Institution: **University of Glasgow**
Unit of Assessment: **B7 – Earth Systems and Environmental Sciences**
Title of case study: **Impact on management and monitoring for authorised discharges, accidental radionuclide releases and planned disposals of radioactive waste**

1. Summary of the impact

UK and international government departments, agencies and the nuclear industry have benefitted from improved understanding of environmental radioactivity and the development of novel, *in situ* gamma spectroscopy by researchers at the Scottish Universities Environmental Research Centre (SUERC, University of Glasgow). The provision of advice and novel data has helped to develop management, monitoring, regulation and human dose assessments for authorised and accidental releases of radionuclides, and to build plans for geological disposal facilities for high and intermediate level radioactive waste.

2. Underpinning research

Accurate knowledge of the concentration, distribution and environmental behaviour of radionuclides, and evaluation of current or potential human radiation exposure, are of fundamental importance for planning, management and regulation of nuclear facilities. The research in three areas has been led by: Professor Angus MacKenzie (Lecturer 1977-91; Senior Lecturer 1991-99; Reader 1999-2005; Professor 2005-present), Professor Gordon Cook (Lecturer 1985-95; Senior Lecturer 1995-2005; Reader 2005-08; Professor 2008-present) and Professor David Sanderson (Lecturer 1986-90; Senior Lecturer 1991-2004; Reader 2004-08; Professor 2008-present) based at SUERC. They have published 80 peer-reviewed research papers in this field and produced 33 technical reports since 1993.

Environmental distribution and behaviour of radionuclides.
Research on the distribution, geochemistry and transfer pathways of radionuclides in marine and terrestrial environments has been led by Cook and MacKenzie with Dr Robert Anderson (RA 1987-2010) and Mr Philip Naysmith (RA 1986-present). This work has radically improved understanding of the rates and mechanisms of key processes controlling the fate of radionuclides released in authorised disposals and in nuclear accidents. Models have been developed that describe environmental radionuclide behaviour and assess resultant human radiation exposure, with implications for waste disposal management practices. Much of the research was commissioned by the nuclear industry to meet specific requirements. Key outputs include:

i. Quantitative understanding of the role of sedimentary processes and aqueous-solid phase partitioning in controlling the environmental behaviour of radionuclides.

ii. Anthropogenic ^{14}C is the dominant contributor to collective human dose commitment from nuclear industry discharges, and research has defined its biogeochemical partitioning, dispersion and background activity for UK coastal marine environments (an essential parameter in radiation dose calculations).

iii. Reconstructing temporal variation in atmospheric ^{14}C concentrations near Sellafield using tree-ring records. This work has enabled evaluation of the relative environmental impact of marine and atmospheric discharges.

iv. Constraining the behaviour of depleted uranium in soils.

Development and use of field-based gamma spectrometry systems.
Sanderson established the first UK airborne gamma spectrometry (AGS) capability for mapping environmental radioactivity. This work was undertaken in conjunction with Dr Alan Cresswell (Research Assistant 1996-present). Key innovations include:

i. Improved systems to provide rapid, stable spectrometry and allow provision of radiometric maps to emergency response organisations within 30 minutes.

ii. Improved mapping techniques and calibration methods for airborne, vehicular and static radiometric spectrometry.
iii. Security-linked work in the UK for detection of concealed radioactive sources.
iv. The first combined semiconductor and high volume scintillation spectrometer arrays for AGS.
v. Baseline, natural variation and environmental AGS surveys of approximately 40% of the UK.
vi. Development of miniature radiometric systems capable of defining radionuclide distributions in urban and rural environments at a spatial resolution of 1-10m.

Sanderson pioneered the development of mobile and airborne gamma spectrometry for emergency response for the nuclear industry, co-ordinating two influential European Framework Programmes: 1. Framework Programme (FP) 4, part of the Radiation Protection Research Programme, and 2. FP5 Research Technological Development and Demonstration project ECOMAGS. This research culminated in 2002 in an international validation exercise involving 150 EU scientists and airborne, vehicular and static measurement teams. The results ('An International comparison of Airborne and Ground-based Gamma Ray Spectrometry' ISBN 0 85261 783 6) have underpinned subsequent work in this area.

Radioactive waste disposal natural analogue studies.
Planning for high and intermediate level radioactive waste repositories depends critically on understanding the long-term behaviour of radionuclides. Research led by MacKenzie has focussed on the use of natural radionuclides to establish rates and mechanisms of key processes for repository performance assessments. SUERC's expertise in this area has resulted in long-term involvement in UK, Swiss, Swedish, Japanese and other multinational research programmes. Understanding has been advanced in areas including:

i. Key processes influencing radionuclide migration in the host rock, e.g. matrix diffusion and sorption.
ii. Potential effects of climate change on deep repository integrity.
iii. Alteration of host rocks as a result of tunnel drilling.

3. References to the research

1. MacKenzie A.B., Scott R.D., Allan R.L., Ben Shaban Y.A., Pulford I.D. and Cook G.T. (1994) Sediment radionuclide profiles: implications for mechanisms of Sellafield waste dispersal in the Irish Sea. *Journal of Environmental Radioactivity* 23, 39–69. (doi:10.1016/0265-931X(94)90504-5)
2. Tyler A.N., Sanderson D.C.W., Scott E.M. and Allyson J.D. (1996) Accounting for spatial variability and fields of view in environmental gamma ray spectrometry. *Journal of Environmental Radioactivity* 33, 213–235. (doi:10.1016/0265-931X(95)00097-T)
3. Cook G.T., MacKenzie A.B., Naysmith P. and Anderson R. (1998) Natural and anthropogenic ^{14}C in the UK coastal marine environment. *Journal of Environmental Radioactivity* 40, 89–111. (doi:10.1016/S0265-931X(97)00061-1)
4. Oliver I.W., Graham M.C., MacKenzie A.B., Ellam R.M. and Farmer J.G. (2008) Depleted uranium mobility across a weapons testing site: Isotopic investigation of porewater, earthworms, and soils. *Environmental Science and Technology* 42, 9158–9164. (doi:10.1021/es8013634) *
5. Drake H., Tullborg E-L. and MacKenzie A.B. (2009) Detecting the near-surface redox front in crystalline bedrock using fracture mineral distribution, geochemistry and U-series dis-equilibrium. *Applied Geochemistry* 24, 1023–1039. (doi:10.1016/j.apgeochem.2009.03.004) *
6. Cresswell, A.J. and Sanderson, D.C.W. (2012) Evaluating airborne and ground based gamma spectrometry methods for detecting particulate radioactivity in the environment: A case study of Irish Sea beaches. *Science of the Total Environment* 437, 285–296. (doi:10.1016/j.scitotenv.2012.08.064) *

* best indicators of research quality

4. Details of the impact

SUERC researchers have had wide-ranging impacts on the UK and international nuclear industry. Expert advice and data provided to government departments, security organisations, the nuclear industry, regulators, local authorities and charities has influenced management and monitoring of authorised discharges, accidental radionuclide releases and planned disposals of radioactive waste. Findings have been disseminated to end users through direct meetings, participation in workshops, reports to funding bodies, conference presentations and publication of research papers.

Research outputs from 1993-2008 continue to have impact today. For example:

British Nuclear Fuels Limited (BNFL)-commissioned research contributed to the development of improved practices for the disposal of radioactive waste, and new protocols for assessment of human radiation exposure (BNFL report H73837B). A review of the knowledge of radioactivity in the vicinity of the Dounreay site that was commissioned by the Scottish Office is part of the evidence base used by the Scottish Environmental Protection Agency (SEPA) in its regulatory oversight of Dounreay (SEPA report 32/98).

Research outputs since 2008 have been utilised in the planning for, and response to, four scenarios relating to the release of radionuclides into the environment:

(1) **Authorised releases of radionuclides from nuclear facilities.**

Expert advice was provided to Sellafield sites in 2010/11 on improved detection methods for "hot particles" in beach sediments. Advanced modelling was used to assess performance limits for field based and airborne gamma spectrometry techniques. This work has identified future options for extending the efficiency and range of searches for the highest activity particles, which carry the greatest radiological risks.

(2) Unplanned releases from nuclear accidents and military activities.

As a consequence of Sanderson's AGS research the importance of airborne mapping as a frontline emergency response has been internationally recognised, as highlighted by the Royal Society report 'Detecting nuclear and radiological materials' (2008).

Immediately after the 2011 Fukushima nuclear accident, the International Atomic Energy Authority (IAEA) asked Sanderson to provide specialist guidance on the interpretation of environmental data received from Japan and other IAEA member states (IAEA Special Service Agreement BC 2892/1/3521). In collaboration with scientists at Fukushima University, additional specialist equipment, assessment and analysis was provided directly to Japanese institutions. During five trips to Japan in 2012 and 2013, Sanderson has employed a SUERC-developed backpack gamma spectrometer to map radiation levels in contaminated areas. Findings were presented at Fukushima University, the National Institute for Environmental Science, and through a Japanese-UK-Nuclear Safety workshop at the British Embassy in 2012. These results have since been published ('Validated Radiometric Mapping in 2012 of Areas in Japan Affected by the Fukushima-Daiichi Nuclear Accident' ISBN 9780852619377).

In response to a perceived gap in knowledge and understanding, the Ministry of Defence (MoD) commissioned a research programme, run by the Natural Environment Research Council (NERC) (2004–2008), into the environmental behaviour of depleted uranium (DU) released in the use of armour-piercing munitions. SUERC provided specialist analytical data and conclusions on the occurrence and behaviour of DU in soils at two UK military sites. Outputs were provided to MoD and Qinetiq via workshops, the DU Programme final report (NERC, 2008), and published papers (e.g. ref 4).

(3) **Potential terrorist radiological threat.**

SUERC researchers produced a series of confidential reports (2009-2011) for the Home Office on detection of radioactive sources using airborne radiometrics in preparation for the Olympics in 2012.

(4) **Planned long-term disposal of radioactive waste in geological facilities.**

Studies of natural radionuclides in environmental contexts have been used to inform performance assessments in several waste disposal programmes, and to help define research strategy of various radioactive waste disposal organisations, as outlined below:

i. Advice was provided, via Nexia Solutions, to the Nuclear Decommissioning Authority (NDA) in 2008 relating to the behaviour of ^{14}C in the UK intermediate level waste repository, contributing to NDA's current research strategy.

ii. As part of the Swedish Nuclear Fuel and Waste Management Company (SKB) programme to select a site for the Swedish high level radioactive waste repository, SUERC was commissioned to carry out research on natural decay series disequilibrium in rock and groundwater samples. The SUERC work was also used to evaluate the risk that potential future glaciations would force oxidising groundwater into the repository. Provision of findings and expertise to SKB was via Terralogica Consultants (Sweden) in coordination meetings (Sweden, Finland, UK) and via reports and published papers (ref 5).

iii. Research on natural radionuclides was used in the International Cyprus Natural Analogue Project to characterise radionuclide uptake by bentonite, which is a key component in planned repositories. Reports from this work (2011, 2013) to Posiva (Finland) and the NDA were central to the repository performance assessment programmes.

5. Sources to corroborate the impact

- Letter from Terralogica (Sweden) and Conterra AB, confirming input to the site selection and characterisation programme. [available from HEI]
- Letter from Programme Director confirming input to the Cyprus Natural Analogue Project. [available from HEI]
- Minutes (prepared by Nexia Solutions) of data elicitation meeting with Cook and MacKenzie (Nov 2008) [available from HEI]
- Royal Society policy document 07/08 stating that airborne systems show promise for emergency response.