Institution: Lancaster University

Unit of Assessment: 12, Engineering

Title of case study: Safer, cheaper and 99% less waste: Lancaster's radioactivity depth profiling research improves the decommissioning process for nuclear fuel storage ponds at Sellafield.

Period when the underpinning research was undertaken: 2006-2014

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:
Malcolm J. Joyce	Professor	1998-present

Period when the claimed impact occurred: 2014 to 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

This case describes the impact of Lancaster research into radioactive contamination measurement on the decommissioning strategy of the Pile Fuel Storage Pond (PFSP) at Sellafield. It has enabled:

- **Sellafield Ltd.** to revise the process by which they will decommission PFSP (the largest, open-air nuclear fuel storage pond in the world) to a strategy affording reduced risk to workers, a 99.5% decrease in the volume of radioactive waste arising (from 2,800m^3 to 14m^3) and a related waste disposal cost saving of GBP140.0 million.
- **Government** (Nuclear Decommissioning Authority), to revise their definition of the safe state to be reached, prior to demolition, of PFSP.
- **Commerce**, enabling REACT Engineering Ltd. to spin out a new business (Createc Ltd.) and forge a new industrial partnership of Createc with Costain plc.
- **Industry** (Createc and Costain), to execute *in-situ* trials at Sellafield to inform the new policy and to support the revision to process specified above.

2. Underpinning research

The research underpinning this case study began with a project awarded to Prof. Malcolm Joyce in 2006, funded by the Nuclear Decommissioning Authority (NDA). This was awarded in response to his proposal to explore the hypothesis that the depth of radioactive contamination in concrete might be determined, remotely, by studying the relative difference in attenuation of photons emitted by the entrained radioactivity; lower-energy X-rays are attenuated more than higher-energy γ-rays and the resulting difference in their intensities is related to the depth.

Initial experiments were carried out at laboratory scale in the Engineering Department at Lancaster University, with sealed radioactive sources and bespoke, sand-filled testbeds which were designed and built by Joyce and Shippen (a PhD student supervised by Joyce). A key finding of this research was the successful resolution of caesium-137 at depth via linear attenuation analysis [3.1, 3.2]. This finding was advanced via a subsequent iCASE studentship (awarded to Joyce in 2008 and co-funded by REACT Engineering Ltd. and NDA), to include cobalt-60 exploiting photon scatter [3.3] and principal component analysis [3.4]. This proved the principle at greater depth, in a variety of construction materials and explored the effects of aggregates and voids [3.5] with several calibration testbeds [3.6]. This research was conducted by Joyce, Adams (the iCASE PhD student supervised by Joyce) and Mellor (of REACT Engineering and subsequently Managing Director of the REACT spin-out, Createc Ltd.).

This research demonstrated that the depth of ^{137}Cs contamination in civil engineering materials could be inferred from the relative difference in intensity of γ-ray and X-ray photons emitted by the entrained radioactivity. Joyce and co-workers also explored the limitations of the technique, in terms of depth and sensitivity, and how it might be scaled up to demonstration

facilities. Fundamentally, the research of Joyce et al. provided the insight that features of the radiation spectrum with contrasting energies, such as X-rays and γ rays from ^{137}Ba and ^{137}Cs, respectively, could be exploited to infer the depth of ^{137}Cs contamination [3.5], given that ^{137}Cs is the most pervasive contaminant nuclide encountered in legacy nuclear facilities. Joyce and co-workers were awarded the James Watt medal for best paper in 2014 by the Institution of Civil Engineers for the research output that constitutes the culmination of this body of work [3.6].
To advance the research towards application, Joyce won a Knowledge Transfer Partnership (KTP, from 2010 to 2012) with REACT Engineering Ltd. on which Shippen was the KTP Associate. In total, 8 journal papers, 8 international conference papers and 2 PhD theses arose from this research. Professor Joyce was employed by Lancaster University 100% for the entire period between 2006 and 2014 during which the underpinning research was done, leading it all.

3. References to the research

[3.1]. 'Profiling the depth of caesium-137 contamination in concrete via a relative linear attenuation model', Alan Shippen and **Malcolm J. Joyce**, *Applied Radiation and Isotopes* 68 (4-5) 631-634 (2010). 18 citations.

[3.2]. 'Extension of the Linear Depth Attenuation Method for the Radioactivity Depth Analysis Tool', B. Alan Shippen and **M. J. Joyce**, *IEEE Trans. Nuc. Sci.* 58 (3) 1145-1150 (2011). 10 citations.

[3.3]. 'Depth determination of buried caesium-137 and cobalt-60 sources using scatter peak data', Jamie C. Adams, Matthew Mellor and **M. J. Joyce**, *IEEE Trans. Nuc. Sci.* 57 (5) pt. 2 2752- 2757 (2010). 8 citations.

[3.4]. 'The determination of the depth of localised radioactive contamination by ^{137}Cs and ^{60}Co in sand with principal component analysis', J.C. Adams, M. Mellor and **M. J. Joyce**, *Env. Sci. Tech.* 45 (19) 8262-8267 (2011). 10 citations.

[3.5]. 'Depth profiling ^{137}Cs and ^{60}Co non-intrusively for a suite of industrial shielding materials and at depths beyond 50 mm', J.C. Adams, **M. J. Joyce** and M. Mellor, *Appl. Rad. & Isot.* 70 (7) 1150-1153 (2012). 10 citations.

[3.6]. 'Finding the depth of radioactivity in construction materials', **M. J. Joyce** et al., *ICE Proc. Energy (invited)* (May 2013) 166 (2) 67-73 (21st March 2012). Winner James Watt medal, October 2014, ICE News (last accessed Nov. 2020) and Lancaster news, last accessed Nov. 2020.

Citations: Google Scholar

Further quality indicators: Funding awarded to **Joyce**: **1)** 'Development of a radioactive depth profile analysis tool', between 1st October 2006 and 30th September 2009, GBP49,000.00, funder: NDA. **2)** 'Depth Profiling', between 1st April 2008 and 30th September 2011, GBP56,000, funder: NDA/REACT Engineering Ltd. **3)** 'Development and commercialisation of a unique radiation analysis concept', between 1st August 2010 and 31st November 2012, GBP140,000, funder: UKRI/REACT Engineering Ltd.

4. Details of the impact

Background

The Pile Fuel Storage Pond (PFSP) is a water-filled, concrete structure at Sellafield (see Fig.1 below). It is 100m long, 7m deep and is open to the environment. It was built in 1948 to store the spent nuclear fuel from the UK's first nuclear reactors that produced plutonium for the UK's earliest nuclear weapons. It has housed a range of spent fuel from various reactors comprising approximately 1000 different forms of radioactive waste.

PFSP is the oldest and the largest, open-air, nuclear fuel storage pond in the world, and is one of the most hazardous legacies in Europe. It is a UK Government 'Major Project', i.e., with an anticipated lifetime cost of more than GBP100.0 million requiring HM Treasury approval. In 2017 and 2018, high-hazard ponds and silos accounted for 29% of GBP2.0 billion spent at Sellafield with PFSP costing GBP20.0 million in that year alone [5.1].

PFSP is deemed a 'high-hazard' meaning that it must be decommissioned in a way that will: '*deliver an end state as soon as reasonably practicable with a progressive reduction in risk and* *hazard'* [5.2]. For PFSP, this comprises reducing the water level in the pond progressively from 2019 to 2029 (known as *dewatering*) and operations to place it in a safe state consistent with a subsequent 10-year period of control and maintenance. This will be followed by demolition of the concrete structure. The nature of the safe state referred to above is subject to extensive prescribed detail and analysis, and is particularly important in the context of this case. The detailed description of the state that results from this assessment is known as the defined interim state; for PFSP this is defined below under 'Context'.

Unlike similar facilities elsewhere (cf., the KW basin at Hanford, USA), the internal surfaces of PFSP were not coated to prevent ingress by contaminated water into its constituent concrete. Consequently, radioactivity has pervaded its structure, severely complicating the ease with which it is dismantled. For example, as the water level is reduced, by way of dewatering, the shielding influence of the water on radiation emitted from radioactivity in its walls will also reduce, increasing radiation exposure. This makes it difficult to estimate the degree of hazard workers will be exposed to after dewatering and increases the uncertainty on how much of the pond structure will need to be removed to achieve the defined interim state, prior to demolition.

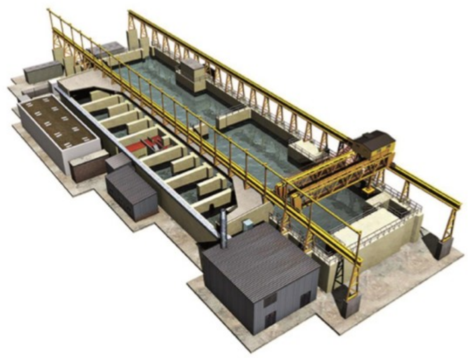


Figure 1: A schematic representation of the PFSP from 'Priority Programmes and Major Projects' (NDA 24102622, 2015)

This case study concerns impact that comprises: i) a formal revision of the accepted decommissioning process; ii) a revision of the defined interim state; iii) the benefit of non-destructive characterisation evidence supporting these revisions, and iv) the economic benefits to the third parties that have exploited the underpinning research.

Context

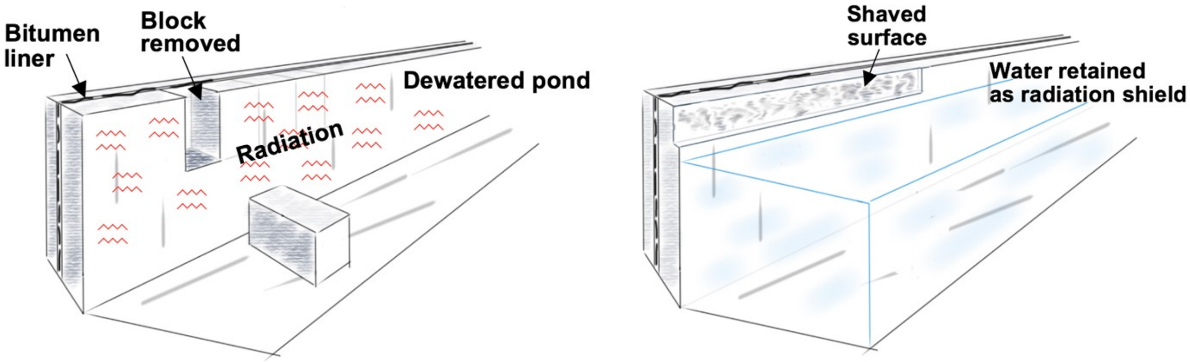
Prior to this impact, the 2015 defined interim state (see above) for PFSP was (quoted from [5.2, p.6]): '*Pond dewatered, concrete liner removed (waste route to be determined), walls without a liner sealed / shielded and R2/C2 radiological conditions achieved. All…debris, …sludge and (radio)activity contained within the pond wall/floor concrete liner will have to be removed from the pond at which time the Interim State will be achieved, and a period of Care & Maintenance commenced prior to Final Decommissioning and Demolition.*' Note: 'R2/C2' refers to the category of engineered precautions and controls necessary in areas contaminated with radioactivity, where R2/C2 the lowest category of controlled area.

Achieving the 2015 interim state would have required: total removal of the water and removal of the spent fuel, sludge and other wastes from the pond; diamond sawing of the concrete walls into blocks; prizing these blocks off the 20mm-thick bitumen layer beneath them; creation of a new walkway external to the building (thus avoiding increased radiation exposure inside the building due to dewatering) and relocation of the services attached to the old one. With the pond empty, and the shielding effect of the water thus removed, removal of the walls would need to have been done entirely remotely due to the high radiation levels. Further, a dedicated disposal route (i.e., to somewhere proven fit-for-purpose) would need to have been established to store the contaminated concrete blocks. The merit of the 2015 interim state was that removing the concrete liner completely would have reduced the *in-situ* radioactivity quickly, offering a relatively fast means by which to achieve the interim state. However, the drawbacks were: *high dose rates, enhanced engineering complexity, limited characterisation data and the need for significant [levels of] remote operations*. [5.2, p.5]. Workshops in April 2017 concluded that the risk with the 2015 scheme was unlikely to be as low as reasonably practicable (ALARP), as required by law.

Characterisation trials that supported a change in the definition of the PFSP interim state

Subsequent to being KTP Associate (see Section 2), Shippen secured a full-time position with Createc Ltd. As a result, the company won a number of industry-based contracts (detailed under Technology transfer etc., below) by which the knowledge and the capability developed in the underpinning Lancaster research was transferred and exploited, including the relationship between photon spectra, attenuation and depth, and knowledge of the apparatus. In March

2014, Createc and Costain sponsored and conducted extensive *in-situ* trials [5.3] at Sellafield based on the underpinning Lancaster research [5.4, 5.5. 5.6], termed the D:EEP (Estimating Entrained Product) trials. These provided (quoting [5.7] section 7.2) *'…crucial information because it can be used to determine the minimum amount of wall material that needs to be removed for bulk decontamination'*. This assessment supported a change in the strategy to remove the radioactivity by shaving the top layer away from the concrete liner, rather than removing the entire liner itself. The distinction between these approaches is illustrated in Figs. 2a and 2b.



a) Strategy prior to impact **b) Strategy after impact**

Figure. 2: Cutaway illustrations of PFSP showing the back wall, bitumen liner and pond floor part-way through preparations to place it in a safe state for long-term maintenance: a) The strategy prior to this impact - pond empty, its wall being cut into blocks placed on the pond floor, for which there was no disposal route. b) Strategy after this impact - water level reduced incrementally (lower dose hence less risk) and wall shaved according to assessment by depth profiling (yielding less radioactive waste of a form compatible with an existing disposal route).

As a result of the application of the underpinning research in the D:EEP trials, the interim state definition was changed in 2017 to require the concrete walls to be shaved to a depth of approximately 10mm, as the water level is lowered at 70-cm intervals (see [5.3, p.45]: '*The project supported a revised dewatering strategy for PFSP…'*) and found [5.8] *'shaving to 3mm reduced surface activities by more than 90% with no significant reduction with further shaving to 6 and 9mm'*, with the benefit that the shavings (being intermediate level radioactive waste, ILW) will be compatible with an existing disposal route. As a result, the revised interim state definition:

i. Carries significantly reduced risk (both in terms of safety and implementation).
ii. Generates significantly less radioactive waste, i.e., given two walls, 2-m thick, shaved to 10mm and a conservative ILW disposal cost of GBP50,000 / m^3, the revised strategy affords a 99.5% reduction in both waste volume (**from 2800m^3 to 14m^3**) and disposal cost (**GBP140.0 million to GBP0.7 million**, i.e., packaged volume ILW £9k/m^3 + £40k/m^3 container, see: NDA Technical note 16518861, conservative since estimates as of February 2012).
iii. The expensive and onerous task of establishing a new disposal route, required for the blocks arising via the original 2015 strategy, is avoided.
iv. The '*very significant'* cost of operating the facility longer than anticipated in the absence of sufficient characterisation data ('hotel' costs) [5.2] and,
v. The impact of this on future generations, are both avoided [5.6, 5.9, 5.10].

The definition of the interim state, revised due to the Lancaster impact, is [5.2, p.5]: '*Pond dewatered, walls shaved and/or shielded (when not reasonably practicable to remove the radiological source term) and R2/C2 radiological conditions achieved at the surface of the remaining structure. Residual pond sludge/debris will have been minimised (subject to ALARP) and any residual material immobilised. Shaved/shielded surfaces will be sealed to prevent leaching/carbonation and encast steels will remain in situ. ILW concrete waste generation will be minimised and exported to downstream plants.*'. As corroborated by Sellafield [5.9], the resulting change in strategy '*…is an important step and cannot be underestimated'*, and further by the NDA [5.10], this research '*had a significant and positive impact on helping to define the strategy for dealing with one of the UK's highest hazard legacy nuclear fuel storage ponds'*.

Consequently, the revised approach removes most of the radioactivity while minimising waste volumes and yields waste in a form for which there is an existing disposal pathway. It does not implicate the pond structure, it is easier to automate than concrete block cutting, it reduces the risk of exposure to operators (as the dewatering is incremental and the shielding effect of the water is retained) and it is also achievable more easily on a remote basis than block removal.

Beyond PFSP, the technique has also [5.3, p.45] been '*tested on a contaminated wall in the FGRP (First Generation Reprocessing Plant))*' and has influenced future plans, i.e., [5.7, sect. 7.2] '*…underpin the dewatering strategy for the tanks and other legacy ponds at Sellafield'* via trials in the Residual Sludge Tanks (RST) where the benefit of underwater deployment [5.3, p. 45] *'...means that future expensive dewatering trials may be avoided'.*

Technology transfer, industry-based grants, employment and commercial impact

Shippen, the KTP Associate [5.11] at REACT Engineering and researcher on the underpinning research, is now *Nuclear Instruments Chief Scientist* with the REACT spin-out, Createc Ltd. Fellow former researcher, Adams, is now *Senior Radiometric Specialist* with Sellafield Ltd. Createc and Costain (combined revenue of more than GBP1.5 billion) formed the D:EEP partnership to commercialise the underpinning research, winning a 5-year, Innovate UK project (GBP350,000 between April 2015 and June 2018) [5.12] (one of a series of related Createc technology development contracts). The D:EEP technology was highly commended in the NDA Group Supply Chain Awards collaboration category and achieved a Sellafield Business Excellence Gold Award relating to its use in the PFSP trials [5.4].

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

[5.1] 'The Nuclear Decommissioning Authority: progress with reducing risk at Sellafield' National Audit Office, HC 1126 SESSION 2017–2019 20 JUNE 2018, p.26. Corroborates costs of PFSP project.

[5.2] 'Review of PFSP Interim State & Dewatering Methods – A Summary Report', RP-LPSERP-015_Proj_00450_C, Sellafield Ltd., 7th September 2017, pp.5-6, and email from the Science and Technology Manager, PFSP, Sellafield Ltd., 18th November 2019. Corroborates impact of research on PFSP at Sellafield.

[5.3] 'The 2017/18 Technology Development and Delivery Summary', Sellafield Ltd, pp.45-46. Corroborates impact of in-situ trials.

[5.4] Government website 'Technologies for measuring radioactivity levels in concrete', NDA 2016, and individual websites Createc, Costain and Costain news (dated 28 November 2019) giving combined information about the trials and confirming Sellafield Business Excellence Gold Award.

[5.5] Createc Ltd. and Costain plc. have prepared a document (hard copy available on request): 'D:EEP Estimating Entrained Product, case studies brochure' that has been distributed at the NDA Supply Chain Conference 2018. This provides a very detailed account of all of the case studies and includes a reference to Lancaster University and the research done by B. A. Shippen (the first PhD student, sponsored by NDA) on p.11.

[5.6] Testimonial from Createc Ltd., 22nd January 2020. Corroborating the impact of the work on the PFSP.

[5.7] 'Annual Research and Development Review 2018/19', Sellafield Ltd. Corroborates impact of work in determining the minimum level of wall material needing removal.

[5.8] 'The 2016/17 Technology Development and Delivery Summary', Sellafield Ltd, p.50. Corroborates no significant different between 3mm shavings and 6mm to 9mm shavings.

[5.9] Testimonial from Sellafield Ltd., 28th July 2020. Corroborating impact of work at the site.

[5.10] Testimonial from the Nuclear Decommissioning Authority, 8th October 2020. Corroborating impact of work on future generations.

[5.11] North West Innovation case book (2014). Evidences the KTP that followed the first NDA PhD bursary on p.22.

[5.12] Press release, dated 15th January 2015 evidencing the Innovate UK funding for D:EEP : 'Costain and Createc develop technology set to revolutionise nuclear decommissioning'