Institution: Cardiff University, School of Engineering
Unit of Assessment: UoA14
Title of case study: Engineering Solutions for High Level Nuclear Waste Disposal

1. Summary of the Impact

Research conducted at the Geoenvironmental Research Centre (GRC), supported by the European Commission via its EURATOM programme, has been instrumental in addressing the long standing global problem of high level nuclear waste disposal. The pioneering development of a sophisticated coupled thermal/hydraulic/chemical/mechanical model of clay behaviour has provided new understanding of the performance of engineered barriers proposed for use in nuclear waste repositories. This has, in an unprecedented development, directly enabled the design of numerous nuclear waste repositories to proceed. The repositories in Sweden and Finland are currently at "Licence application" and "Construction" phases, respectively. Therefore the impacts claimed during the REF period are: significant impact on ***engineering design***, leading to improved ***environmental conditions***; considerable ***economic investment*** and marked impact on ***public policy and services.***

2. Underpinning Research

The behaviour of clay soils, in relation to nuclear waste repositories, was insufficiently understood prior to Cardiff University's research. Key research developments since 1993 are outlined below.

Thermo/Hydro/Mechanical (THM) behaviour: The first step in developing a suitable model of THM behaviour was to extend the GRC's research on coupled thermo/hydraulic behaviour [3.1] to accommodate soil deformation [3.2]. This was achieved in collaboration with International co-workers, notably Professors Alonso and Gens at UPC Barcelona, who were developing new models of unsaturated soil deformation. This work was carried out as part of major European Commission funded research, under the EURATOM programme. This yielded the first approach to simulating coupled THM behaviour.

Micro/macro behaviour of clays*:* The GRC's investigation (1996-2003) into the re-saturation behaviour of clay barriers in a large-scale, in-situ experiment at Atomic Energy of Canada's (AECL) underground research laboratory established that neither the duration nor the pattern of moisture influx could be predicted accurately using a conventional hydraulic conductivity model. It showed that the expansion of the microstructure of the bentonite reduced the pore spaces available for water transport in the macrostructure, as the material, overall, was constrained from swelling. This in turn was likely to reduce the material's hydraulic conductivity and was of major significance in the estimation of repository re-saturation times [3.3]. This work was extended [3.4] to include heating. Simulation of pre-heating phases demonstrated that the model could describe the hydraulic regime in the host rock and isothermal infiltration into the buffer.

Chemical reaction modelling*:* The above work demonstrated very clearly the importance of the physico-chemical behaviour of bentonitic soils. A multicomponent transport formulation was therefore developed and coupled with a multiphase geochemical reaction model. This was achieved by coupling the THM and chemical transport model with a geochemical reaction model (MINTEQA2). The coupled model was applied to study various aspects of chemical behaviour during the period of heating and hydration in the buffer [3.5]. Several relevant hydro-geochemical features were then incorporated between 2007 and 2012, from a theoretical modelling approach at micro scale to the inclusion of multicomponent diffusion. The existing THCM model was coupled with an advanced geochemical model (PHREEQC), which allows high ionic concentrations and kinetically-controlled geochemical reactions to be simulated [3.6].

***Computational Modelling Aspects**:* A simulation of the Prototype Repository experiment, undertaken by the Swedish Nuclear Fuel and Waste Management Co. (SKB), demonstrated that parallel computation is invaluable because of the complex, highly coupled nature of the problem. The temperature field was found to be three-dimensional, with the effect of adjacent canisters' heat output influencing the temperature within other deposition holes. In addition, the significance of the backfill as a substantial sink for pore-water was demonstrated, reproducing the saturation time exhibited experimentally. The geological supply of water was critical to the hydration rate.

This research, in addition to the wider work of the Centre, has directly led to the GRC being awarded the 2013 Queen's Anniversary Prize for Higher and Further Education. Members of the GRC contributing to the research are: **Prof H R Thomas**, (Director of GRC in post since establishment), **Dr P J Cleall, Dr S C Seetharam, Dr P J Vardon** and **Dr M Sedighi.**

3. References to the Research

3.1 **Thomas H.R**. and Li C.W.L. (1997) An assessment of a model of heat and moisture transfer in unsaturated soil, *Géotechnique*, Vol 47 No 1 pp 113–131, DOI: 10.1680/geot.1997.47.1.113

3.2 **Thomas H.R**. and He Y. (1998) Modelling the behaviour of unsaturated soil using an elastoplastic constitutive model*, Géotechnique,* Vol 48 No 5 pp 589–603, DOI: 10.1680/geot.1998.48.5.589

3.3 **Thomas H.R**., **Cleall P.J**., Chandler N., Dixon D. and Mitchell H.P. (2003) Water infiltration into a large scale in-situ experiment in an underground research laboratory – physical measurements and numerical simulation, *Geotechnique*, Vol 53 No 2 pp 207-224, DOI: 10.1680/geot.53.2.207.37263

3.4 **Thomas H.R**., **Cleall P.J**., Dixon D. and Mitchell H.P. (2009) The coupled thermal-hydraulic-mechanical behaviour of a large scale in-situ heating experiment, *Geotechnique*, Vol 59 No 4 pp 401-413, DOI:10.1680/geot.2009.59.4.401

3.5 **Cleall P.J**., **Seetharam S.C**. and **Thomas H.R**. (2007) Inclusion of some aspects of chemical behaviour of an unsaturated soil in thermo/hydro/chemical/mechanical models. II Application and transport of soluble salts in compacted bentonite, *ASCE Journal of Engineering Mechanics*, Vol 133 No 3 pp 348-356, DOI: 10.1061/(ASCE)0733-9399(2007)133:3(348)

3.6 **Thomas H.R.**, **Sedighi M**. and **Vardon P.J.** (2012) Diffusive reactive transport of multicomponent chemicals under coupled thermal, hydraulic, chemical and mechanical conditions, *Journal of Geotechnical and Geological Engineering*, Vol 30 No 4 pp 841-857, DOI: 10.1007/s10706-012-9502-9

4. Details of the Impact

Route to Impact: Cardiff University's research has been integral to overcoming major obstacles associated with high level nuclear waste disposal. Approximately 250 to 300 Ktons of high level nuclear waste is in temporary storage facilities worldwide. Multinational governments and international nuclear authorities, such as the International Atomic Energy Authority (IAEA), have long recognised the necessity for a permanent disposal solution. The preferred route is deep geological disposal. Not only does this absolve the necessity for constant supervision and maintenance, and reduce security risks associated with ground level storage, but it prohibits future generations from inheriting a nuclear waste legacy. However, whilst theoretically appropriate, the technical complexities of achieving this have meant the aim remained unrealised. The enormous timescale over which high level nuclear waste is radioactive and deadly to all living organisms (in excess of 100,000 years) poses a huge challenge to governments and international nuclear authorities to ensure no nuclear releases reach surface level, resulting in catastrophic health and environmental threats. The computerised model developed at the Geoenvironmental Research Centre (GRC) provides innovative predictions of the behaviour and long term durability of engineered clay barriers (consisting of bentonite) under specific repository conditions. The research was funded by the EC under their EURATOM programme, a programme that is part-

funded by the EC itself, and part-funded by European Nuclear Waste Disposal Authorities [5.1]. The work performed was therefore immediately "captured" by the Waste Disposal Authorities (for example, in the UK, Sweden, Finland, Spain, Canada and Germany) and could be deployed in various aspects of the performance assessment of geological repositories [5.2]. The findings increased international governments' confidence in the ability to accurately model and forecast the behaviour of engineered clay barriers. Subsequently, several countries issued licences and have begun the process of constructing nuclear waste repositories.

Impact on Engineering Design: Given their inherent complexity, application of the newly developed THM/THCM models to repository design can only be achieved via the use of numerical methods of analysis. In the GRC's case, this yielded the computer program called COMPASS, which was developed in-house. This program can be used to simulate the behaviour of a nuclear waste repository over a period of many years. The main design criteria that can be considered via the use of the software are in relation to:

- The temperature effects and the borehole spacings required, to ensure that the maximum specified temperatures are not exceeded.
- The hydraulic effects and the total time for re-saturation of the repository; this design parameter marks the end phase of the initial life of a repository.
- The mechanical effects, the swelling pressures and displacements that are generated as a result of moisture ingress.
- The chemical effects, a repository's response due to changes in the chemical composition of the pore water.

All of the above are key features in the overall design of a repository. They are principal elements of a safety assessment and, consequently, are fundamental factors in a Licence Application. The software has been accessed and applied (as aforementioned, via the EURATOM programme) by International Nuclear Waste Disposal Authorities. Work with SKB, the Swedish Nuclear Fuel and Waste Management Company, for example, was conducted at a specially built Underground Research Laboratory (URL), the Aspoe Rock Laboratory, on the island of Aspoe (http://www.skb.se/default____24417.aspx). During the REF period, work conducted at the URL was used to inform decisions regarding the site selection for a final repository. The search had been ongoing for 20 years but was narrowed to two options, Forsmark and Oskarshamn. The results of the research provided new insights into the behaviour of the bentonite buffer under a range of conditions, as described above, and determined the suitability of the rock at each site. Subsequently, in June 2009, SKB made the decision to locate the repository at Forsmark. This heralded a landmark event in the process of achieving a fully operational nuclear waste repository. Based on the site selection, an application to construct the repository was submitted to the Swedish Radiation Safety Authority and the environmental court in March 2011. The Swedish repository at Forsmark is expected to be filled by 2025 [5.3].

The greatest progress has been made in Finland, where the repository design is similar to the Swedish concept. Posiva, the Finish nuclear waste management company (also part of the EURATOM research programmes), has significantly benefited from Cardiff's unique research. Excavation and design work at the selected site (Olkiluoto) began in 2004 (http://www.posiva.fi/en/research_development/onkalo). Between 2008-2013, excavation of the access tunnel to the repository (named Onkalo) was completed. In February 2012 this reached the target depth of 455m below ground. In December 2012 the final design plans were also completed [5.4]. These would not have been possible without Cardiff University's research, which is cited in official reports describing the technology employed at Onkalo [5.5]. Posiva have publicly stated that '*the long-term safety of final disposal is, above all, based on carefully studied, complimentary engineered barriers'* [5.6]. The design plans formed the basis of an application for a full construction licence, which was submitted to the Radiation and Nuclear Authority of Finland (STUK) in December 2012. In April 2013, STUK reported a positive response to initial reviews of the licence application. Activity at Onkalo is now focused on structural work; the final disposal of nuclear waste at the repository is scheduled to start in 2020 [5.7].

Global nuclear authorities support for Onkalo is illustrated by endorsement from the IAEA In August 2012 the Director, General Yukiya Amanom, visited Onkalo in a two day official visit. He stated that `*This development is good news for Finland and for the world, since Finland's success as a forerunner in mastering this significant engineering challenge will offer alternatives for other nations seeking to sustainably and responsibly manage spent fuel*.' [5.8]

Impact on Public Policy and Services: The disposal of high level nuclear waste is a worldwide problem and the GRC's research has been taken up on a global scale. In particular, the GRC has been designated by the IAEA as a "Centre of Excellence/Expertise" [5.9]. In this context, the GRC is a founder member of the Agency's Underground Research Facilities Network (URF), dedicated to "*building confidence in the geological disposal of high level nuclear waste*". The role of the network is to deliver training and demonstration activities related to high level nuclear waste. Training courses and coordinated research programmes are pursued, with the overall objective of transferring good practice from countries with developed programmes, such as in Scandinavia, to those countries that are just beginning to embark on the difficult task of implementing a geological disposal option. Virtually all of the countries with a civil nuclear programme take part. The GRC has participated extensively in these programmes, via the delivery of training courses and execution of research programmes. It is claimed that the impact of the work is significant, particularly in relation to the important issue of capacity building. It is anticipated that this will help "build confidence" in the geological disposal programme worldwide. Since 2007 the GRC's Director (Prof H R Thomas) has served as Chair to the network and in this capacity has also been instrumental in shaping and guiding policy developments in this area.

Economic Impact: £200M investment has been made from 2008-2013, by SKB, as a direct consequence of the research. The final cost of Onkalo is expected to be €3.3B. However this sum is markedly less than the expense of continuing storage of high level nuclear waste (at Sellafield in the UK, for example, this amounts to £1.6B per year, in addition to the cost of cleanup and maintenance work, which is priced at £67.5B - http://www.nao.org.uk/report/managing-risk-reduction-at-sellafield/). The activities that the research has enabled, highlighted by the scale of investment, are a major step towards a permanent long-term solution to high level nuclear waste disposal. [5.10]

In summary, the research conducted at the GRC has orchestrated a major development in nuclear waste disposal. The resulting impact has had both global reach and significance.

5. Sources to corroborate the Impact

5.1) ftp://ftp.cordis.europa.eu/pub/fp5-euratom/docs/projrep-prototype-repository_en.pdf *Confirms Cardiff's involvement in the ERATOM programme and the organisations that were subsequently able to use the research.*

5.2) ftp://ftp.cordis.europa.eu/pub/fp6-euratom/docs/theresa-project-presentation-flyer-v2_en.pdf *Confirms the use of the research by the EC and international Nuclear Waste Authorities.*

5.3) Executive Secretary at SKB. *Confirms the use and impact of the research for SKB.*

5.4) Senior Adviser at Posiva. *Confirms the use and impact of the research at Posiva*.

5.5) http://www.skb.se/upload/publications/pdf/TR-06-10.pdf *Relates to the use of the research and impact at Onkalo.*

5.6) http://www.foronuclear.org/en/news/latest-news/construction-licence-application-for-final-repository-in-finland *Confirms the use and impact of the research by the Nuclear Waste Authorities in Finland.*

5.7) http://www.stuk.fi/ajankohtaista/tiedotteet/en_GB/news_840/?t=2013-5-18-17-8 *Evidence of the impact of the research regarding the repository in Finland.*

5.8) http://www.iaea.org/newscenter/news/2012/dgfinland.html *Evidence of the global impact of the research.*

5.9) http://www.nuclearliaison.com/nl-research *Confirms the GRC is a IAEA Centre of Expertise.*

5.10) Executive Secretary at SKB. *Confirms the financial investment made post 2008.*