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Current and emerging technologies for the remediation of difficult-to-measure radionuclides at nuclear sites

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Difficult-to-measure radionuclides (DTMRs), defined by an absence of high energy gamma emissions during decay, are problematic in groundwaters at nuclear sites. DTMRs are common contaminants at many nuclear facilities, with (often) long half-lives and high radiotoxicities within the human body. Effective remediation is, therefore, essential if nuclear site end-state targets are to be met. However, due to a lack of techniques for *in situ* DTMR detection, technologies designed to remediate these nuclides are underdeveloped and tend to be environmentally invasive. With a growing agenda for sustainable remediation and reduction in nuclear decommissioning costs, there is renewed international focus on the development of less invasive technologies for DTMR clean-up. Here, we review recent developments for remediation of selected problem DTMRs (^{129}I , ^{99}Tc , ^{90}Sr and ^3H), with a focus on industrial and site-scale applications. We find that pump and treat (P&T) is the most used technique despite efficacy issues for ^{129}I and ^3H . Permeable reactive barriers (PRBs) are a less invasive alternative but have only been demonstrated for removal of ^{99}Tc and ^{90}Sr at scale. Phytoremediation shows promise for site-scale removal of ^3H but is unsuitable for ^{129}I and ^{99}Tc due to biotoxicity and bioavailability hazards, respectively. No single technique can remediate all DTMRs of focus. Likewise, there has been no successful site-applied technology with high removal efficiencies for iodine species typically present in groundwaters (iodide/ I^- , iodate/ IO_3^- and organoiodine). Further work is needed to adapt and improve current techniques to field scales, as well as further research into targeted application of emerging technologies.

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Environmental significance

The presence of difficult-to-measure radionuclides (DTMRs) in groundwaters at nuclear sites poses significant threats to ecosystems and human health due to their long half-lives and high radiotoxicities. Addressing this remedial challenge is vital for achieving nuclear site end-state targets and minimizing environmental impacts. Our study critically evaluates current and emerging technologies for DTMR remediation, revealing that no single technique is universally effective for all DTMRs of focus, and highlights areas for further research. This work contributes to the broader understanding of DTMR remediation in the context of sustainable environmental management, emphasising the need for continued development of less invasive and more efficient remediation technologies to protect ecosystems and public health.

1 Introduction

Groundwater contamination at nuclear sites is extensive, containing many types of organic, inorganic and radioactive contaminants *e.g.* Hanford Site (Washington, USA)¹ and Sellafield (Cumbria, UK).² Some of these radioactive contaminants (*e.g.* ^{137}Cs and ^{60}Co) emit high-energy gamma radiation during decay, making them detectable and quantifiable remotely using *in situ* gamma spectrometry.³ However, several isotopes found in groundwaters and soils emit alpha, beta or low-energy

gamma radiation, making them challenging to identify using conventional, non-intrusive methods.⁴ Complex laboratory analysis is needed for detailed measurements of these Difficult to Measure Radionuclides (DTMRs), which include $^{241,240,239}\text{Pu}$, ^{129}I , ^{99}Tc , ^{90}Sr , ^{14}C , and ^3H . Further, DTMRs have varying mobilities in groundwater, making their site distributions difficult to characterise. Development of targeted remediation and risk management strategies is consequently hindered, potentially reducing their efficacy. The range of mobilities also limits the application of scaling factors, a commonly used technique at nuclear facilities that involves measuring the ratio of an easy-to-measure radionuclide to a DTMR in a material, *e.g.* ratio of ^{137}Cs : ^{90}Sr in a spent nuclear fuel container, and applies it to any on-site instance where that material is present, *e.g.*

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spent nuclear fuel leak in the subsurface.⁴ If, in this example, ⁹⁰Sr migrates through groundwater slower than ¹³⁷Cs, the two radionuclides will eventually form separated plumes in different areas of the site. When the leak is discovered, it will be assumed that the ⁹⁰Sr is present with the ¹³⁷Cs in the ratio previously ascertained. This means that the true ⁹⁰Sr plume extent may remain undetected, whilst facility time and money is spent remediating the ¹³⁷Cs plume for ⁹⁰Sr despite its reduced activity in this area of the subsurface.

DTMRs are abundant at many nuclear sites worldwide. For example, at the Hanford Site, the most contaminated nuclear facility in the United States,⁵ ¹²⁹I, ⁹⁹Tc and ³H plumes covered 58 km², 2 km² and 58 km² of land area, respectively, in 2021.⁶ The plume boundaries were defined by concentrations in excess of 0.037 Bq L⁻¹ (1 pCi L⁻¹) of ¹²⁹I, 33.3 Bq L⁻¹ (900 pCi L⁻¹) of ⁹⁹Tc and 740.0 Bq L⁻¹ (20 000 pCi L⁻¹) of ³H, which are upper limits of the drinking water standard set by the U.S. Environmental Protection Agency (USEPA).⁷ Similarly, in 2016, Sellafield borehole monitoring detected up to 164 000 Bq L⁻¹ of ³H, over 16 times greater than the World Health Organisation (WHO) drinking water limits.² The same borehole continued to exceed the drinking water limits in 2021, although the exact activity was not stated.⁸ Many DTMRs are long-lived and will remain a significant problem over human (and site operation and decommissioning) lifetimes, making effective remediation at nuclear sites a necessity for the protection of local populations and for eventual, successful, release of this land to public use following decommissioning.

Although all forms of land remediation were once considered beneficial (or their costs considered acceptable), it is now recognised that remediation technologies require careful planning and management to avoid excessive negative impacts on the environment.⁹ The Sustainable Remediation Forum UK (SuRF-UK) define sustainable remediation as “*the practice of demonstrating, in terms of environmental, economic and social indicators, that the benefit of undertaking remediation is greater than its impact and that the optimum remediation solution is selected through the use of a balanced decision-making process*”.¹⁰ International guidelines have been produced to encourage standard practices in sustainable remediation e.g. the American Society for Testing and Materials (ASTM) Standard Guide for Greener Cleanups¹¹ and the International Organization for Standardization (ISO) Soil Quality – Sustainable Remediation procedures,¹² incorporating a wider socio-economic outlook alongside the assessment of a technology's feasibility and implementation at a particular site. Sustainable approaches to remediation are also being introduced to nuclear decommissioning documentation e.g. Section 8.2 of the Nuclear Decommissioning Authority Strategy 2021,¹³ encouraging standard practices at a number of sites. Responsible clean-up in the nuclear sector is especially important, owing to the hazardous nature of materials held on-site, making sustainable remediation an important area for development.

Several reviews have been published on nuclear site remediation, including those by Hossain,¹⁴ Alby *et al.*,¹⁵ Sharma *et al.*¹⁶ and the International Atomic Energy Agency (IAEA),¹⁷ with the development of more sustainable techniques in recent years well-documented. However, DTMR-specific work focuses

mostly on laboratory analyses e.g. IAEA⁴ and Thierfeldt and Deckert¹⁸ rather than *in situ* detection and removal, and consequently there are no comprehensive reviews on remediation for these nuclides. Technologies and applications focusing on *in situ* DTMR removal from groundwater remain underdeveloped compared to radionuclides that are easier to detect. This knowledge gap hinders the ability of assessors to fully remediate a site effectively, as numerous groundwater and soil samples must be obtained and tested. This is a slow, expensive, and labour-intensive process, as laboratory analysis increases the time taken for DTMR data to be collated and acted upon, slowing the implementation of immediate measures such as locating and isolating radionuclide leaks. Greater subsurface sampling also increases the risk to site operators, as working in close proximity to radionuclides for prolonged periods may expose workers to substantial dose.

Today, many nuclear sites are nearing or have reached the end of their operational lifetimes,¹⁹ and require decommissioning in order to achieve end-state land quality targets. At a number of these facilities, DTMRs comprise large proportions of the remaining radionuclides (examples given above), making effective, low-cost clean-up technologies vitally important for achieving remediation targets. Here, we review both conventional and sustainable remediation techniques at site-scale for four DTMRs that are highly mobile in groundwaters and compare advantages and disadvantages for each technology. Techniques such as subsurface walls (for example, as applied at the Fukushima Daiichi Nuclear Power Plant to limit off-site ³H transport²⁰) have been excluded from this review as they do not actively remediate groundwater, but instead channel plumes to allow further radioactive decay to occur before off-site migration can happen. We aim to highlight knowledge gaps in DTMR remediation and inform future work by addressing key issues that remain in the management of these radionuclides and their risk. The reviewed DTMRs are ¹²⁹I, ⁹⁹Tc, ⁹⁰Sr and ³H. These radionuclides have been selected as they either emit gamma radiation of <100 keV or do not produce gamma emissions during decay.²¹ In addition, ¹²⁹I and ⁹⁹Tc both have high abundances in nuclear wastes^{22–24} and long half-lives of 15.7 × 10⁶ years and 2.11 × 10⁵ years, respectively.²¹ As a result, hazard mitigation through natural attenuation is not feasible over human lifetimes, making effective nuclide remediation the only option for achieving nuclear site end-state targets. In comparison, ⁹⁰Sr and ³H have much shorter half-lives and are likely to only present issues over decadal to century timescales but are included here due to their presence in large quantities at a number of nuclear facilities internationally. High abundances in wastes are especially pertinent for ³H and make development in its remediation globally important; frequent progression reviews can enhance the growth and implementation of new technologies to combat this problem.

2 DTMRs in the environment

2.1 Interaction between soils and groundwater

The movement of nuclides in the environment can vary depending on the conditions and materials present. The degree



of ion mobility can be described using the partition coefficient (K_d ; eqn (1)), which shows the ability of an ion to adsorb onto a given medium, rather than remaining in solution. K_d (mL g^{-1}) is defined as:

$$K_d = \frac{\text{radionuclide on adsorbent at equilibrium (mg g}^{-1}\text{)}}{\text{radionuclide in solution at equilibrium (mg mL}^{-1}\text{)}} \quad (1)$$

A K_d of $<1 \text{ mL g}^{-1}$ shows that negligible adsorption is occurring and the radionuclides are remaining in solution, whilst high K_d values (e.g. 1000 mL g^{-1} or greater) indicate a high level of contaminant sorption.

While the K_d test approach can provide a simple method for demonstrating the proportion of an ion in groundwater and soil, the approach has drawbacks. It is highly dependent on the starting concentrations of radionuclide, as a greater abundance of the contaminant will likely bind to the adsorption sites more quickly and result in the adsorbent reaching capacity in smaller volume of solution. The method is also influenced by various factors of environmental aqueous geochemistry (e.g. the preferential uptake of competing ions onto adsorption sites, pH, redox potential *etc.*),²⁵ and groups additional attenuation processes, such as precipitation and diffusion into pores, into a single 'sorption' term.²⁶ The K_d test method also assumes that adsorption is instantaneous and fully reversible which may not be true under real-world conditions.²⁵ Despite the limitations, K_d test methods provide an intuitive method for comparing the extent of elemental partitioning between two media and are consequently popular in sorption-based literature (and are therefore utilised in this review).

2.2 DTMRs of focus

2.2.1 Iodine. ^{129}I is a fission product of ^{235}U (0.71% yield) with a half-life of 1.57×10^7 years.²¹ Significant groundwater contamination from ^{129}I exists at the Hanford Site and Savannah River Site (SRS) nuclear facilities in the USA,^{6,27} although the isotope is also found in smaller concentrations at other facilities, such as Sellafield.² The dominant forms of iodine in the environment are iodate (IO_3^-) and iodide (I^-).²⁸ Laboratory studies have shown that reactions between iodine and organic material in soils and groundwater (e.g. humic and fulvic acids^{29,30}) lead to the formation of organoiodine (org-I) compounds, which can increase or decrease the environmental mobility of iodine depending on the products created.³¹ IO_3^- , I^- and org-I compounds can co-exist in groundwaters, further complicating the behaviour and mobility of iodine in these environments.²⁷ Typical Hanford sediments of quartz- and feldspar-rich sands have a low I sorption, with K_d s of $0-8.1 \text{ mL g}^{-1}$ and $0.8-7.6 \text{ mL g}^{-1}$ for I^- and IO_3^- , respectively.³²⁻³⁴ Quartz-rich surface aquifer sediments from SRS also have low I^- K_d s, ranging from 0.06 to 8.8 in starting solutions of 10^{-2} to $10^3 \text{ }\mu\text{M I}^-$.³¹ These high mobilities in groundwater are a result of IO_3^- and I^- existing as anions, which are repelled by the negative surface charges of material in soils at typical environmental pHs.³⁵ Laboratory experiments have shown that IO_3^- can have K_d s up to 90 times greater than I^- when mineral

phases such as iron oxides are present in soils.^{36,37} However, the aforementioned nuclear sites generally have low abundances of these in the subsurface, as reflected by the low iron content in experimental samples e.g. SRS³¹ and Hanford.³⁴ Further, I^- K_d s remain almost unaffected in comparison to Hanford and SRS values, suggesting that iodine migration in groundwater would still be a concern at nuclear sites with higher iron oxide concentrations within the subsurface where I^- is the dominant form of I present.

2.2.2 Technetium. ^{99}Tc is a high-yield fission product of ^{235}U (6.13%), with a half-life of 2.11×10^5 years.^{21,22} In oxidising conditions, Tc(vii) is the dominant species in the form of pertechnetate, TcO_4^- , whereas reducing conditions produce Tc(iv) and primarily form $\text{TcO}_2 \cdot n\text{H}_2\text{O}$,³⁸ where n can range between 0.44 and 4.22.³⁹ Tc(vii) has a high solubility and, hence, high mobility in water, with an approximate K_d of $0-1 \text{ mL g}^{-1}$,^{22,32,40} but Tc(iv) is only sparingly soluble e.g. K_d s of $15-280 \text{ mL g}^{-1}$ have been estimated for sediment at Forsmark and Laxemar-Simpevarp sites in Sweden.⁴¹

2.2.3 Strontium. ^{90}Sr is another high-yield ^{235}U fission product (5.73%) with a 28.91 year half-life.²¹ The chemistry of Sr is similar to that of Ca,⁴² with Sr often existing in aqueous environments as a divalent ion that is either hydrated or bound to small organic compounds.⁴³ Sr(II) has been found to have K_d s of $10-25 \text{ mL g}^{-1}$ in quartz-rich Hanford sediment.⁴⁴ However, mobility can be reduced through sorption onto fulvic and humic acids⁴⁵ and clays, resulting in much higher K_d s e.g. $\sim 10^3$ estimated for the subsurface at Sellafield.⁴⁶

2.2.4 Tritium. ^3H is an activation product with a half-life of 12.32 years.²¹ It results from collisions between neutrons and stable ^2H nuclei found within reactor materials, such as control rods and water coolant.²⁴ These materials are commonplace at nuclear facilities, and so ^3H remobilisation and leakage during storage is a risk for sites globally.⁴⁷ ^3H is also generated through ternary fission, or through neutron interaction with boric acid dissolved in the coolant/moderator of pressurised water reactors. ^3H exists as tritiated groundwater at nuclear sites,^{2,48} resulting from isotopic exchange between ^3H and $^1\text{H}_2\text{O}$ already present in groundwater.⁴⁰ As a result, the K_d for ^3H is considered to be 0 mL g^{-1} , although slight sorption in sandy soils (K_d range of $0.04-1 \text{ mL g}^{-1}$) has been previously reported.⁴⁹ In some circumstances, where organically-bound tritium (OBT) is the dominant form of ^3H present (e.g. in discharges from radiopharmaceutical facilities), greater retention of ^3H on solid phase materials may be observed.⁵⁰

Key characteristics of each of the above DTMRs are given in Table 1. All of ^{129}I , ^{99}Tc , ^{90}Sr and ^3H emit beta particles,²¹ which can result in health issues for humans if significant quantities build in the body through ingestion or inhalation. For example, thyroid cancers can be caused by both ^{129}I ⁵¹ and ^{99}Tc ⁵² exposure, and skeletal abnormalities can develop as a result of ^{90}Sr incorporation into bones.⁵³ Whilst ^3H does not accumulate in specific parts of the body, the 10 day and 40 day biological half-lives of tritiated water and OBT, respectively, make the radionuclide a potential hazard once inside humans.⁵⁴ Defining the specific risk that DTMRs pose can be complex due to a number of variables, including the exposure pathway to an individual



Table 1 Summary of the radionuclides of focus

	^{129}I	^{99}Tc	^{90}Sr	^3H
Half-life (years) ²¹	15.7 million	211 100	28.91	12.32
Gamma decay energy (keV) [absolute intensity (%)] ²¹	39.6 [7.51]	89.5 [6.5×10^{-4}]	No gamma emitted	No gamma emitted
Oxidation state(s) in groundwater [speciation]	+5 [IO_3^-] ²⁸ −1 [I^-] ²⁸	+7 [TcO_4^-] ²² +4 [typically TcO_2] ³⁸	+2 [Sr(II)] ⁴³	0 [$^3\text{H}^1\text{HO}$] ² 0 [$^3\text{H}_2\text{O}$] ²
Typical K_{ds} (mL g ^{−1})	0.8–7.6 [IO_3^-] ³³ 0–8.1 [I^-] ^{32,33}	0–1 [Tc(VII)] ³² 15–280 [Tc(IV)] ⁴¹	10–25 [quartz-rich] ⁴⁴ ~10 ³ [clays] ⁴⁶	0–1 [all sediment] ⁴⁹

(inhalation, ingestion, skin contact, *etc.*), the body part(s) that come into contact with radiation, the age of the person (children and the elderly may potentially be more affected compared to adults), *etc.*⁵⁵ This has led to differences in the dose limits and risk management guidelines given by regulatory bodies at both national and international levels. Many countries regulate radiation exposure based on IAEA recommendations and WHO guidelines, although the USA is a notable exception to this with the Environmental Protection Agency (EPA), Department of Energy (DOE) and Nuclear Regulatory Commission (NRC) overseeing public and nuclear site worker protection. The limits and recommendations set by these organisations provide clarity on the end-state targets for remediation projects and can also determine the suitability of a particular technology for the clean-up or risk schemes implemented.

3 Current treatment methods

3.1 Pump and treat

Pump and treat (P&T) is the most commonly applied method for *ex situ* groundwater clean-up at nuclear sites.^{56,57} The technique works by pumping groundwater from the subsurface and treating it through adsorption, ion-exchange or chemical (*e.g.* redox) processes (Fig. 1). Decontaminated water can then be discharged at the surface or pumped back into the ground.⁵⁸ The present-day appeal of the technique for site remediators is its proven track record of generally remediating facilities to a desired level.⁵⁹ P&T can be very effective at removing groundwater-mobile elements (*e.g.* Cr(VI))⁶⁰ but is less effective for elements that strongly sorb to sediments (*e.g.* Pu and Am⁶¹). Subsurface permeability can also affect remedial efficiencies, with finer-grained media requiring longer time periods to reach the same clean-up goals as coarser sediment.⁶² This can further complicate remediation in substrates with dual porosities (caused either through materials with differing permeabilities or as a result of a variation between matrix and fracture porosities). The technology also incurs large financial costs during both the initial setup and operation and maintenance phases, making only long-term projects economically viable.

Adsorption is performed by pumping extracted groundwater through a column filled with one or more adsorbent materials such as clay minerals, activated carbon, iron oxides and metal-organic frameworks.^{63,64}

Radionuclides bind to the surface of the adsorbents, whilst groundwater passes through the column. Ion exchange is a similar process, but the adsorbent contains a non-toxic ion,

such as Cl^- ,⁶⁵ that counter-balances the charge of the adsorption sites.⁶⁶ If the radionuclide has a greater electrochemical potential than the starting ion, the two are exchanged and the radionuclide is retained on the adsorbent.

Site-scale iodine remediation through P&T has not been effectively implemented at nuclear facilities, despite ^{129}I plumes being present at sites such as Hanford and SRS.²⁸ Laboratory trials of various materials including Purolite A530E ion exchange resin and granular activated carbon (GAC) were performed at Hanford, with K_{ds} of 78 and 76 mg L^{−1} observed, respectively (in simulated Hanford groundwater containing 1.0 mg L^{−1} IO_3^-).^{67,68} However, none of the tested adsorbents will be efficient enough to decrease the activity below 0.037 Bq L^{−1} (1 pCi L^{−1}; 6 µg L^{−1}) – the USEPA drinking water standard⁶⁷ – before the area's active remediation period ceases in 2047.⁶⁹ The poor ^{129}I uptakes were generally caused by the adsorbents' preference for I^- over IO_3^- , whilst on-site groundwater conditions favour IO_3^- speciation over I^- (77.5% of stable iodine at the site exists as IO_3^- , 19.6% as I^- and 2.6% as org-I).⁶⁷ Due to being only a small percentage of total ^{129}I speciation⁶⁷ and having a variety of potential properties depending on the organic molecules present,⁷⁰ laboratory studies do not focus on determining K_{ds} for org-I for Hanford. As a result of the poor adsorbent uptake capacities, as well as alternative remedial technologies also being ineffective, there is no current strategy for long-term ^{129}I clean-up of the Hanford site.⁷¹ A Technical Impracticability waiver has therefore been drafted for the USEPA.⁷²

Adsorption of technetium, in combination with other contaminants, onto Purolite A532E and DOWEX 21K ion exchange resins is being utilised at the Hanford Site.^{73,74} Groundwater P&T influent streams are pumped into the facility where they are passed through a train of DOWEX columns followed by A532E columns, before being released back into the subsurface.^{73,75} DOWEX was first installed into the P&T system in 2015 and is used primarily for U adsorption.⁷⁵ As a result, despite laboratory K_{ds} measuring 1800–19 800 mg L^{−1} in double deionised water (DDI) containing NO_3^- (90–99% uptake to resin; 0–104 mM NO_3^- ; all with 200 ppb ^{99}Tc) and >19 800 mL g^{−1} in DDI containing SO_4^{2-} (>99% uptake; 0–10 mM SO_4^{2-} ; all with 200 ppb ^{99}Tc),⁷⁴ resin used in the Hanford P&T columns between 2015 and 2017 showed no Tc adsorption.⁷⁵ By contrast, Purolite A532E has been chosen for targeted ^{99}Tc uptake, and is the successor to the A530E resin, a microporous form of the A532E⁷³ which had a 92.1% ^{99}Tc removal efficiency in the Hanford P&T facility in 2020.⁷⁶ No information on A532E Tc



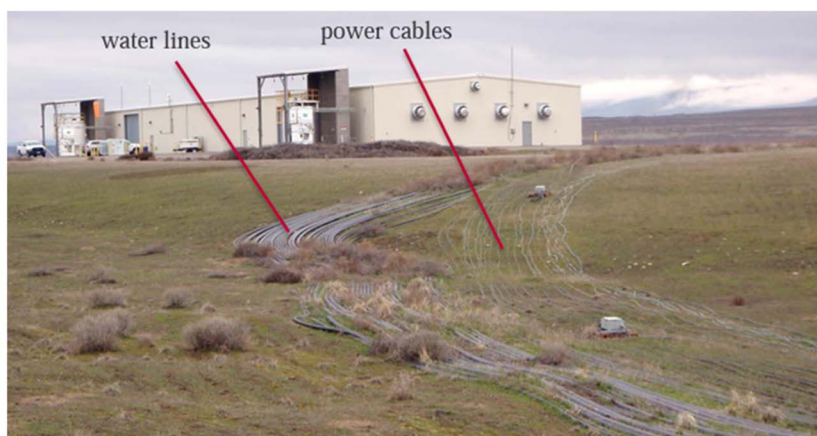
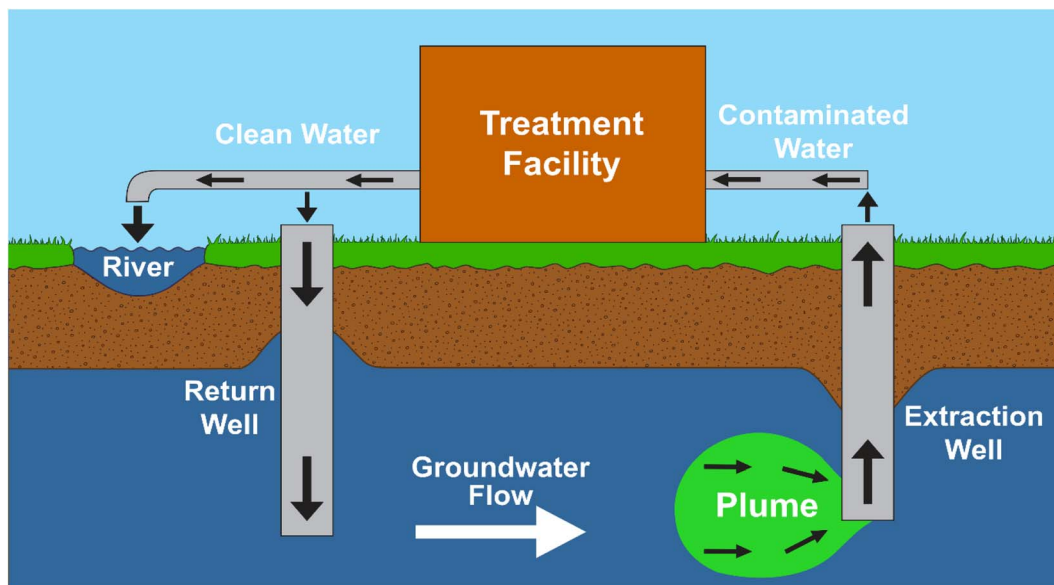


Fig. 1 Top – Diagram illustrating the P&T process. The plume of contaminated groundwater (green) is extracted and treated, before being either pumped back into the subsurface or released as surface waters. Middle – Photo from Mackley *et al.*⁵⁸ showing a typical P&T extraction well at Hanford, with monitoring equipment attached. Bottom – Photo from Mackley *et al.*⁵⁸ showing water pipes and power cables running between a Hanford P&T facility and monitoring wells.

uptakes in the same P&T system could be found, although Saslow and coworkers have recorded K_{ds} of $>19\,800\text{ mL g}^{-1}$ ($>99\%$ resin uptake) in double deionised water containing 200 ppb ^{99}Tc .⁷³ This figure remained constant with NO_3^- and

SO_4^{2-} present at concentrations up to 20 mM and 10 mM, respectively, exceeding the levels seen in P&T influent streams (1.61 and 0.60 mM for NO_3^- and SO_4^{2-} , respectively) between 1st June 2021 and 30th May 2022 (data cited in ref. 73). Whilst this



high degree of ^{99}Tc selectivity shows promise for A532E's application at site scales, there is a need for larger pilot trials to support results of simplified laboratory set ups. As the P&T system continues to operate at Hanford, future work by Saslow and coworkers will look at the performance of both A532E and DOWEX 21K with flowing groundwater, and scale up models to predict the efficacy with varying P&T influent chemistry.

P&T remediation was also attempted for the removal of ^{90}Sr plumes from the Brookhaven Graphite Research Reactor (BGRR), former Pile Fan Sump (PFS) and the Waste Concentration Facility (WCF) areas at Brookhaven National Laboratories (BNL) in 2005.⁷⁷ Although Sr K_d s in the sediment were high enough to indicate that plume migration off site was unlikely, the project was initiated to avoid public concerns over a managed natural attenuation approach.⁷⁸ Maximum pre-treatment ^{90}Sr activities for the BGRR, PFS and WCF plumes were 116.6 Bq L^{-1} (3150 pCi L^{-1} ; recorded in 2003), 20.9 Bq L^{-1} (566 pCi L^{-1} ; recorded in 1997) and 57.7 Bq L^{-1} (1560 pCi L^{-1} ; recorded in 2003), respectively.⁷⁷ By the end of 2021, borehole activities had decreased to 0.47 Bq L^{-1} (12.7 pCi L^{-1}), 0.88 Bq L^{-1} (23.9 pCi L^{-1}) and 1.93 Bq L^{-1} (52.2 pCi L^{-1}) in the BGRR, PFS and WCF – reductions of 99.5%, 96% and 97%, respectively.⁷⁹ The ion exchange resin used, and its respective K_d , have not been disclosed publicly by the site. Plume remediation efforts were assisted by the low mobility of Sr in the sediment, allowing the most contaminated subsurface areas to be easily identified and targeted. However, between 2003 and 2021 the plumes split into multiple smaller entities, possibly as a result of remediation efforts targeting and removing the highest-activity zones which are typically in the middle of plumes, making the residual contamination difficult to track. Further, plumes had migrated underneath buildings which complicated monitoring. As a result, ^{90}Sr activities are anticipated to be higher in certain areas where monitoring wells are not currently set up, although the areal extent of these high-activity regions are thought to have decreased significantly compared to 2004 plume boundaries.⁷⁹ The remediation project aims to reduce ^{90}Sr activities to below the 0.3 Bq L^{-1} (8 pCi L^{-1}) drinking water standard by 2070.

P&T is ineffective for ^3H remediation as the radionuclide can be exchanged with protons in water.^{2,48} Adsorbents and ion exchange resins cannot distinguish between $^1\text{H}_2\text{O}$, $^3\text{H}_2\text{O}$ and $^3\text{H}^1\text{HO}$, rendering P&T unsuitable for ^3H clean-up projects. Despite this, sites such as SRS and Brookhaven have previously attempted to pump tritiated water up-gradient of a plume and keep it in a continuous loop until radioactive decay reduces the activities to acceptable levels.⁸⁰ However, the SRS system was costing \$1 000 000 per month to maintain and, in the process, was potentially mobilising more contamination.⁸⁰ The operations were ceased after 6 years, with approximately \$50 million having been spent on setup and \$100 million on maintenance over their lifetimes.

3.2 Permeable reactive barriers

Permeable Reactive Barriers (PRBs) are a relatively inexpensive, passive and *in situ* remediation method for groundwater. They

consist of a reactive medium that is placed into the subsurface, perpendicular to the direction of groundwater flow (Fig. 2).^{81,82} The reactive medium converts contaminants into an immobile or less harmful form, whilst allowing groundwater to pass through the barrier.^{81,83}

Records of iodine remediation through PRBs at nuclear sites could not be found. This is surprising considering substances such as organic material may appear as good candidates for a low-cost reactive medium. Covalent bonding and complexation of I onto organic material such as humic acid has been observed at bench scale^{84,85} and in field observations at facilities such as Hanford⁸⁶ and SRS.⁵ However, the lack of application is likely due to a poor understanding of interactions between iodine and natural organic matter⁸⁷ in addition to its susceptibility to redox reactions within organic compounds, caused by microorganisms and materials within the subsurface.⁸⁸ Bench-scale experiments performed on organic-rich SRS soil have shown conversion of inorganic I into particulates, colloids and dissolved org-I after a 31 day equilibration period.⁸⁹ This is thought to be caused by the oxidising and reducing capacity for I^- and IO_3^- in the soil, creating reactive intermediates such as I_2 and HOI during the conversion between the iodine +5 and -1 species. These intermediates may subsequently react with organic material before they can be converted back to I^- and IO_3^- . Due to the variety of water solubilities that organic molecules can have, long-term iodine immobilization could be compromised depending on the organic material present, making it an unsuitable adsorbent.

^{99}Tc is amenable to PRB remediation *via* reduction due to the variation in solubility between Tc(VII) (as TcO_4^- ; soluble in water) and Tc(IV) (as TcO_2 ; solid).³⁸ When Tc(VII) in groundwater comes into contact with a suitable reactive barrier, it may be reduced to Tc(IV) which facilitates precipitation, immobilising the Tc and limiting its environmental spread.⁹⁰ Examples of suitable reactive barrier materials include zero-valent iron (ZVI), a cheap, frequently used medium in PRBs.⁹¹ Laboratory experiments on ZVI obtained a K_d of 2700 mL g^{-1} for ^{99}Tc at an initial concentration of 38.2 Bq L^{-1} (1031 pCi L^{-1}).⁹² ZVI adsorbents have been deployed at scale, for example, in two PRBs at the Oak Ridge Site, Tennessee, 1997, to chemically reduce and immobilise Tc.⁹³ In this study the radionuclide was found within the Bear Creek Valley and Upper East Fork Poplar Creek watersheds, both comprising of Maynardville Limestone.⁹⁴ The first PRB, referred to here as 'PRB 1' (for configuration see Fig. 2a), was a 68 m long \times 6–9 m deep section comprising of 80 tonnes of ZVI, and the second, 'PRB 2' (for configuration see Fig. 2b), was a 67 m long \times 8 m deep trench containing 1500 L of ZVI and peat moss.⁹³ Monthly testing over a 3 year period established that the two PRBs reduced Tc levels in groundwater, although final concentrations were not publicly reported. However, precipitation of iron-based minerals decreased permeability in both barriers, reducing the lifespan of PRB 1 to between 15 and 30 years, whilst causing PRB 2 to completely cease operations within an unspecified time period.

A typical setup for a PRB requires infrastructure to contain the reactive medium, with optional features such concrete walls (Fig. 2b) that channel water flow to be added at the site



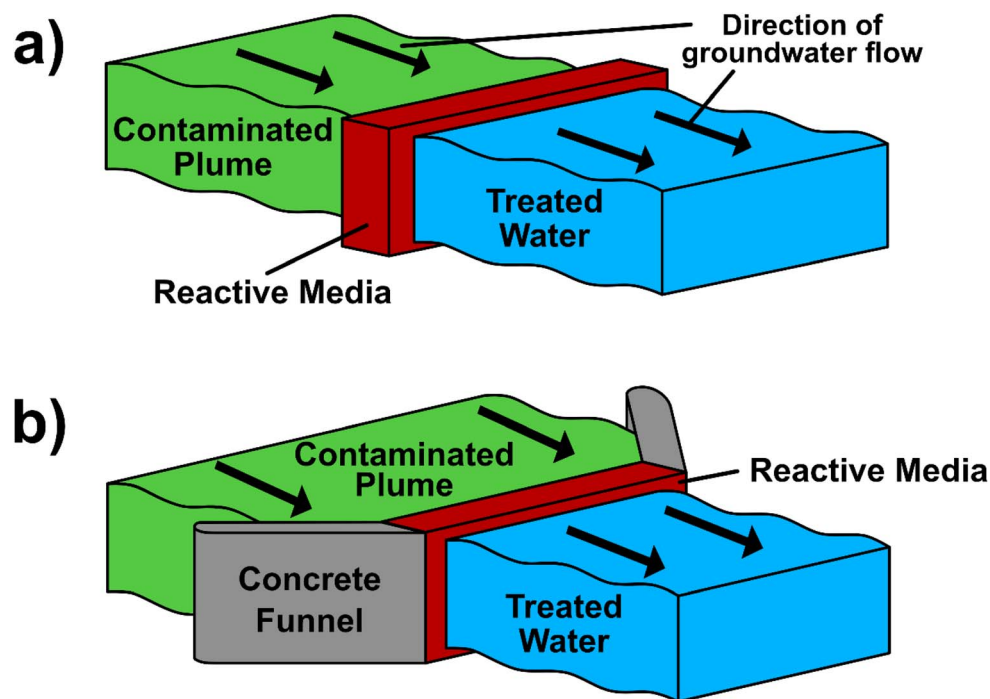


Fig. 2 Top – Diagram illustrating permeable reactive barriers in (a) continuous and (b) funnel and gate configurations at the Oak Ridge Y-12 Site, Tennessee. In both instances, contaminated groundwater passes through a reactive medium, where contaminants are removed, and clean water passes out the other side. Funnel and gate configurations have the addition of concrete barriers to channel groundwater flow. Bottom – Photos from ITRC⁸² showing unsupported (left) and temporary trench box (right) excavation during PRB installation at non-nuclear industrial sites. Reactive media is poured into the hole to complete the PRB.

remediators' discretion. However, a less invasive approach was adopted at the Hanford site to reduce the ^{90}Sr activity reaching the Columbia River.⁹⁵ A solution of Ca, citrate and PO_4^- was added to the groundwater through boreholes,^{96,97} creating a diffuse, continuous calcium phosphate (apatite) barrier that formed *in situ* from a series of discrete points at the surface.⁹⁸ Once formed, Ca in the apatite will substitute with Sr in the plume, as the existence of strontiapatite is more thermodynamically favourable than the initial hydroxyapatite.⁹⁹ Four pilot boreholes were initially injected between 2006 and 2008, with pre-barrier activities ranging from 36.5 Bq L^{-1} to 171.3 Bq L^{-1} (972 pCi L^{-1} to 4630 pCi L^{-1}) ^{90}Sr .⁶ As of 2021, activities within the boreholes have dropped to $4.1\text{--}23.5 \text{ Bq L}^{-1}$ ($111\text{--}635$

pCi L^{-1}) – a decrease of 77–91% compared to the respective pre-barrier maximum ^{90}Sr activities. The variance in reduction efficiencies is likely caused by a variability in the apatite concentrations surrounding the boreholes. To avoid a significant loss of apatite over time, the mineral constituents are reinjected into boreholes with increasing ^{90}Sr activities, allowing specific areas of the barrier to be targeted and rejuvenated without the need to dig up large sections of the barrier. ^3H is not amenable to PRB attenuation for two reasons; the technique is typically limited to redox-sensitive elements that have variable solubilities in groundwaters, and tritiated groundwater is permeable to PRBs.



3.3 Phytoremediation

Phytoremediation is an *in situ*, passive and low-cost method that uses plants (and their associated microorganisms) for remediation over medium- to long-term periods.^{100,101} The technique involves the use of at least one of the following main processes^{102,103} (Fig. 3):

- (1) Phytoextraction – removal of contaminants from soils and shallow groundwaters and accumulating them in above-ground shoots.
- (2) Phytovolatilization – extraction of volatile radionuclides from soils and subsequently releasing them in a gaseous form.

(3) Phytostabilisation – reduction of a contaminant's bioavailability within the subsurface.

(4) Phytofiltration – filtration of contaminants by plant roots or seedlings through adsorption or absorption.

(5) Phytostimulation – removal of contaminants through plant roots and their rhizospheric microorganisms.

(6) Phyto/rhizodegradation – degradation of organic contaminants by plants/rhizospheric microorganisms.

¹²⁹I has been considered as a target contaminant for phytovolatilization, but concerns have been raised over the health risks associated with its bioaccumulation within humans if

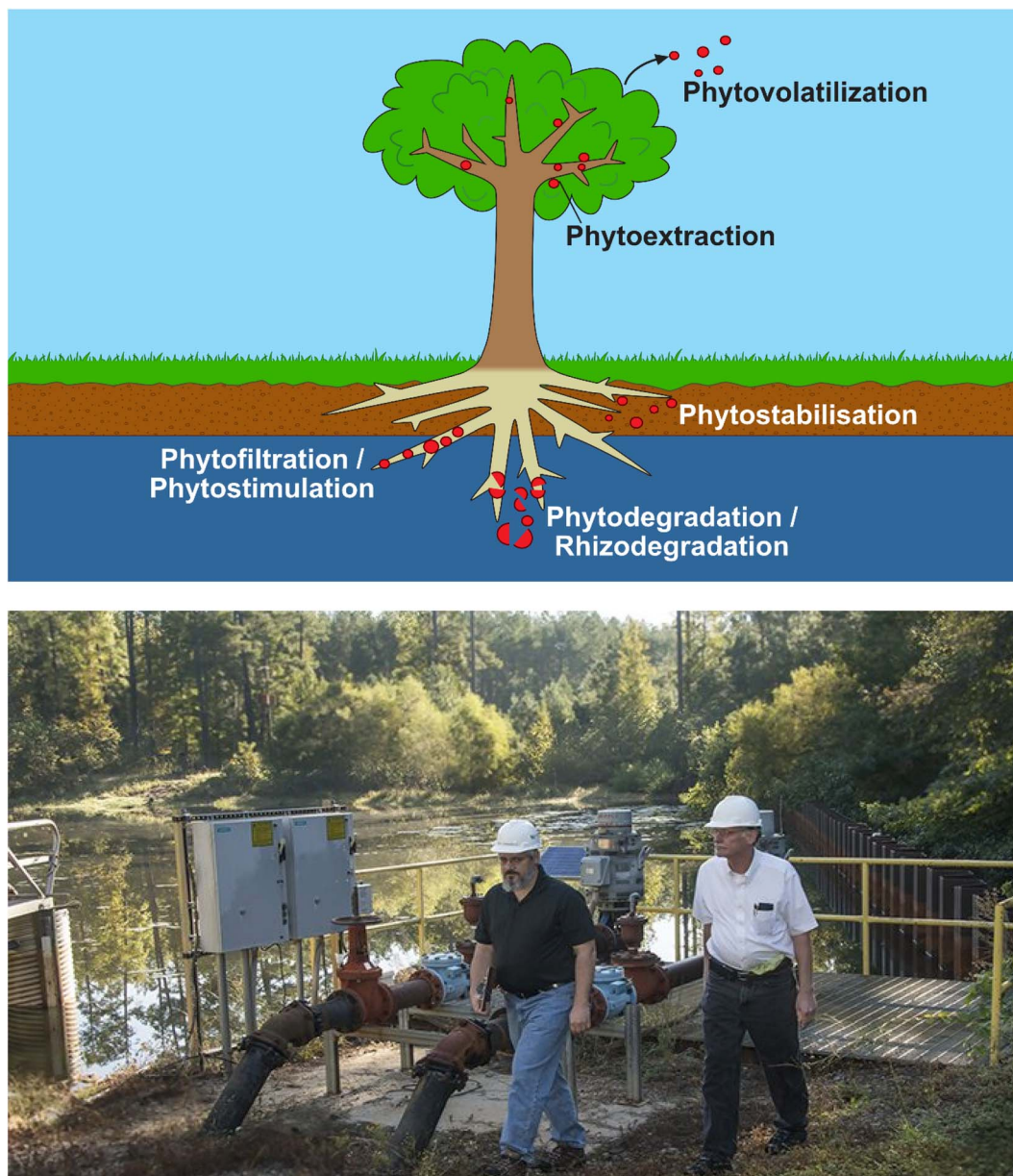


Fig. 3 Top – Sub-processes of phytoremediation, showing phytovolatilization, phytoextraction, rhizofiltration and phytostabilization. ³H is released into the environment through the former-most option, diffusing into the atmosphere through leaves rather than being expelled by the roots. Bottom – Photo from DOE¹¹² showing Savannah River Nuclear Solutions engineers examining pumping equipment next to the ³H-contaminated groundwater storage pond. Water is pumped from the pond and used to irrigate the surrounding woodland, where evaporation and phytovolatilization release ³H into the atmosphere.



over recent decades. These technologies have been used less extensively than those previously mentioned but could provide an alternative, viable, approach if more traditional remediation strategies are deemed unsuitable for a given scenario.

4.1 Bioimmobilization

Bioimmobilization involves the use of bacteria or plants to decrease the water solubility of aqueous contaminants through changes in oxidation state and therefore promoting precipitation of solid phases.^{114,115} The process can be performed either through the introduction of new organisms to an area or by promoting the growth of organisms already present in the target environment.^{114,116} Field-scale, *in situ* bioimmobilization of ⁹⁹Tc was conducted at the Oak Ridge site by Istok and coworkers in 2004.¹¹⁴ It was suggested that chemical reduction of radionuclides including Tc could be performed by microbial colonies already present within facility sediments. Although the microorganisms required for this are apparently present within the subsurface,¹¹⁷ factors such as competing electron acceptors (*e.g.* NO₃⁻) and numbers of microbial colonies within the sediments limit the efficiency of Tc reduction.¹¹⁸ Further, reducing conditions are required within the subsurface, both for promoting the growth of metal-reducing bacteria (*e.g. Geobacter*) and for maintaining Tc in its insoluble 4+ oxidation state.¹¹⁴ These anaerobic conditions can be generated by the addition of electron donors into a system, allowing bacteria to reduce NO₃⁻ and, subsequently, metals for respiration in the absence of O₂. In this field trial, single-well, push-pull tests were used to inject multiple rounds of ethanol (acting as an electron donor) into a shallow aquifer to monitor ⁹⁹Tc reduction. All results were corrected to account for the Tc dilution that occurred when the clean test solution mixed with contaminated borehole groundwater. Initial tests showed that Tc(VII) could not be reduced when NO₃⁻ was present, as microorganisms would preferentially reduce NO₃⁻ during respiration. However, the first ethanol injection resulted in Tc(VII) concentrations reducing from ~13 200 pM to ~5800 pM (56.1% reduction) within 400 hours and to ~3700 pM (72.0% reduction) within 600 hours. In comparison, NO₃⁻ concentrations dropped from ~140 mM to ~40 mM (71.4% reduction) within 400 hours and ~25 mM (82.1% reduction) by 600 hours. Multiple injections were performed into the same borehole over several months, with the seventh ethanol injection causing a Tc(VII) reduction from ~12 000 pM to ~1000 pM (91.7% reduction) within 400 hours, although no further data were collected after this time period. Concurrently, the initial ~125 mM of NO₃⁻ dropped to negligible levels (~100% reduction) after ~35 hours and stayed constant for the following ~365 hours. After the seven biostimulating ethanol injections, a test solution was created without the electron donor, and inserted into the borehole. The absence of ethanol had no negative effect on Tc(VII) reduction, with concentrations decreasing from ~11 000 pM to ~1000 pM (90.9% reduction) within 400 hours and remaining constant for up to 500 hours post-injection. Initial NO₃⁻ concentrations of ~120 mM dropped to ~70 mM (41.7% reduction) within 400 hours and ~35 mM (70.8% reduction) by 600 hours. These experiments

4 Emerging treatment methods

In efforts to produce more effective and sustainable remediation, additional techniques have been applied at nuclear sites

show that *in situ* ^{99}Tc reduction is possible when NO_3^- is simultaneously consumed through bacterial denitrification; promoted *via* the use of cheap electron donors such as ethanol. Despite this, there does not appear to have been further work on this at site scales. In addition, pilot-scale bioimmobilization studies for ^{129}I , ^{90}Sr and ^3H could not be found. In addition to the reasons given for their unsuitability regarding phytoremediation (see Section 3.3) the absence of ^{129}I , ^{90}Sr and ^3H studies is likely because the dominant chemical species present in water for ^{129}I (5+ and 1-) and ^{90}Sr (2+) are all highly soluble and would therefore have further requisites for immobilization to occur (adsorption sites, reactive media, *etc.*), whilst tritiated water would not be immobilised as it cannot be distinguished from light water with this technique.

4.2 Chemical/colloid injection

Injection is the process of inserting a material into the subsurface that can either manipulate the oxidation states of pollutants to promote their precipitation, or provide active sites for contaminants to adsorb onto.¹¹⁹ The injected material can be chosen to remove multiple compounds simultaneously, such as variants of zeolites that can treat heavy metals,¹²⁰ or to target specific contaminants, such as Savannah River Site's project for multiple submicron AgCl injections to treat a migrating ^{129}I plume.¹²¹ AgCl was intruded into the subsurface as it can react with this radionuclide to form Ag^{129}I , which is insoluble in water and, thus, is immobilised and retained within the aquifer.¹²² The first set of injections occurred throughout 2011, in 7 temporary boreholes that were distributed in an approximately semi-circular shape with a diameter of ~ 70 m. Only the well closest to the injection sites showed a definitive ^{129}I decrease after treatment. Activities for this well between October 2009 and October 2011 averaged at 5.0 Bq L^{-1} (135 pCi L^{-1}), but decreased to 2.9 Bq L^{-1} (77 pCi L^{-1}) shortly before the injections.¹²¹ Measurements of $1.7\text{--}2.6 \text{ Bq L}^{-1}$ ($46\text{--}70 \text{ pCi L}^{-1}$) were recorded in the first 6 months, before a sharp increase to 3.7 Bq L^{-1} (99 pCi L^{-1}) in the 7th month. A range of 2.9 to 4.0 Bq L^{-1} (79 to 109 pCi L^{-1}) was reported for the remaining 5 months of monitoring. All other wells, which were further away from the injection boreholes, show ambiguous or no evidence of ^{129}I activity reductions, suggesting that remediation is only effective within close proximity to the injection sites. Ag migration data indicated limited particle movement after subsurface deposition. Of the total AgCl solution volume that was permitted to be injected in 2011, only half was used. As a result, the remaining volume was used in 2015 to boost the project's long-term efficiency.¹²² 7 new boreholes were used to concentrate the AgCl barrier to the east of the original wells, with the 2015 group spaced across ~ 35 m. It was reported that 5 of the 7 wells had ^{129}I decreases between 25% and 65% and one well upgradient of the barrier detected no change, with the final borehole not discussed.^{122,123} However, activities for each of the wells were not provided in these reports, and other possible sources for raw borehole data are not publicly available, meaning the percentage reductions given here could not be independently verified. Given the apparent success of both 2011 and 2015

injections, a third round was approved in 2018 and performed in 2019.¹²³ The insertion site distribution consisted of 15 wells with a broadly linear configuration spanning ~ 35 m, aligned perpendicular to groundwater flow. This was based on the $1.2\text{--}2.4$ m AgCl diffusion radius that formed around previous boreholes, allowing the formation of a single, continuous zone in the subsurface¹²² comparable to Hanford's ^{90}Sr permeable treatment barrier (see Section 3.2). Results from the most recent injections will be disclosed in the site's 2022 Corrective Action Report.¹²³ Subsurface AgCl insertion will continue until 2040, when the area will transition to natural monitored attenuation.¹¹⁰ However, whilst this technique shows promise at SRS, applications on other nuclear sites may not be feasible due to the toxic nature of Ag,⁸⁸ and so careful consideration and planning must be taken to avoid adverse consequences on the ecology and surrounding environments of nuclear facilities.

4.3 Combined electrolysis catalytic exchange

Combined Electrolysis Catalytic Exchange (CECE) is a ^3H remediation technique for detritiating effluent and groundwaters.¹²⁴ Contaminated feed water is pumped into a containment cell and electrolysed, converting liquid H_2O into H_2 and O_2 gases. The energy required to electrolyse tritiated water is greater than that required for light water, meaning that ^3H will concentrate in the remaining feed solution whilst light water is driven off. Deionised water is also added to the system to recapture any ^3H that is electrolysed, as the radionuclide will preferentially exist as liquid H_2O over gaseous H_2 .¹²⁵ Pilot-scale trials have shown high detritiation factors *e.g.* >100 ;¹²⁶ 1000 when used with heavy water – a more difficult separation than with light water.¹²⁷ However, the system is expensive to operate and at present is not able to remediate large volumes of water, making it unsuitable for processing large water flows or volumes with relatively low ^3H activities.¹²⁶ The application of CECE has been evaluated for ^3H contaminated groundwater at the Fukushima site (known as ALPS-treated water) but, due to the high cost and small treatment volumes, the technology was deemed unsuitable for ^3H remediation¹²⁶ and these waters will instead be discharged to sea.¹²⁸ For similar reasons, the 2022 Hanford ^3H wastewater treatment review determined that whilst the Modular Detritiation System® (a commercialised version of the CECE process) shows promise for effective ^3H removal in the future, the modifications required for use with large volumes of liquid make it currently infeasible for on-site application with groundwaters.¹²⁹

5 Comparison of main techniques

The “tried and tested” attitude towards P&T at nuclear sites makes it appealing for site remediators. Many government-funded remediation projects are ultimately paid for by the taxpayer, who want cheap and effective technologies that optimise project efficiencies. The financial, and potentially political, consequences of a technique that is ineffective or that mobilises additional contaminants could be high, often make P&T the most attractive option. In addition, the technique allows for



convenient testing of groundwater before discharge, ensuring that remediation targets are always being met. However, P&T can be expensive to operate due to the infrastructure required for an *ex situ* technique. This was highlighted in a 2001 study on 32 United States Environmental Protection Agency (USEPA) P&T sites in North America, where the average capital and yearly operational costs were \$4 900 000 and \$770 000, respectively at 2001 prices.¹³⁰ Site selection criteria included the presence of a full-scale remediation system and operator reports on aquifer clean-up targets and technology costings. Although the technique is expensive, the total cost for each project will depend on the price per unit of reactive medium as well as the frequency at which the medium needs to be replaced. Further, multiple types of reactive media may be required if different contaminants are to be treated simultaneously, further increasing operational costs, but this can reduce the remediation timeframe in comparison to using a single, less selective medium that removes a lower proportion of radionuclides in favour of competing ions such as HCO_3^- , NO_3^- etc.

The passive nature of PRBs offers benefits over P&T including a decrease in the number of staff required for daily operation, lowering the long-term function and maintenance costs, and minimal infrastructure, which reduces initial costs. 15 USEPA facilities in North America and an additional site in Northern Ireland were also examined in the EPA¹³⁰ P&T study, and their costings compared. The selection criteria for the survey required a full-scale system with capital costs provided, although annual maintenance costs were a necessity as only 2 of the sites had been operating long enough for accurate prices to be determined. The average capital costs for the 16 PRB sites was \$730 000 – more than 6 times cheaper than the average P&T capital costs, as determined by the same study. Annual operational and maintenance costs of \$78 000 and \$120 000 were recorded for the US National Coast Guard Support Centre (North Carolina) and the Intersil (California) sites. Although the lack of case studies reduces the certainty as to whether these costs are truly reflective of PRB projects, both available examples are ~7 times lower than the \$770 000 equivalent for P&T. From this study, PRBs appear to be a much cheaper alternative to P&T but multiple factors can influence the final cost, including the price of the reactive medium and the lifetimes of both the barrier and the wider remediation project. PRB placement is important for financial and remedial success, as the technique can only remediate groundwater that passes through it, making it unsuitable for contamination spread over large areas. Consequently, the decision as to whether a PRB or P&T is the best remediation approach will be highly site-specific. An updated version of a cost comparison report for different remediation techniques could not be found. Further, no list of remediation techniques deployed specifically at nuclear sites could be obtained, and only one site in the EPA report included radionuclide clean-up (Oak Ridge Site, Tennessee (see Section 4); capital costs of \$900 000). This highlights the absence of financial data available to site operators when designing remedial strategies and demonstrates the need for readily accessible information to promote more sustainable options in the nuclear industry.

The primary appeal to phytoremediation is its passive nature, although active enhancements such as the SRS irrigation system can boost the removal efficiency (and may be necessary in some cases to allow plant establishment and growth). A direct result of passive techniques are the relatively low costs compared to conventional pump and treat methods. For example, implementation of the irrigation system at the SRS came at an initial cost of \$5 000 000, with an additional \$500 000 needed per year.⁸⁰ In comparison, the average set up cost for 32 American P&T sites was \$4 900 000, followed by \$770 000 per annum. Although these figures are similar, phytoremediation without an irrigation system would drastically reduce the overall cost and make the technique much more financially favourable. Additional, unique benefits can come from phytoremediation projects, including greater protection from flooding, improved site aesthetics and supporting or reintroducing native plant and animal species to the local area.¹³¹ However, the depth at which remediation can occur is limited to the depth of plant roots, only making it a suitable alternative to P&T in shallow groundwaters. The same constraint applies to areal extent, meaning that large areas of contaminated land would require large numbers of plants for remediation to be effective. The long-term chemical and physical forms of targeted radionuclides must be understood before implementation, as processes such as phytovolatilization may mobilise contaminants that pose a greater risk to wildlife and humans in air than when retained within sediments (or within the subsurface). Further, phytoremediation is only able to extract radionuclides that are taken up by the plants' roots, resulting in contaminants with lower bioavailabilities remaining in the subsurface. In comparison, P&T can extract any radionuclides that are mobile in groundwater regardless of their bioavailability, takes up less space at a site and extracts groundwater from any depth, although higher costs may be associated with deeper extraction wells.

Both phytoremediation and PRBs had a range of field-scale pilot projects performed in the late 1990s and early 2000s,^{48,93,132} likely as a result of the globally increasing costs and tightening of restrictions associated with the 'dig and dump' approach to contaminated materials.¹³³ Although each technique on its own is unlikely to be used in favour of P&T for simultaneous treatment of all DTMRs discussed here, a combination of these more sustainable methods may be superior to conventional remediation; for example, phytovolatilization and PRBs could be used to remove ^{99}Tc , ^{90}Sr and ^3H with minimal upkeep and maintenance. However, limitations of these practices, such as the area of land available and radionuclide selectivity of each technique, make this unsuitable for groundwater application on the majority of nuclear sites. This highlights the need for new techniques that can be used in combination with PRBs and phytoremediation to enhance the number of DTMRs that can be remediated in a sustainable way. Emerging *in situ* technologies under active development for DTMRs include electrokinetic remediation¹³⁴ and silica grouting,¹³⁵ although further work is needed to show efficacy for both DTMRs and for field-scale application.



6 Conclusions

In line with the growing demand for sustainable remediation at nuclear sites, we have reported on techniques for the removal of DTMRs from groundwaters. Whilst a variety of possible remediation techniques exist for ^{129}I , ^{99}Tc , ^{90}Sr and ^3H , the differing physical and chemical properties of these DTMRs result in a need for site-specific implementations. P&T is, by far, the most commonly applied technique and can effectively remediate ^{99}Tc and ^{90}Sr . However, ^{129}I and ^3H cannot be treated by this method, as current adsorbents are not capable of effective ^{129}I uptake, and $^3\text{H}_2\text{O}$ and $^3\text{H}^1\text{HO}$ are not differentiable from groundwater H_2O . *In situ* techniques can also be applied for remediation, although their application should be evaluated to determine their suitability on a site-by-site basis. PRBs (including colloidal or chemical injection systems, such as that applied at the Hanford site for ^{90}Sr) can be a more financially favourable technology in comparison to P&T due to the minimal infrastructure required but offer fewer advantages for less sensitive radionuclides and depend upon the selection of an appropriate reactive media. Phytoremediation is a low-cost method for ^3H removal and offers secondary environmental and social benefits but operates over long timescales and is not suitable for elements with low bioavailabilities (^{99}Tc) or where bioaccumulation presents a risk to humans (^{129}I).

Of the examined technologies, none are effective at removing all of ^{129}I , ^{99}Tc , ^{90}Sr and ^3H . This highlights the need for simultaneous growth in research areas looking at improving the efficiency of current techniques, enhancing the development of “treatment train” approaches (potentially including natural attenuation for shorter-lived DTMRs), and continued progression of emerging technologies to minimise scenarios where no remediation strategies are appropriate. Alternative techniques such as electrokinetic remediation and silica grouting are being developed but their application towards DTMRs (with the exception of $^{90}\text{Sr}^{134,136}$) remains unreported, particularly at larger (field or field pilot) scale. The need for advancement in this area is clear but current progress is hindered due to the difficulty associated with measuring DTMRs *in situ*. Although rapid screening techniques for these radionuclides is a developing area (e.g. studies by Hou,¹³⁷ Warwick *et al.*¹³⁸ and Zaffora *et al.*¹³⁹), a co-evolution with the advancement of remediation technologies would help to optimise both research fields. If this were to occur, site operators would be able to make better-informed decisions on remediation strategies using real-time, high-resolution plume data, leading to more intelligent groundwater clean-up. This synergy would greatly benefit the capability of remedial projects globally, consequently reducing the financial burden for nuclear sites and governments as more effective action can be taken to ensure that thorough and comprehensive DTMR removal occurs.

Conflicts of interest

There are no conflicts to declare.

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