Institution: University of Huddersfield

Unit of Assessment: UoA5

Title of case study: Improving the understanding and simulation of gas generation from Radioactive Waste Disposal Sites.

Period when the underpinning research was undertaken: Sept 2003–December 2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Prof P N Humphreys	Professor	Oct 2003 – Present
Dr S P Rout	Senior Lecturer	Sept 2015 – Present

Period when the claimed impact occurred: October 2003–December 2020

Is this case study continued from a case study submitted in 2014? No

1. Summary of the impact

There is international agreement that deep geological disposal facilities (GDF) are the preferred option for the management of radioactive wastes. The safety of these facilities depends on the time it takes for the radioactive material to return to the surface. These return times are determined through the use of mathematical models which represent the processes controlling the transport of these materials. Microbes control a number of key processes in GDFs since they are able to degrade radioactive wastes and enhance or retard the transport of radioactive elements, for example through the generation of gases such as methane. Prof Humphreys and his research group have uniquely worked at the interface between fundamental research and model development since 2003 with a specific focus on waste degradation, gas generation and associated impacts on radioactive transport. This research has allowed more factually accurate and appropriate models to be applied to GDF in conjunction with Nuclear Waste Management Organisation Canada, Low Level Waste Repository Ltd UK, Radioactive Waste Management UK and Ontario Power Generation.

2. Underpinning research

The underpinning research is focussed on improving the fundamental understanding of gas generation processes relevant to radioactive waste disposal and the representation of these processes in the models used to predict the impact of GDF for radioactive waste. This has involved the development of modelling approaches such as those used for the Canadian Deep Geologic Repository (DGR) [3.1] and C-14 disposal in the UK [3.2]. These modelling approaches are underpinned by fundamental research into the underlying microbial processes that lead to the generation of gases under repository conditions. A UK GDF is likely to have extremely alkaline environments due to the large amounts of cement used. These hyper alkaline environments generate complexing agents [3.3] able to enhance the transport of radioactive elements. Our research has demonstrated that complex microbial communities can survive under these hyper alkaline conditions, ferment these complexing agents and generate methane [3.3] a key issue in GDF safety assessments. Survival at these pH values is dependent on biofilm formation [3.4] which mediates the pH levels experienced by the individual organisms [3.5]. Contrary to some current models, our recent research on methanogenesis has demonstrated that the hydrogenotrophic rather than the acetoclastic pathway is the dominant methane generating pathway at alkaline pH [3.6]. This observation will change the way gas generation in GDF is assessed worldwide, moving away from a focus on the acetoclastic pathway to a system dominated by hydrogen consumption. This observation will have an international impact, since

significant amounts of hydrogen are predicted to accumulate within a GDF due to its generation by anaerobic corrosion. Hydrogen consumption within a GDF will reduce repository pressures and remove a key driving force for the release of gaseous C-14 bearing gases from these facilities.

3. References to the research

3.1 J Avis, P Suckling, N Calder, R Walsh, P Humphreys, F King (2014) T2GGM: A Coupled Gas Generation Model for Deep Geologic Disposal of Radioactive Waste. *Nuclear Technology,* **187**(2): 175-187. DOI 10.13182/NT13-83 [can be supplied on request]

This paper is a joint publication between scientist from the UK and Canada, with the work reported arising from the Canadian Deep Geological Disposal Facility project. The Journal is an international, peer reviewed publication focussed on the practical applications of nuclear science and technology which has been in print since 1965. The Journal has an international editorial board and is listed on Scopus, Web of Science and Pub Med.

3.2 C Doulgeris, P Humphreys (2019) A modelling approach to assess the environmental/radiological impact of C-14 release from radioactive waste repositories, *Journal of Environmental Radioactivity*, V 205–206, pp 61-71. DOI 10.1016/j/jenvrad.2019.05.2009

The Journal of Environmental Radioactivity is an international peer reviewed publication affiliated to the International Union of Radioecology which has been in print since 1984. It has a wide international editorial board, reviewers and authors and is indexed on PubMed, Scopus and Science citation Index amongst others.

3.3 S P Rout, C J Charles, E J Garratt, A P Laws, J Gunn (2015) Evidence of the Generation of Isosaccharinic Acids and Their Subsequent Degradation by Local Microbial Consortia within Hyper-Alkaline Contaminated Soils, with Relevance to Intermediate Level Radioactive Waste Disposal. *PLoS ONE* 10(3): e0119164. DOI:10.1371/journal.pone.0119164

PLoS One is an international peer-reviewed gold open access, scientific journal published by the Public Library of Science since 2006. The Journal accepts papers from a wide variety of scientific disciplines and has an international editorial board and reviewers drawn from across the globe. PloS One is indexed on all major indexing sites.

3.4 C J Charles, S P Rout, E J Garratt, K Patel, A P Laws, P N Humphreys (2015) The enrichment of an alkaliphilic biofilm consortia capable of the anaerobic degradation of isosaccharinic acid from cellulosic materials incubated within an anthropogenic, hyperalkaline environment. *FEMS Microbiology Ecology* 07/2015; DOI:10.1093/femsec/fiv085

FEMS Microbiology Ecology is published by the Federation of European Microbiology Societies in associated with Oxford University Press. It is an international peer reviewed journal with a wide authorship and an international editorial board. The Journal is indexed on all major indexing sites.

3.5 C. J. Charles, S. P. Rout, KA Patel, S. Akbar, AP Laws, B. R. Jackson, SA Boxall, P. N. Humphreys: (2017) Floc formation reduces the pH stress experienced by microorganisms living in alkaline environments. *Applied and Environmental Microbiology* 01/2017; 83(6):AEM.02985-16., DOI:10.1128/AEM.02985-16

Applied and Environmental Microbiology is an international peer-reviewed scientific journal which has been published by the American Society for Microbiology since 1953. It is an international peer reviewed journal with a wide authorship and an international editorial board. The Journal is indexed on all major indexing sites.

3.6 R. M. Wormald, S. P. Rout, W. Mayes, H. Gomez, P N Humphreys (2020) Hydrogenotrophic methanogenesis under alkaline conditions. *Frontiers in Microbiology*, 11(3077). DOI 10.3389/fmcib.2020.614227

Frontiers in Microbiology is a gold open access international per reviewed Journal. The Journal has a wide international authorship and an international editorial board. The Journal is indexed on all major indexing sites

4. Details of the impact

Effective radioactive waste disposal is of international importance. A number of organisations have benefitted from the conceptualisation of gas generation and associated models outlined above. They have also consulted with Professor Humphreys as an expert to contribute to safety cases, for licence applications for new disposal facilities and assessments relating to existing disposal facilities.

Example projects include:

Nuclear Waste Management Organisation (NWMO): is based in Canada and Professor Humphreys contributed to their licence application for a deep geologic repository for low and intermediate level radioactive waste. The Director for Safety and Technical Research at NWMO said: "*As we were not experts in microbial activity, we turned to Dr. Humphreys as a recognized expert in the field, and in particular in the context of waste repositories. Dr. Humphreys provided the conceptual and mathematical framework for us to model the potential gas generation and determine how to adjust our repository design such that this was not an issue. The model provided both a practical level of detail for our purposes, as well as providing an authoritative recognition of the key factors. Specifically, his model was incorporated into our reference safety assessment computer code and used for the licence-basis calculations. Ultimately in the licencing hearings, this part of our analysis was accepted …. The technical part of the licence application was concluded in 2015*" [E1]. Subsequently the model that Prof Humphreys helped to develop has been used to evaluate a number of other radioactive waste disposal options in Canada [E2, E3].

Low Level Waste Repository Ltd (LLWR): operates the UK's principal facility for the disposal of solid low level radioactive waste. It does this under permit granted by the Environment Agency. The permit requires a valid Environmental Safety Case (ESC) to demonstrate that disposal is safe and that the repository will continue to be safe in the future. Professor Humphreys's research has contributed to updated conceptual models of C-14 gas generation and release from different waste types (e.g. organic wastes, irradiated metals, irradiated graphite) enabling updated C-14 impact calculations [3.2]. This work significantly underpinned the ESC (originally approved in 2011). This enabled LLWR to secure a variation to their permit in November 2015 [E4] as described by the Head of Science and Engineering: "*The outcomes of his work have helped significantly to substantiate safe disposal of wastes containing other complexing agents, such as citric acid, enabling us to successfully apply for a variation to our permit to allow consignors to dispose of waste containing these hitherto prohibited materials*" [E5].

Professor Humphreys collaborated with Quintessa on this work for LLWR and Quintessa's Managing Director stated: "*This more realistic assessment reduced the potential impacts of C-14 gas compared with the 2011 ESC, meaning that the LLWR will be suitable for the disposal of all the LLW identified in the UK Radioactive Waste Inventory that may be generated over the next ca.100 years*" [E6].

Radioactive Waste Management (RWM) Ltd: The UK's civil nuclear legacy represents the largest environmental restoration programme in Europe and is a major public liability. RWM are responsible to government for the geological disposal of higher activity waste (HAW). Using the single step model for gas generation developed by Professor Humphreys [3.1] RWM were able to improve their understanding of coupled gas generation, multiphase flow and re-saturation in a Geological Disposal Facility (GDF) which then provided input to the generic safety case for a HAW repository. RWM's understanding of gas generation and repository re-saturation behaviour was improved, including issues associated with upscaling from models of individual vaults to models of an entire GDF. RWM used this new knowledge in their Gas Status Report in 2016, which describes RWM's current understanding of how gas generation affects the long-term performance and safety of a GDF. More recent work [3.6] is assisting it the development of RWM's current understanding of gas generation processes. The Environmental Safety Officer of RWM said: "*Professor Humphreys work contributes to the knowledge base underpinning our safety case and which develops UK skills and capability in this important area*" [E7].

Ontario Power Generation (OPG): In 2015, acting as a consultant for Quintessa, Professor Humphreys provided support for the extension of the T2GGM model [3.1] to enable its application to gas generation from spent nuclear fuel disposal and the inclusion of the calculations in the assessment document for a repository. A joint review panel reviewed the application recommending approval and noted that: "*the associated studies (including gas studies) had provided the panel with confidence that OPG's assessment was comprehensive and satisfied regulatory requirements*" [E5].

5. Sources to corroborate the impact

E1. Letter of Support from NWMO.

E2. NWMO (2018) Seventh Case Study: Reference Data and Codes. Rpt No: NWMO-TR-2018-10 https://www.nwmo.ca/~/media/Site/Reports/2019/05/28/18/59/NWMOTR201810.ashx?la=en
See page 142 where Suckling, P., J. Avis, N, Calder, O. Nasir, P. Humphreys, F. King and R. Walsh. 2015. T2GGM Version 3.2: Gas Generation and Transport Code. NWMO-TR-2015-13. Toronto, Canada is referenced.

E3. Canadian Nuclear Laboratories (2017) Safety Case for the In-Situ Decommissioning of the NPD Waste Facility Rpt No: 64-03610-SAR-002: https://www.cnl.ca/site/media/Parent/64-03610-SAR.pdf
See pages 4-35, 7-2 and 7-3 where reference to the T2GGM code is made, T2GGM was co-developed by Prof Humphreys.

E4. LLWR site: Environmental Safety Case and Permit Approval.
https://www.gov.uk/guidance/llwr-site-environmental-safety-case-and-permit-approval

E5. Letter of Support from Quintessa Ltd.

E6. Letter of Support from LLWR Ltd.

E7. Letter of Support from RWM Ltd