Institution: University of Sheffield

Unit of Assessment: 13C - Electrical and Electronic Engineering, Metallurgy and Materials: Materials Science and Engineering

Title of case study: Influencing international policies on nuclear waste disposal

1. Summary of the impact

An innovative deep borehole disposal (DBD) concept for radioactive waste, pioneered at the University of Sheffield, resulted in significant impact on geological disposal strategy with an international reach. In the USA, our work contributed to a change in geological disposal strategy, with our concept described by the Director of Sandia National Laboratory as a "legitimate and a viable alternative [to the mined, engineered repository model] worthy of deeper consideration" [S1]. The Presidential *Blue Ribbon Commission* report on *America's Nuclear Future* recommended that DBD be taken forward to a practical pilot demonstration, now funded by the US Department of Energy (DOE) [S2]. Sheffield's work on DBD influenced Sweden's regulators and Environmental Court to reconsider approval of a mined repository by SKB. Our work has impacted on the UK approach to waste management, with DBD now included in the Nuclear Decommissioning Authority (NDA) [S3] bid to accelerate the Government's *Managing Radioactive Waste Safely* programme.

2. Underpinning research

A proposal for a safer, more economical and environmentally sound disposal scheme for high-level nuclear waste, utilising deep, geological boreholes, was pioneered by researchers at the University of Sheffield [R1, R2]. This concept is referred to as Deep Borehole Disposal (DBD).

The novelty and distinctiveness of Sheffield research involved the recognition that mined repositories (at geologically shallow depths) are unlikely to provide the necessary long-term isolation from the biosphere required for emplaced radioactive wastes to decay to a safe condition (ca. 10^6 years). Sheffield's research suggested that a new approach, which placed greater emphasis on the geological barrier, would be a more secure and environmentally preferable alternative. Our concept uses large diameter boreholes to bury radioactive waste between 3 and 5 km deep in the Earth's crust, beyond the reach of near-surface groundwater, using geology to isolate the contamination risk until decay had rendered the waste radiologically harmless.

Ground breaking research carried out by the Sheffield group resulted in international recognition and acceptance of the feasibility of the DBD concept as described in Section 3. This research included:

- Development of an ingenious system combining mechanical support for the waste packages and superior sealing properties (use of a special lead-tin alloy deployed as a fine shot) [R3].
- Lab-scale demonstration of granite melting and recrystallization [R4], as proof of the "rock-welding" concept for sealing of water-filled boreholes by down-hole heating.
- Mathematical modelling of the disposal of heat-generating spent fuel or high level waste glass, to demonstrate the feasibility of the DBD system with respect to heat flow [R5-R6].

The timeline for the research and resulting impact is summarised thus:

- BNFL was approached in the early 1990s and considered the concept favourably, describing it as "e*nvironmentally more robust than other methods currently proposed or practised world-wide".* In 1993, BNFL funded research at Sheffield to further develop the concept, led by Prof. F. Gibb which attracted further funding (>£1M) from EPSRC (GR/T08975/01) among others.
- From 1993 to 2001, research was integrated within the new Immobilisation Science Laboratory in the Department of Materials Science and Engineering, and focused on demonstrating the viability of the concept [R4]. An important outcome was the introduction of an innovative

approach to sealing the boreholes by a process of melting and recrystallizing the host rock, referred to as "rock welding" [R5-R6], as presented to the British Association for the Advancement of Science annual meeting in 1999.

- In 2003 a seminal paper was published [R2], drawing the attention of the international nuclear community to the potential of the DBD concept. Dr Travis joined the group and the research was expanded to include numerical modelling, especially of heat flow related to the disposal of heat-generating wastes such as spent fuel. This work, funded by EPSRC (GR/T08975/01), expanded the DBD concept to disposal of a much wider range of spent fuels and high-level wastes, e.g. [R2, R5, R6]. The research led to the award of two patents: for the introduction of novel high-density support matrices for spent fuel disposal (WO2008125803 (A1)), and for the introduction of a deep borehole scheme for the disposal of waste plutonium (WO2008032018 (A2)). The work on plutonium disposal was presented at the 2007 Materials Research Society meeting, receiving considerable media coverage.
- Since 2007, research has focused on the disposal of the high burn-up spent fuels likely to be generated in new Generation III reactors, including mixed oxide (MOX) fuels (in keeping with the UK Government's policy for the recycling of plutonium). Our most advanced modelling codes have shown that the higher heat outputs of such spent fuels pose no problems in the DBD concept, in contrast to mined repositories where they necessitate additional measures, delays and costs [R6].

From 1993-2012, 5 academic staff [led by Prof. F. Gibb & Dr K. Travis], 2 external associates, 2 PDRAs and 3 PhD students have been involved in the key underpinning research.

3. References to the research

References that best indicate the quality of the research are indicated with asterisks (***):

R1*** F.G.F. Gibb, A new scheme for the very deep disposal of high-level nuclear wastes. *Journal of the Geological Society of London,* **157** (2000) 27-36 doi: 10.1144/jgs.157.1.27

R2 N. Chapman, & F.G.F. Gibb, A truly final waste management solution**:** is very deep borehole disposal a realistic option for high-level wastes or fissile materials? *Radwaste Solutions,* **10,** 26-37. (http://epubs.ans.org/?p=rs:10)

R3 F.G.F. Gibb, N.A. McTaggart, K.P. Travis, D. Burley, & K.W. Hesketh, High-density support matrices: key to the deep borehole disposal of spent nuclear fuel. *Journal of Nuclear Materials,* **374** (2008) 370-377. doi: 10.1016/j.jnucmat.2007.08.017

R4 P.G. Attrill, F.G.F. Gibb, Partial melting and recrystallization of granite and their application to deep disposal of radioactive waste; Part 1 – Rationale and partial melting; Part 2 – Recrystallization. *Lithos,* **67** (2003)103-133.

R5*** F.G.F. Gibb, K.P. Travis, N.A. McTaggart, & D. Burley, A model for heat flow in deep borehole disposals of high-level nuclear waste. *Journal of Geophysical Research,* **113** (2008) B05201, doi: 10.1029/2007JB005081

R6*** F.G.F. Gibb, K.P. Travis, & K.W. Hesketh, Deep borehole disposal of higher burn up spent nuclear fuels. *Mineralogical Magazine,* **76** (2012) 3003-3017. doi: 10.1180/minmag.2012.076.8.16

4. Details of the impact

Following presentation to the British Association in 1999 there was much media interest [S4] and the Sheffield proposals featured in a House of Lords debate on the Science & Technology Committee's report on *Nuclear Waste* [S5]. With publications [R1 & R2] the interest became more international [S4] and the impact spread in the USA, UK, Sweden and elsewhere, as described below.

Impact in the USA. In 2003 the Massachusetts Institute of Technology 'Think Tank' report for the US government on *The Future of Nuclear Power* [S6] recommended that DBD be considered for the disposal of US spent fuel.

In the USA, a mined repository at Yucca Mountain, Nevada was originally scheduled to take its first spent nuclear fuel in 1998. However, technical and political problems led to increasing delays. Consequently, the DOE was forced to pay substantial sums to power-generating utilities to continue storing spent fuel at their nuclear power plants, awaiting disposal. In 2010, the Obama administration cancelled the Yucca Mountain programme (despite expenditure of >$10 billion), and established the Presidential Blue Ribbon Commission (BRC) on America's Nuclear Future, to conduct a comprehensive review of waste management policy and recommend a new strategy. Influenced by our publications, Sandia National Laboratory (SNL) approached Sheffield in 2010 to form a consortium partnership with MIT, producing joint publications and workshops [S7], leading to favourable media coverage [S8]. A major impact was that DBD became incorporated into the Blue Ribbon Commission's thinking. The Blue Ribbon Commission's 2012 report to the Secretary for Energy [S2] contained a central recommendation (p.27) that "*The United States should undertake an integrated nuclear waste management program that leads to the timely development of one or more permanent deep geological facilities for the safe disposal of spent fuel and high-level nuclear waste.*" Further, it stated specifically (p.95) that "*the Commission has identified deep boreholes as a potentially promising technology for geologic disposal that could increase the flexibility of the overall waste management system and therefore merited further research, development and demonstration*". The report featured (p.31) a key diagram from one of the Sheffield publications [R2] and cited others (p.137) in support of its deliberations and conclusions. The Director of Sandia National Laboratory, says Sheffield work "*led to several members of the BRC taking a personal interest and to the substantial discussion of DBD disposal concepts in the draft and final BRC report, including the citation of some of your own work*" [S1].

In 2012, the US DOE commissioned and funded the Sandia NL - Sheffield – MIT consortium to prepare a "roadmap" for the research, development and practical demonstration of the concept, with Sheffield contracted to develop the plan and research programme. Among the unique aspects of this roadmap arising from the Sheffield research is the use of high-density support matrices and the sealing of the boreholes by "rock welding". All of this is clear evidence of the influence of the University of Sheffield's pioneering research [S1] on US energy policy and the future development of the deep borehole concept within it.

Impact in the UK. In 2007 Committee on Radioactive Waste Management (CoRWM) was reconstituted to advise the Government on development of policy and Prof. F. Gibb was appointed to CoRWM by the Minister. The Government accepted CoRWM's recommendations for geological disposal policy and in 2008 published its *Managing Radioactive Waste Safely* White Paper [S9] setting out a framework for the implementation of geological disposal in a mined repository with deep borehole disposal regarded as an 'alternative'. The Nuclear Decommissioning Authority has published plans for a geological disposal facility to take the first legacy high-level wastes and spent fuel by 2075. However, it has recently come under significant Government pressure to accelerate implementation and has reported [S3] on possible options in which it includes the deep borehole disposal of high level waste in its scenario to maximise acceleration.

The Sheffield work is clearly the source of much of the NDA's knowledge of the concept and has influenced these developments. Two members of the Sheffield research team have been closely involved with the NDA (Prof. F. Gibb through CoRWM, consulting and presenting at NDA-sponsored conferences and Prof. N. Chapman as chair of NDA's Technical Advisory Panel).

Impact in Sweden. In 2012 the Swedish Nuclear Fuel and Waste Management Company (SKB) applied to the regulator and Environmental Court to begin construction of a mined repository for the disposal of spent fuel at the Forsmark site. The choice of a mined repository is being challenged on the grounds that it is potentially not as safe, secure or environmentally friendly as the DBD concept and is therefore not the "best available technology". The case against regulatory approval is

underpinned by evidence from the Sheffield publications and a report by Prof. F. Gibb on SKB's case against the use of deep boreholes [S10]. The Court has subsequently requested SKB reconsider the DBD concept.

The use of deep bore holes as opposed to mined repository will have a future economic impact. To illustrate the potential cost savings in a UK context, the boreholes required to dispose of the country's legacy inventory of vitrified high-level waste in the NDA's "scenario 3" [S3] would cost around £220M compared with the NDA's current plans for disposal in a £4.3 billion mined repository.

5. Sources to corroborate the impact

S1. Letter from the Director, Sandia National Laboratory, Albuquerque, NM, corroborates the contribution that Sheffield made to introducing deep borehole disposal into the US policy.

S2. Blue Ribbon Commission on America's Nuclear Future. Report to the Secretary for Energy, January, 2012. http://www.brc.gov. (pages 27, 31, 95, 137)

S3. Review of options for accelerating implementation of the Geological Disposal programme. (2011) NDA Report No. NDA/RWMD/083 (http://www.nda.gov.uk/documents/upload/Geological-Disposal-Review-of-options-for-accelerating-implementation-of-the-Geological-Disposal-programme-December-2011.pdf)

S4. BBC News (Self-sealing nuclear waste disposal plan, 15/09/99); The Times (Nuclear waste 'tomb' plan, 15/09/99); New Scientist (Dead and buried, 18/09/99); Financial Times (Rock solid solution to nuclear disposal, 30/09/99); Science (Rock solid waste solution, 11/08/03); Nature – Science Update (Nuclear waste could bury itself, 13/08/03); Wissenschaft-Online (Granitgrab fur Atommull, 15/08/03); The Daily Telegraph (Fergus Gibb's 'granite coffin' may finally reconcile us to the beauty of nuclear power, 13/11/04).

S5. Hansard – House of Lords. 29/10/99. Nuclear Waste: Science and Technology Committee Report http://www.publications.parliament.uk/pa/ld199899/ldhansrd/vo991029/text/91029-01.htm#91029-01_head1 confirms that deep borehole technology was subject to debate.

S6. The Future of Nuclear Power: An Interdisciplinary MIT Study. 2003. Page 11 includes recommendation to launch a research programme to determine the viability of DBD. http://web.mit.edu/nuclearpower/pdf/nuclearpower-full.pdf).

S7. Deep Borehole Disposal of Nuclear Waste: Report from a Sandia-MIT Workshop on March 15, 2010 in Washington, DC. (2) Pilot Testing Deep Borehole Disposal of Nuclear Waste: October 26, 2011 Albuquerque, NM Workshop Report. Sandia National Laboratory, Albuquerque, NM 87185-0754.

S8. Geoscientist (Journey to the centre of the Earth, Jan.2008, The Geological Society); New Scientist (Drilling deep under the US to dispose of nuclear waste, 31/03/10); New Scientist (let the Earth itself take care of US high-level nuclear waste, 3/04/10).

S9. Managing Radioactive Waste Safely: A Framework for Implementing Geological Disposal. (2008) Defra, HMSO. Cm7386. (ISBN 9780101738620, Cm 7386 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/68927/7386.pdf)

S10. The Director, MKG – Swedish NGO office for Nuclear Waste Review, PO Box 7005 SE407-31, Goteborg, Sweden can corroborate that the case against regulatory approval is underpinned by evidence from the Sheffield publications.