Institution: University of Sheffield		
Unit of Assessment: B-12 Engineering		
Title of case study: Innovative technology for radioactive waste management		
Period when the underpinning research was undertaken: 2008–2019		
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:**
Hyatt, N.C.	Professor of Nuclear Materials Chemistry	2002–present
Hand, R.J.	Professor of Glass Science & Engineering	1989–present
Corkhill, C.L.	Reader of Nuclear Materials Corrosion	2014–present
Utton, C.A.	Research Fellow	2009–present
Thorpe C.L.	Postdoctoral Researcher	2016–2018
Period when the claimed impact occurred: 2014–2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Sheffield's research has enabled higher activity radioactive waste to be incorporated and immobilised in novel glass wasteforms ready for disposal. The reach of impact is international with uptake of knowledge and technology throughout the UK nuclear industry, the Ministry of Defence, and the US Department of Energy. The extensive impact includes influencing national policy decisions to construct a new thermal treatment plant at Sellafield with the delivery of three demonstrators with investment costs exceeding £100m; uptake of new practices within the international nuclear waste decommissioning industry; and enhancing public awareness of the risks and solutions of radioactive waste treatment and disposal.

2. Underpinning research (indicative maximum 500 words)

Higher Activity Waste (HAW) refers to all radioactive material that has no further use. HAW cannot be disposed of directly; it must be safely treated, packaged, and temporarily stored, pending future policy decisions on the creation of long-term disposal facilities.

HAW is classified into High, Low, and Intermediate Level Waste (HLW, LLW, and ILW). In 2019, the UK's Nuclear Decommissioning Authority estimated the current volume of ILW to be 102,000m^3 with over 66% of it in an untreated or partly treated state. It forecasts that an additional 145,000m^3 of ILW will arise over the next century with 60% of all ILW coming from Sellafield. Ultimately, 97% of all ILW is destined for geological disposal and when packaged the volume will double.

A significant proportion of ILW comprises Plutonium Contaminated Material (PCM). PCM is challenging to manage due to the high radiotoxicity of plutonium and its long half-life. Standard cement encapsulation technologies are not able to process a significant quantity of PCM, and existing vitrification technologies used for HLW are incompatible with ILW treatment. This has left waste owners with no compliant treatment technology.

Innovative work by the University of Sheffield has led to the design, manufacture, and performance assessment of glass and ceramic materials for the immobilisation of plutonium residues and legacy ILW. This research has developed confidence that these waste packages

will be disposable in a future disposal facility and the surrounding evidence base for the safety case.

Sheffield developed silicate glass formulations for treatment of wet ILW at the Hinkley Point A nuclear power station, for Magnox South Sites Ltd. **[R1]**. This work demonstrated the suitability of silicate glass formulations for immobilisation of a wide envelope of simulant ILW waste streams of complex and heterogeneous radiological, chemical and physical constitution. Sellafield Ltd. took up the approach to assess feasibility of application to PCM wastes. Sheffield successfully demonstrated the vitrification of representative simulant PCM waste types, using blast furnace slag as a glass former, to produce a passively safe and disposable product with a volume reduction of between 80-95% **[R2]**. Sheffield's research developed the first comprehensive mechanistic understanding of glass corrosion in a cement-based ILW disposal concept, providing UK stakeholders with confidence in the disposability of this glass wasteform **[R3]**. This work attracted interest from the US Department of Energy and this led to the development of a test methodology to assess the disposability of Hanford vitrified wastes **[R4, R5]**.

Tackling the massive challenges surrounding ILW volumes was addressed through research into hot isostatic pressing (HIP). Sheffield's research showed that processing legacy ILW Magnox-sludge (a colloidal suspension) by HIP resulted in a glass-ceramic wasteform that successfully immobilised radioactive and chemotoxic elements, whilst achieving significant waste volume reduction between 75-80% **[R6]**.

In summary, this research has developed and validated novel glass wasteforms **[R1, R6]** that meet stringent regulatory requirements and exceed the current performance of existing treatment methods **[R3, R6]**. Furthermore, through reducing volume **[R2, R6]**, improving passive safety (through oxidation of organic and metallic materials and the removal of water), increasing waste material compatibility **[R2]**, and superior material stability **[R3, R2]**, we have provided the underpinning evidence and demonstration **[R4, R5]** that has led to the assurance of new disposal routes for previously intractable ILW waste streams, which can be implemented through appropriate policy.

3. References to the research (indicative maximum of six references)

University of Sheffield researchers and students in **bold**

R1. Bingham, P.A., **Hyatt, N.C. & Hand, R.J.** 2013. Vitrification of UK intermediate level radioactive wastes arising from site decommissioning. Initial laboratory trials. *Glass Technology: European Journal of Glass Science and Technology Part A, 54*, 1, 1-19. http://eprints.whiterose.ac.uk/171425/. Cited by 4.

R2. **Hyatt, N.C., Schwarz, R.R., Bingham, P.A., Stennett, M.C., Corkhill, C.L., Heath, P.G.**, **Hand, R.J.**, James, M., Pearson, A. & Morgan. S. (2014). Thermal treatment of simulant plutonium contaminated materials from the Sellafield site by vitrification in a blast-furnace slag. *Journal of Nuclear Materials, 444*, 1–3, 186-199. https://doi.org/10.1016/j.jnucmat.2013.08.019. Cited by 6.

R3. **Utton, C.A., Hand, R.J., Bingham, P.A., Hyatt, N.C.,** Swanton, S.W. & Williams, S.J. (2013). Dissolution of vitrified wastes in a high-pH calcium-rich solution. *Journal of Nuclear Materials, 435,* 1–3, 112-122. https://doi.org/10.1016/j.jnucmat.2012.12.032. Cited by Cited by 45.

R4. **Thorpe, C. L., Hand, R. J., Hyatt, N. C.,** Kruger, A. A., Kosson, D. S., Schweiger, M. J., Riley, B. J., & **Corkhill, C. L.** (2017). Evaluation of novel leaching assessment of nuclear waste glasses. *MRS Advances, 2*(11), 635–640. https://doi.org/10.1557/adv.2016.656

R5. **Thorpe C.L., Mann, C., Fisher A.J., Hand R.J., Hyatt N.C.**, Riley B.J., Schweiger M.J., Mayer J., Arendt C., Kruger A.A., Kosson D., **Corkhill C.L.** (2018). Evaluation of Novel Leaching Assessment for Nuclear Waste Glasses. *Proceedings of Waste Management, 18314*. http://eprints.whiterose.ac.uk/171428/. Received American Nuclear Society Award for Best Oral Presentation and Paper at WM symposia 2018. Cited by 0.

R6. **Heath, P. G.,** Stewart, M. W. A., Moricca, S., & **Hyatt, N. C.** (2018). Hot-isostatically pressed wasteforms for Magnox sludge immobilisation. *Journal of Nuclear Materials, 499*, 233–241. https://doi.org/10.1016/j.jnucmat.2017.11.034. Cited by 1.

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

Sheffield's research in radioactive waste management, generating internationally significant impact for the safe disposal of ILW. An expert advisor to the nuclear power industry who represented the U.K. on the Euratom Science and Technology Committee and was the sole international advisor on the U.S. Department of Energy, Nuclear Energy Advisory Committee comments, "*Sheffield's research led by Professor Hyatt, on the effectiveness of thermal processes to treat ILW and specifically the advanced vitrification technology (employing blast furnace slag) has presented a pioneering solution that mitigates the devastating threats posed from contact with nuclear waste. [...] Ultimately a lower volume of waste, in a more passively safe state, is produced. This underpins enhanced long-term stability, affording unprecedented protection to the public and the environment.*" **[S1] [R1, R2, R3, R6]**.

Economic investment and impact on public policy within the nuclear industry

The sector is risk averse, both policy development and uptake of new processes have been historically difficult. However, Sheffield's research has orchestrated policy debate, decisions, acceptance, and significant investment in its innovative thermal treatment vitrification technology **[R1, R2, R3, R6]**.

Professor Hyatt is a member of the BEIS Nuclear Innovation and Research Advisory Board (2014-2016 & 2018-current), which advises Ministers, Government Departments and Agencies on issues related to nuclear research and innovation in the UK **[S2a]**. Since November 2019, both Professor Hyatt and Dr Corkhill have been members of the BEIS Committee on Radioactive Waste Management **[S2b]**. The 12-person expert panel provides independent scrutiny and advice to the UK Government on the long-term management of higher activity radioactive wastes. The aforementioned nuclear power industry expert advisor stated that Professor Hyatt has provided, "*invaluable advice in the Committee's deliberations*" **[S1]**.

Radioactive Waste Management (RWM) is the implementer of UK Government policy for the geological disposal of higher active radioactive waste and is leading a multi-generational, multi-billion-pound project at Sellafield. RWM has applied Sheffield's research to support the delivery of the UK's radioactive waste strategy **[R1, R2, R3]**. The Head of Research and Environment at RWM, comments "*The research conducted by Professor Hyatt is included in RWM technical reports; it underpins our environmental safety case and is included in our Science and Technology Plan*" (2016 & 2020 issues). He summarises, "*Overall, Professor Hyatt's research is regarded as particularly impactful to stimulate positive understanding and acceptance of a long-term solution to nuclear waste disposal"* **[S3, S4]**.

Sheffield's research into advanced vitrification processes **[R2]** has been utilised by Sellafield Ltd. The Business and Technology Manager at Sellafield Ltd. commented, "*Sheffield's research is of national importance and has allowed Sellafield Ltd to develop a new developing treatment and disposal strategy based around thermal treatment technologies.*" He continues that it has been *"instrumental in the decision to construct a new thermal treatment plant at Sellafield and*

proceed to delivery on three separate thermal treatment demonstrators for ILW [2017 and 2019]*, [...] The investment costs exceed £100 million."* **[S5]**.

The Project Director at Costain (the UK's leading smart infrastructure solutions company), states, "*Neil's research has been instrumental in obtaining a contract with Sellafield* [2019] *to utilise thermal treatment technology for the disposal of plutonium contaminated material. This* [Text removed for publication] *would not have proceeded (based on process risk) without Neil's valuable contributions*" **[S6, S7] [R2, R3]**. He continues, "*Over a dozen technical reports within Costain include Neil's research. This has unquestionably had a significant influence on understanding and boosted uptake of thermal treatment technologies within Costain and the wider nuclear waste industry*" **[S6]**.

The Ministry of Defence (MoD) has also been greatly influenced by Sheffield's research **[R1, R2]**. The UK currently has 20 obsolete nuclear submarines awaiting decommissioning, which are a source of significant public criticism and ongoing costs whilst a suitable ILW disposal route is determined. Costain applied Sheffield's work under the approval of the MoD to demonstrate the feasibility of thermal treatment within a production environment. The work stimulated policy debate and according to Costain's Project Director, Sheffield's research on thermal technologies *"importantly demonstrated feasibility, providing Costain with the necessary scientific understanding and evidence to be confident that this concept would be viable within a production environment. The MOD subsequently approved the next phase of trials, which were again dependent on Neil's research and resulted in a tender for a full scale production plant."* **[S6, S7]**.

Sheffield's research has been adopted by the US Department of Energy, resulting in a change of policy on the vitrification process for low-activity radioactive wastes at the Hanford nuclear facility, the most contaminated nuclear site in the USA with projected clean-up costs (2019) between $323bn - $677bn **[S8 page ES-2]**. Specifically, Sheffield's work has developed a new test for glass encapsulation durability **[R4, R5],** which the Glass Scientist at the U.S. Department of Energy at Hanford confirms, "*has been included in the revision of the U.S. Environmental Protection Agency's standard methodology (SW-846) testing protocol"* as well as proving the safety of a range of glass products **[S9]**. They continue, "*This has reduced conservatism in glass batch formulation for Hanford wastes, enabling a wider compositional envelope and waste loading to be tolerated. The benefits are reduced processed waste volumes and lower operational costs arising from a reduction of the Waste Treatment and Immobilization Plant mission*" **[S9]**.

Impact on understanding, learning and participation

Sheffield's research on thermal treatment technologies for nuclear waste has been extensively promoted to the public e.g. **[R1, R2, R3, R6]**, significantly enhancing awareness of the necessity to manage appropriately, all types of HAW and engagement with the identification of a final disposal facility. This includes dissemination in more than 20 radio and television interviews (BBC News/Radio), over 30 published news articles and online media and a documentary (Clan Productions). Estimated reach is 1.1 million people **[S10]**.

5. Sources to corroborate the impact (indicative maximum of 10 references)

S1. Confidential testimonial letter from the Hon President National Skills Academy for Nuclear and who represented the UK on the Euratom Science and Technology Committee and the sole international advisor on the US Department of Energy, Nuclear Energy Advisory Committee (2020). Corroborates the benefits of the new thermal vitrification technology, how Sheffield's work has reduced the risk to the public and the environment, and

Professors Hyatt's roles in the BEIS sponsored Nuclear Innovation Research Advisory Board and Committee on Radioactive Waste Management.

S2. Combined: Confirmation of Neil Hyatt's role on the Department for Business, Energy & Industrial Strategy (BEIS) committees.

a) Nuclear Innovation and Research Advisory Board. (Accessed 5 March 2021). https://www.nirab.org.uk/our-members

b) Committee on Radioactive Waste Management. (Accessed 5 March 2021). https://www.gov.uk/government/organisations/committee-on-radioactive-waste-management/about#members

S3. Confidential testimonial letter from the Head of Research and Environment at RWM (2020). Corroborates influence in guiding RWM's radioactive waste technology strategy.

S4. Second issue of RWM Geological Disposal Science & Technology Plan, May 2016. Lists the Technical Programme Tasks Sheets underpinned by Hyatt's research, which are found in Appendix B pages 162, 217, 219, 249, 251, 252, 254, & Appendix D page 6. (Accessed 14 Sep 2020). https://bit.ly/3eWxk97

Third issue of RWM Geological Disposal Science & Technology Plan, October 2020. Lists the Technical Programme Tasks Sheets underpinned by Hyatt's research, which are found in Appendix B pages 259, 516, 519, 521, 523, & Appendix C page 716. (Accessed 26 Feb 2021). https://bit.ly/38XAeqA

S5. Confidential testimonial letter from the Business and Technology Manager at Sellafield (2020). Corroborates impact on their thermal treatment strategy and associated investment decisions.

S6. Confidential testimonial letter from the Project Director at Costain (2020). Corroborates a) role in winning a contract with Sellafield b) influencing understanding and uptake of thermal treatment of Plutonium Contaminated Waste (PCM) within Costain & c) role in de-risking technology options for MoD Submarine radioactive waste.

S7. Press release from Costain reporting both the thermal treatment demonstrator and the MoD contracts (2019). (Accessed 1 Feb 2021). https://www.costain.com/news/news-releases/costain-appointed-for-sellafield-nuclear-waste-trials/

S8. Hanford Lifecycle Scope, Schedule and Cost Report (2019), page ES-2. Reports the projected clean-up costs of the Hanford site. (Accessed 9 Sep 2020). https://www.hanford.gov/files.cfm/2019_Hanford_Lifecycle_Report_w-Transmittal_Letter.pdf

S9. Confidential testimonial letter from the Glass Scientist at the Office of River Protection, U.S. Department of Energy - Hanford Site (2020). Corroborates how the Sheffield developed test for glass encapsulation durability has changed vitrification process policy leading to a shortening of the overall site decontamination project.

S10. BARB, BBC commissioner and social media viewing figures.