **NE**) £75,789;
- SKIN (EU FP7, 2010 - **NE**) £105,814;
- AMASS (EPSRC , 2011 - **NE**) - £104,669;
- The Impacts of Aqueous Phase Degradation Products from PVC Additives on Radioactive Waste Management (AMEC, 2013 - **NE**) - £45,000;
- Decommissioning, Immobilisation and Storage solutions for Nuclear waste inventories) (EPSRC ,2013 - **NE**) £352,124;
- Long -lived Radionuclides in the Surface Environment (NERC, 2013 - **NE**) £406,065

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

Research within the Unit principally impacts on national and international policy in respect of safe disposal of radioactive wastes, a problem whose long term global significance cannot be overstated. The scope of expertise within the Radiochemistry Research Group at Loughborough University has ensured that the reach of the impact spans a range of different aspects with international dimension. Examples from four areas are given below, dealing with in turn: design of deep geological repositories for nuclear wastes, the effect of organic matter on radionuclide speciation-solubility, marine discharges, and management of non-nuclear sources of radioactive materials (NORM). Examples from the first three areas contribute to the broader remit of safeguarding the environment, while the final studies show how the Unit has shaped policy.

- **Safeguarding the Environment**

Concerns regarding the efficacy of cement as a backfill for conditioning radionuclides as low solubility, immobile species originally led to an avoidance strategy being implemented in nuclear disposal programmes, for example in Finland and Sweden. Although excluding cement entirely is impossible with a deep geological repository, the apparent dichotomy between approaches in national programmes has been exploited by opponents of nuclear waste disposal (and hence new build) to illustrate the uncertainties in process understanding and supporting technologies. Research carried out at Loughborough University has helped reduce the uncertainty by highlighting where cements can fulfil their design function and where components of the system require modification. Specifically, it has been shown that the presence of organic complexants, either natural (humic/fulvic acids) **[3.3]** or anthropogenic **[3.2]** (cellulose degradation products, superplasticisers) can enhance the mobility of otherwise immobile species. Conversely, species that are routinely treated as unretarded through engineered barriers and host rocks in safety case analyses (e.g. technetium, iodine) have been shown to bind effectively to mineral phases; *i.e.* existing models are overly conservative. **Evidence that these findings impact on future programmes can be found in revised research and implementation programmes**, for example consideration of alternative backfill materials (e.g. phosphate-amended cement in the Waste Isolation Pilot Plant, USA; prohibition of superplasticisers in Finland) and manufacture of modified superplasticisers by UK industry (Grace Chemicals). Radio-labelled NOM has been utilised by Loughborough researchers to investigate contaminant transport through a sandy aquifer at the Drigg repository, Cumbria and through the Boom Clay at Mol, Belgium. **These studies were used to estimate the importance of organic complexing ligands in facilitating the migration of uranium and plutonium, being cited in Post Closure Safety Cases for each site [5.1], [5.2]**.
David Read, Professor of Radiochemistry at Loughborough University was one of three independent scientists asked to assess the feasibility of technetium abatement technologies on behalf of the Environment Agency. Following acceptance by British Nuclear Fuels Limited of recommendations made by Loughborough University researchers regarding the use of tetraphenylphosphonium bromide (TPPB) as a technetium sequestering agent, **a £100m treatment plant was commissioned and discharges of ^{99}Tc to the Irish Sea are now reduced by 90% compared to previous levels [5.3].** The corollary was accumulation of a new waste-form whose long-term behaviour when encapsulated in cement was unknown. Fundamental research, commissioned at Loughborough (2004-2011) has established the stability of this waste and shed light on its potential behaviour in the geosphere **[3.4, 3.5, 5.4]**.

- **Shaping Policy**

An enormous volume of radioactive waste is created each year by the production and combustion of fossil fuels and exploitation of industrial minerals. Gross under-estimation of the problem by both industry and Government became apparent during revision of the Environmental Permitting Regulations (EPR) from 2009 onwards. The financial implications of choosing a particular threshold for regulation and clearance of radioactively-contaminated land are enormous and, inevitably, a compromise needs to be reached between the level of environmental protection sought and the finite resources available for remediation. Early drafts of the EPR not only omitted key NORM-producing industries but miscalculated the effect of aggregating progeny radionuclides from the two main natural decay chains (^{238}U and ^{232}Th). The consequence was overly restrictive limits that would have driven many businesses overseas. **Input by Loughborough University researchers to consultation documents led to a much improved legislative framework (EPR 2011) [5.5].** The intervention during the formulation of this framework prevented highly damaging changes to Exemption Orders that would have made production of *inter alia* advanced TiO_2 and Zr coatings in the UK non-viable. Similar considerations apply to the China Clay industry of SW England where successful remediation of NORM contamination is allowing regeneration of 700ha brownfield land under the Government's EcoTown initiative. This has also impacted European policy; it is noted that China Clay for example, which is also produced in France and the Czech Republic is still not included in the current version of the Basic Safety Standards (EC COM 2012, IAEA 2011) but will be in the next revision following its adoption in the UK. A Loughborough spin-in company (Enviras Limited) was launched in 2011; sited on campus it provides high quality UKAS accredited radiochemical analysis specifically for supporting the remediation of radioactively contaminated land. **[5.6]**

- **Training the Next Generation of Nuclear Specialists**

The third aspect of the Unit's impact stems from its ability to deliver a strong grounding in radiochemical work for a large number of students both at Undergraduate (e.g. via the 2nd and 3rd year modules "Radiochemistry" and "Physical and Radiochemistry" respectively) and Postdoctoral levels. Such training has impacted significantly on the effectiveness of bodies such as the Nuclear Decommissioning Authority who currently employ undergraduate and doctoral graduates from the Unit in a range of senior positions. Many other organisations whose activities hinge on radiochemical expertise have employed undergraduate and postgraduate students who have benefited from the research environment in the Unit, through their doctoral work (with17 students engaged in PhD work during the REF period) and undergraduate/MSc research projects etc.

5. Sources to corroborate the impact

5.1 "The 2011 Environmental Saftey Case Near Field", LLW Repository Limited, LLWR/ESC/R(11) 10021 (2011)
5.2 "Review of sorption values for the cementitious near field of a near surface radioactive waste disposal facility; Project near surface disposal of category A waste at Dessel", NIRAS-MP5-03 DATA-LT(NF), Version 1 (2009).
5.3 "An assessment of the availability of Tc-99 to marine foodstuffs from contaminated sediments", The Centre for Environment, Fisheries and Aquaculture Science, Environment Report RL 09/08, (2008).
5.4 [Text removed for publication]

5.5 ENVIRONMENTAL PROTECTION, ENGLAND AND WALES;The Environmental Permitting (England and Wales) (Amendment) Regulations 2011.
5.6 http://www.enviras.co.uk/Recent_Projects.html