Remediation Techniques for Radioactive Contaminated Land on Nuclear Licensed Sites

Regulatory Research Register Project RRR-052

[redacted]

Prepared For: Office for Nuclear Regulation (ONR)

Date: 29 July 2020
Report Reference: R2043
Version Number: Issue 1
Client Contract Reference: ONR/T3476

Add value.
Inspire trust.

Contact: [redacted]
TÜV SÜD – Nuclear Technologies Division
[redacted]

Registered in Scotland No. SC215164
Napier Building, Scottish Enterprise
Technology Park, East Kilbride,
Glasgow, G75 0QF

TUV SUD Limited
CEO: Chris Guy

Phone: +44 (0) 1925 816996
www.tuv-sud.co.uk/nuclear

TUV SUD Limited
Nuclear Technologies Division
Chadwick House, Birchwood,
Warrington, WA3 6AE

Verification Sheet

Document Title	Remediation Techniques for Radioactive Contaminated Land on Nuclear Licensed Sites
Document Number	NT/7225002059/R2043 Issue 1
Client	Office for Nuclear Regulation (ONR)
Project Title	Provision of Phase 2 of ONR-RRR-052 – Delivery of a guidance document on remediation techniques for radioactively contaminated land on nuclear licensed sites

	Signature	Name	Date
Prepared	[redacted]	[redacted]	29/07/20
Verified	[redacted]	[redacted]	29/07/20
Approved	[redacted]	[redacted]	29/07/20
Client Approved	[redacted]	[redacted]	29/07/20

Verification Statement

This document has been internally verified and approved by Nuclear Technologies prior to issue to the client. The scope of the verification was to confirm that:

- The document has been verified and approved by SQEP personnel
- The modelling/calculations performed are accurate and correct
- The references are approved
- The document is internally self-consistent

Disclaimer

The information in this document is the property of TÜV SÜD and may not be used for any purpose other than for which it is supplied without the express written consent of TÜV SÜD - Nuclear Technologies Division.

DOCUMENT ISSUE/AMENDMENT SHEET

Issue No.	Date	Description of changes
Draft A	05/02/20	Working draft (A) issued to Client ahead of peer review workshop.
Draft B	10/02/20	Working draft (B) addressing Client comments for workshop distribution
Draft C	03/04/20	Working draft (C) incorporating comments from workshop attendees
Issue 1	29/07/20	First issue incorporating final comments from Client

SUMMARY

The Office for Nuclear Regulation (ONR) has vires for regulating radioactively contaminated land on nuclear sites in Great Britain (GB) under the Nuclear Installations Act 1965 (NIA 65) and the Energy Act 2013. In order to help inform its regulatory judgements and decisions relating to the remediation of radioactively contaminated land on nuclear licensed sites, ONR has instigated a regulatory research project to develop guidance in this area.

This Regulatory Research Register Project, RRR-052, has been undertaken by TÜV SÜD – Nuclear Technologies Division (NT) on behalf of the ONR. It aims to provide a comprehensive guide to ONR Inspectors on the remediation techniques for radioactively contaminated land currently available for use in the GB nuclear industry. It includes information on the effectiveness and applicability of these techniques with a focus on the factors that need to be considered when selecting them.

This project does not to identify the 'best' remediation techniques for use in the GB nuclear industry, but rather is a guide for use by ONR Inspectors to inform them of the remediation techniques available, and the considerations that need to be taken into account by the licensee or duty holder when selecting the appropriate remediation technique. It is important to note that remediation is more than just the physical work; it encompasses a range of management, programming, and stakeholder engagement etc, aspects that are just as vital. However, the focus here is on the selection of remediation techniques, although some guidance on broader aspects is provided.

The purpose of this guidance is to inform ONR Inspectors on remediation techniques that may be practicable in a GB nuclear site license context, and the considerations that need to be taken into account by the licensee when selecting the appropriate remediation technique. Information is provided on:

- Regulatory and industry guidance for Land Quality Management (LQM);
- Approaches to technical selection of remediation approaches;
- Example remediation approaches; and,
- Learning from industry.

Site Inspectors are also advised to ensure that they are familiar with the LQM training modules within 'N38 - ONR Regulation of Radioactive Waste and Decommissioning'.

ABBREVIATIONS

ALARA	As Low As Reasonably Achievable
ALARP	As Low As Reasonably Practicable
APL	Active Pollutant Linkage
BAT	Best Available Techniques
BPM	Best Practicable Means
C&M	Care and Maintenance
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980
CIRIA	Construction Industry Research and Information Association
CL:AIRE	Contaminated Land: Applications in Real Environments
CLDP	Contaminated Land Developed Principles
CM	Conceptual Model
CNSS	Civil Nuclear Security and Safeguards
Cs-134	Caesium-134
Cs-137	Caesium-137
CSM	Conceptual Site Model
DQRA	Detailed Quantitative Risk Assessment
EGLM	Expert Group on Legacy Management
EPA	Environmental Protection Agency
EPR 16	Environmental Permitting (England and Wales) Regulations 2016
FRTR	Federal Remediation Technologies Roundtable
FSC	Final Site Clearance
GB	Great Britain
GPG	Good Practice Guidance
GQRA	Generic Quantitative Risk Assessment
GRR	Management of radioactive waste from decommissioning of nuclear sites: Guidance on Requirements for Release from Radioactive Substance Regulation
HRGS	High Resolution Gamma Spectrometry
HSE	Health and Safety Executive
HSWA	Health and Safety at Work (etc) Act 1974
IAEA	International Atomic Energy Agency
IC	Intelligent Customer
LA-LLW	Low Activity Low Level Waste
LCRM	Land Contamination Risk Management
LLW	Low Level Waste
LQF	Land Quality File
LQM	Land Quality Management
LQMP	Land Quality Management Plan
MADA	Multi-Attribute Decision Analysis
NDA	Nuclear Decommissioning Authority
NIA	Nuclear Installations Act
NISDF	Nuclear Industry Sector Directors Forum
NEA	Nuclear Energy Agency
NGO	Non-governmental Organisations

NICOLE	Network for Industrially Contaminated Land in Europe
NORM	Naturally Occurring Radioactive Material
NT	TÜV SÜD - Nuclear Technologies Division
OA	Options Appraisal
OECD	Organisation for Economic Co-operation and Development
ONR	Office for Nuclear Regulation
PRA	Preliminary Risk Assessment
RA	Risk Assessment
RAEP	Redundant Active Effluent Pipeline
RATDS	Remedial Action Technology Data Sheets
REPS	RSR Environmental Principles
RL	Radioactively Contaminated Land
RPL	Relevant Pollutant Linkages
RS	Remediation Strategy
RSR	Radioactive Substances Regulation
RTP	Remediation Technique Profile
SAFEGROUNDS	SAFety and Environmental Guidance for the Remediation of contaminated land on UK Nuclear and Defence Sites
SAPs	Safety Assessment Principles
SARA	Superfund Amendments and Reauthorization Act of 1986
SNIFFER	Scotland and Northern Ireland Forum For Environmental Research
SFAIRP	So Far As Is Reasonably Practicable
S-P-R	Source-Pathway-Receptor
SQEP	Suitably Qualified and Experienced Person
STFC	Science and Technologies Facilities Council
SuRF-UK	Sustainable Remediation Forum UK
SWESC	Site-Wide Environmental Safety Case
TAG	Nuclear Safety Technical Assessment Guide
TNT	Trinitrotoluene
UKAEA	United Kingdom Atomic Energy Authority
WMP	Waste Management Plan

CONTENTS

1 INTRODUCTION

The Office for Nuclear Regulation (ONR) has vires for regulating radioactively contaminated land on nuclear sites in Great Britain (GB) under the Nuclear Installations Act 1965 (NIA 65) and the Energy Act 2013. In order to help inform its regulatory judgements and decisions relating to the remediation of radioactively contaminated land on nuclear licensed sites, ONR has instigated a regulatory research project to develop guidance in this area.

This Regulatory Research Register Project, RRR-052, has been undertaken by TÜV SÜD – Nuclear Technologies Division (NT) on behalf of the ONR. It aims to provide a comprehensive guide to ONR Inspectors on the remediation techniques for radioactively contaminated land currently available for use in the GB nuclear industry. It includes information on the effectiveness and applicability of these techniques with a focus on the factors that need to be considered when selecting them.

The International Atomic Energy Agency (IAEA) [1] defines remediation as "*Any measures that may be carried out to reduce the radiation exposure due to existing contamination of land areas through actions applied to the contamination itself (the source) or to the exposure pathways to humans*". It then goes on to note that "*Decommissioning can entail activities that are similar to remediation (also an authorised process), such as removal of contaminated soil from an area within the authorised boundary of a facility, but in this case, such removals are normally referred to as clean-up activities and are typically performed under the authorisation for decommissioning*". For the purpose of this guidance, the terms 'remediation' and 'clean-up' are considered to be synonymous and for consistency with other GB regulation and guidance, the term remediation is used.

This project does not aim to identify the 'best' remediation techniques for use in the GB nuclear industry, but rather as a guide for use by ONR Inspectors to inform them of the remediation techniques available, and the considerations that need to be taken into account by the licensee or duty holder when selecting the appropriate remediation technique. It is important to note that remediation is more than just the physical work; it encompasses a range of management, programming, and stakeholder engagement etc, aspects that are just as vital. However, the focus here is on the selection of remediation techniques, although some guidance on broader aspects is provided.

The guidance is focused on remediation techniques for radioactively contaminated land. However, it is acknowledged that there can be a mix of radioactive and non-radioactive contamination on a site and this is discussed as well.

Production of this guidance has involved engagement of duty holders and the environmental regulators, in addition to the ONR, through a workshop held in February 2020 and through seeking document review feedback from a range of stakeholders. The organisations that have been engaged in the development of this guidance are listed in Appendix A.

ONR provide further internal guidance to their inspectors via Land Quality Management (LQM) training modules, therefore, it is advised that readers also refer to 'N38 - ONR Regulation of Radioactive Waste and Decommissioning' which *"aims to provide delegates with an understanding of the key principles of radioactive waste management and decommissioning from a regulatory perspective".* This includes *"the regulation of LQM on nuclear licensed sites and covers ONR's expectations and regulatory responsibilities for LQM, and the legal basis for enforcing LQM".*

1.1 BACKGROUND

The GB nuclear sector (new build, operational and decommissioning) encompasses civil nuclear and defence related sites (nuclear deterrent). For the purpose of this guidance, 'nuclear' is defined as those facilities and operators that are regulated by the ONR relative to the Nuclear Installations Act 1965 and the Energy Act 2013.

The nuclear industry can be broadly categorised into nuclear fuel production and reprocessing; research establishments; nuclear power stations; defence establishments; radiochemical production; and waste disposal / management sites. Across Scotland, Wales and England, the ONR currently regulates 36 licensed nuclear sites.

The GB nuclear history started in the 1930s with nuclear fission experiments; test reactor build started in the 1940s, and the world's first commercial nuclear power station was opened in 1956 at Calder Hall near Sellafield, West Cumbria. Most of the GB nuclear sites in existence have a history of nuclear operations over many decades and in some instances of the order of 80-years. Some sites were also repurposed from other older industrial activities, including defence related operations.

Operational and previous uses, including unplanned incidents can lead to a range of land quality issues. These can include radioactive contamination of the surface of the ground, in the ground and in groundwater. Here 'ground' is taken to mean natural and made ground and can include on-ground or in-ground structures such as slabs and pipes etc. 'Groundwater' is taken to be water present in soils or underlying rock, whether or not it can yield a usable quantity of water (whether for drinking, irrigation, or process water etc).

In addition to radioactive contaminants, polluting or hazardous chemical contaminants may be co-located, such as elevated concentrations of metals, hydrocarbons and chlorinated solvents etc. Other hazardous substances may also be present, such as asbestos. Note that non-radioactive contamination is regulated by the environment agencies, not the ONR. The condition of the ground considering different radionuclide and hazardous and polluting substances is known as land quality, and management of this is known as land quality management (LQM). Management activities can include remediation of ground (including features in the ground, such as drains) and/or groundwater[1].

Operators should have arrangements in place to prevent the contamination of land and groundwater (e.g. Site Licence condition 34). Where contamination has already occurred, arrangements should be in place to remediate the contamination, whether on or arising from the nuclear licensed site. Potential remediation approaches are discussed in this document.

1.2 PURPOSE AND SCOPE

The purpose of this guidance is to inform ONR Inspectors on remediation techniques that may be practicable in a GB nuclear site license context, and the considerations that need to be taken into account by the licensee when selecting the appropriate remediation technique. It also aims to support higher-level regulatory documents such as the ONR Safety Assessment Principles (SAPs) for nuclear facilities [2] specifically in relation to the safe management of radioactively contaminated land ('RL') on nuclear licensed sites and also the ONR Nuclear Safety Technical Assessment Guide (TAG) on 'Land Quality Management' [3]. The guidance is focused on those facilities and duty holders that operate under the NIA 65 and the Energy Act 2013 and relates to 'day-to-day' operations. Emergency response and post-accident activities are outside the scope of this guidance. Equally, the work does not consider 'radioactive contaminated land' as designated as a 'special site' under Part 2A of the Environmental Protection Act 1990, as this regime does not apply on nuclear licensed sites. As noted, this guidance relates to remediation techniques, it does not cover site investigation aspects such as characterisation of contamination. Equally, it does not consider the decision-making process or regulatory requirements that may lead to the requirement for remediation being identified.

The scope of this guidance in the overall remediation programme is illustrated in Figure 1. Figure 1 is based upon the process of managing land contamination as set out in CLR11 [4], where the solid red line shows the focus of this guidance document and the dotted line indicates where following steps of the process are discussed to place the identification of feasible remediation options into context. It is noted here that, at the time of writing, CLR11 has been placed into archive and will be formally withdrawn during 2020 to be replaced by Land Contamination Risk Management (LCRM) [5] which is discussed further in Appendix B and is available to access at https://www.gov.uk/guidance/land-contamination-how-to-manage-the-risks. Figure 1 Contains public sector information licensed under the Open Government Licence v3.0. http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/.

The focus of this work is on radioactive contamination of the surface of the ground, in the ground and in groundwater; however, some reference is given to addressing other polluting or hazardous substances for situations where mixed contamination may be found.

The scope of the work incorporates minor in-ground features, for instance drainage systems that are considered in a LQM context. The work does not consider management needs of major below ground structures that are more likely to be considered in a facility decommissioning programme.

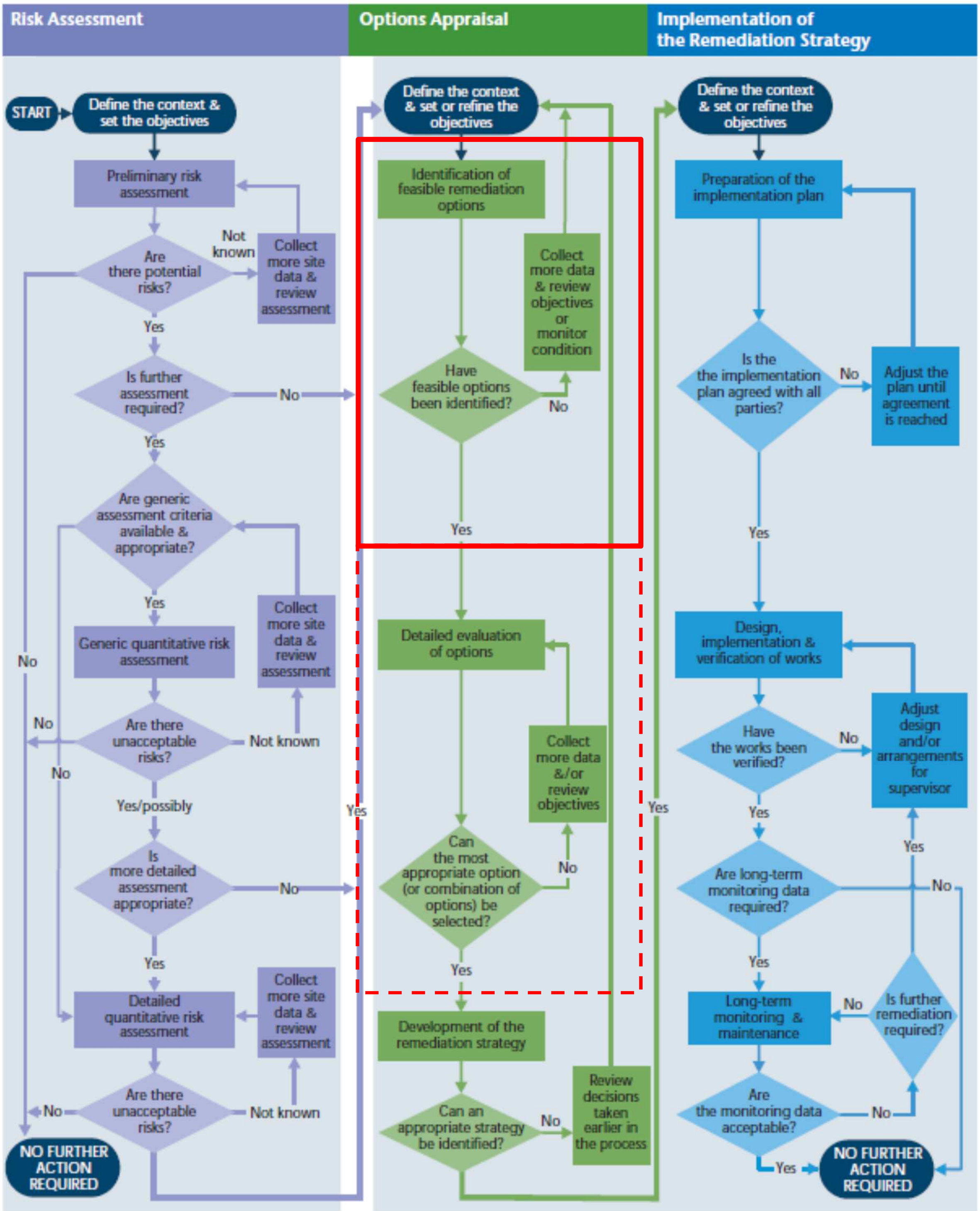
This work is not meant to be definitive, rather to provide a guide on factors to be considered and outline discussions are provided along with signposts to sources of more detailed information. It is also noted that the UK Government has consulted on proposals to improve the legal framework for the regulation of nuclear sites in the final stages of decommissioning & clean-up. One of these proposals would be to introduce an additional route to end the licensee's period of responsibility if the licensee were able to demonstrate to ONR's satisfaction that the criteria in the 2014 Paris Convention Decommissioning

[1] It may also include management of surface water features; these are not however specifically covered here.

Exclusion had been met [6]. Under this proposal, sites (or parts of sites) that had met the exclusion criteria, and where ONR was satisfied that nuclear safety and nuclear security matters had been fully resolved, could then be delicensed by ONR. For the remaining period up to the site end state regulation of safety would then be regulated by HSE, and regulation of any remaining radioactive substances including residual wastes and land contamination would pass to the environmental regulator [7, 8].

Figure 1 Indicative Scope of this Guidance Document

Figure 1 The process of managing land contamination



Note: The process may apply to one or more pollutant linkages each of which may follow a different route. For some linkages, it may be possible to stop at an early stage – others will progress all the way through the process. The level of complexity of each stage may also vary and in some cases may be very simple.

1.3 STRUCTURE OF THIS GUIDANCE

The following sections of this guidance document describe:

- Regulatory and industry good practice guidance in areas of LQM, options appraisal and demonstrating optimisation etc are given in the section on LQM Considerations (Section 2).
- The process to apply in terms of remediation technique selection including attributes to consider is described in the section on Remediation Technique Selection (Section 3).
- Various remediation approaches that could be considered are given in the section on Remediation Techniques (Section 4).
- Learning from industry in the remediation technique selection process (Section 5).
- Summary points (Section 6).

A range of supporting information is provided in a series of appendices.

2 LAND QUALITY MANAGEMENT CONSIDERATIONS

2.1 INDUSTRY GOOD PRACTICE GUIDANCE

In terms of the analysis and selection of a preferred remediation solution, there are several industry good practice guides that may be relevant in support of both the technical decision making and practical delivery aspects of any successful remediation scheme. Although all of these key guidance documents are not necessarily focussed upon radiological contamination or to implementation on nuclear licensed sites, they provide clear principles and frameworks which can be followed in any given scenario. A summary of regulatory guidance is provided in Appendix B and it is important to note that remediation activities may have to consider a range of licensing, environmental permitting and planning interfaces.

2.1.1 Contaminated Land: Applications in Real Environments (CL:AIRE)

'Contaminated Land: Applications in Real Environments' (CL:AIRE)[2] is an independent not-for-profit organisation established in 1999 to stimulate the regeneration of contaminated land in the UK by raising awareness of, and confidence in, practical and sustainable remediation technologies. CL:AIRE supports a number of industry initiatives, including the development of guidance documentation and has helped to develop more efficient regulation initiatives. The activities of CL:AIRE are not specific to the nuclear industry. Nonetheless, many nuclear site operators and associated suppliers are Principal Members of CL:AIRE.

CL:AIRE offer a wide range of guidance relative to remediation options appraisal, selection, implementation and verification[3] and related things such as the Definition of Waste: Code of Practice (DoW CoP) [9] which aims to allow the reuse of excavated materials on-site or their movement between sites. The 'Sustainable Remediation Forum UK' (SuRF-UK)[4] is also a CL:AIRE led framework for assessing sustainability of soil and groundwater remediation [10]. The framework has been developed to help assessors take account of relevant sustainable development criteria in selecting the optimum land-use design, determining remedial objectives for contaminated land and groundwater, and in selecting a remediation strategy and technique. The document sets out SuRF-UK's recommendations on where sustainability issues should be considered in land contamination risk management decisions within the UK, including within the planning and contaminated land systems within England, Wales, Scotland and Northern Ireland.

The SuRF-UK framework also embodies the CLR11 [4] process (see Appendix B for further discussion) and identifies two fundamental stages at which sustainability can be considered:

1. The project/plan design stage when some of the most influential decisions about the remediation solution can be embedded into a wider sustainable project design as part of a strategy across a portfolio of sites or a site-specific masterplan; and
2. The point of remediation options appraisal, selection and implementation when the decision is about selecting the optimum remedial strategy or technique.

CLR11 refers to the need for sustainable remediation and key assessment points align with CLR11 'risk assessment', 'options appraisal' and 'implementation' stages.

The process of identifying sustainable remediation is defined by SuRF-UK [10] 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."*

The framework presented (and the associated guidance and tools) is intended to be a voluntary initiative, but one that has environmental regulator support. The framework does not make recommendations on the sustainability of any specific

[2] https://www.claire.co.uk/
[3] https://www.claire.co.uk/information-centre/cl-aire-publications
[4] https://www.claire.co.uk/projects-and-initiatives/surf-uk

remediation technologies or approaches, but rather provides a framework for assessors to identify the optimum solution on a site-by-site basis.

Since the publication by SuRF-UK, an International Standard (ISO 18504 Soil Quality – Sustainable Remediation) was published in 2017 [11] focussed upon the sustainability aspects of remediation projects. This document reflects many of the values of the SuRF-UK Framework and provides detailed social, economic and environmental '*indicators*' and '*metrics*' to be considered during the process of comparing remediation options and identification of a preferred management option.

Sustainability is an attribute discussed in Section 3.2 , therefore, it is important to be aware of the tools and processes available and their relevance to the scale and complexity of a scheme prior to reviewing remediation options so that the sustainable nature of each can be understood.

2.1.2 CIRIA and SAFEGROUNDS

The 'Construction Industry Research and Information Association' (CIRIA) is a neutral, independent and not-for-profit body. SAFEGROUNDS[5] (SAFety and Environmental Guidance for the Remediation of contaminated land on UK Nuclear and Defence Sites), and subsequently SAFEGROUNDS+, was a CIRIA managed forum and learning network that began in 1998. It focused on providing guidance on the management of contaminated land and non-active/low activity waste from nuclear and defence site decommissioning. It used a collaborative and consensus-forming approach to guidance development. Although the learning network has not been active for a number of years, the guidance developed remains highly relevant and use of SAFEGROUNDS guidance is considered to represent good practice.

In terms of this document, the most relevant SAFEGROUNDS guidance documents are CIRIA W28 (2009) 'Guide to the Comparison of Contaminated Land Management Options', [12] and CIRIA W29 (2009) 'Good Practice Guidance for the Management of Contaminated Land on Nuclear-licensed and Defence Sites' Version 2 [13].

This W28 guide is primarily for those responsible for developing and applying a process that compares options for managing contaminated land on nuclear-licensed and defence sites. A procedure is presented for comparing contaminated land management options and identification of a preferred option for a particular scenario. Different processes of comparison are presented which may be suitable for a range of scenarios from simple isolated issues to complex interrelated site-wide issues.

The guide was developed, based upon the Environment Agency CLR11 framework [4], and directly relates to Stage 2 of the Environment Agency assessment approach of 'Options Appraisal' (see Appendix B). W28 does not cover Stage 3 'Remediation Strategy', which covers the decisions and details around how the preferred option would be practically implemented. Knowledge of the available and more commonly used remediation techniques, such as those presented within this guidance document is a critical element in delivering a meaningful Options Appraisal.

The W29 guidance was developed to help those responsible for the management of contaminated land and to inform other stakeholders. It applies to legacy radioactive, mixed radioactive and non-radioactive contamination within the framework of what was CLR11.

Five key principles were developed and aligned into the three stages of the CLR11 process:

- Key Principle 1 Protection of people and the environment.
- Key Principle 2 Stakeholder involvement.
- Key Principle 3 Identifying the preferred management option.
- Key Principle 4 Immediate action.
- Key Principle 5 Record-keeping.

Within the Options Appraisal stage of the SAFEGROUNDS W29 guidance, four steps are identified:

1. Site owner/operator and stakeholders identifying, assessing and comparing feasible remedial options.
2. Site owner/operator identifying preferred strategy, with stakeholder input.
3. Regulators, decision makers and stakeholders assessing and developing the proposed remediation strategy.

[5] http://safegrounds.com/guidance.htm

4. Site owner/operator deciding on the strategy to be adopted, demonstrating how involvement impacted on the decision-making process.

It is these steps which are most relevant to the information presented within this guidance document. The identification of a full range of possible remediation options from the outset and then demonstrating which of those are applicable to the UK sector and likely to be achievable within a specific given scenario are critical.

2.1.3 Other Sources of Guidance

Remediation options may be evaluated through the framework of BPM or BAT assessments (BPM and BAT are considered to be synonymous, and the term BAT is used here). In support of the management of the generation and disposal of radioactive wastes (including in terms of land remediation), the Nuclear Industry Safety Directors Forum published in 2010, good practice guidance (GPG) on BAT demonstration [14].

The GPG on BAT notes that in broad terms, BAT means the latest stage of development of processes, facilities or methods of operation which is practicable and suitable to limit waste arisings and disposals. BAT applies throughout the lifetime of a process, from design to implementation, operation, maintenance and decommissioning.

Identification and implementation of BAT implies a balanced judgement of the benefit derived from a measure and the cost or effort of its introduction. The level of effort expended to resolve an issue, and to record the selection process, should be proportional to the scale of the challenge, the range of options available and the extent to which established good practice can be used to assist in the decision-making process. Nonetheless, guidance and precedent make clear that practicable measures to further reduce health, safety and environmental impacts can be ruled out as not reasonable only if the money, time, trouble or other costs involved would be “grossly disproportionate” to the benefit. The following principles should also be taken into account:

- Sustainable development;
- Waste hierarchy and waste form;
- The precautionary principle;
- The proximity principle.

It notes that subject to meeting regulatory obligations, the identification and application of BAT takes into account all relevant circumstances. It then states that BAT may be established by reference to previous studies or good practice (qualitative assessment), or as an independent comparison of detriments and benefits (a quantitative or semi-quantitative appraisal). The general rule is that the level of effort expended to identify and implement BAT should be proportionate to the scale of the issue to be resolved. In many cases, studies will be constrained by one or more factors, depending upon the assessment context. A number of assumptions may also be required, particularly where long timescales are considered. Whichever approach is adopted, the process, and any underpinning constraints or assumptions, must be documented and justified.

The identification of BAT is an important element within the decision-making process, but, does not necessarily represent the final decision. For instance, a study may be inconclusive, in that more than one approach may be regarded as essentially equivalent. In such a case, an element of judgement is required. Likewise, a decision may be influenced by other factors, either known at the time of the initial assessment or emerging subsequently. It is therefore important to keep decisions under review.

In terms of quantitative or semi-quantitative appraisals, options may be evaluated relative to a number of criteria or attributes. The 2016 Nuclear Decommissioning Authority (NDA) ‘Value Framework’ [15] provides a tool that supports the requirements for optimisation and optioneering across a broad range of applications and includes example attributes to consider. It provides a broad approach to answering key questions such as:

- What is the definition of the issue to be addressed?
- What are you trying to achieve?
- What are you trying to avoid?

The Value Framework also advises a duty holder to identify all potential options, including 'do nothing' or 'do minimum' options. All options should then be screened to produce a 'short-list' of credible options for further consideration where they are assessed to identify a single preferred option. This preferred option is then fully reviewed prior to implementation.

It is therefore important to understand the range of remediation techniques which should be included in the long-list of options and then to justify how that list is constrained based upon the particular scenario.

The Nuclear Energy Agency (NEA) is a specialised agency within the Organisation for Economic Co-operation and Development (OECD), an intergovernmental organisation of industrialised countries. It has published in 2014 guidance on 'Site Remediation and Restoration during Decommissioning of Nuclear Installations' [16]. The document presents learning from experience, identifying aspects of remediation planning and technology selection which have been problematic. Key issues surrounding site remediation which the document captures include poor problem definition, lack of stakeholder engagement (including regulatory bodies) and inadequate characterisation. It also identifies different techniques which are globally used or are planned to be used for soil and groundwater remediation. In many cases remediation of radioactive contamination and non-radioactive contamination is dealt with using the same technique. In fewer cases, different techniques were proposed.

In terms of remediation of radioactive contamination and non-radioactive contamination of soil, the report identified examples of:

- Excavating and removing contaminated soil and other wastes;
- In-situ stabilisation;
- Installing caps, walls or other types of containment;
- Other types of action, such as monitoring or natural attenuation.

In terms remediation of radioactive contamination of groundwater, the report identified examples of:

- Pump and treat;
- In-ground barriers;
- Other types of action, such as monitoring or natural attenuation

In terms of remediation of non-radioactive contamination of groundwater, the report also identified examples of pump, treat and re-inject.

In 2016, the NEA also reported on 'Strategic Considerations for the Sustainable Remediation of Nuclear Installations' [17]. This notes that "Sustainable remediation" represents remediation actions and goals that are informed by an understanding of the safety and environmental benefits, the impacts of remediation activities, and the social and economic benefits and impacts, including the impacts on natural resources and climate change, both in the short term and the long term. It notes that it is important that contamination from radioactivity is identified promptly and remediated according to a risk assessment that demonstrates appropriate protection of humans and the environment, and that a sustainability assessment shows remediation will have a net benefit.

It then goes on to state that:

> *"Traditional site remediation approaches typically focus on the reduction of contaminant concentrations to meet goals or risk-based levels, with an emphasis on the remediation programme cost and time frame. In the case of radioactive contaminants, this has typically meant the disposal of affected soils or water treatment media at licensed waste repositories. In contrast to a traditional remediation approach, sustainable remediation is a holistic approach to remediation that considers wider environmental, social and economic impacts, and aims for a balance in the net effects. The objective of the approach is to achieve risk-informed remedial goals through more efficient, sustainable strategies that conserve resources and protect air, water and soil quality through reduced emissions and other waste burdens. Sustainable remediation also simultaneously encourages the reuse of remediated land and enhanced long-term financial returns on investment; it does not necessarily take the site back to past or pre-operational conditions."*

Finally, the NEA 2019 report on Challenges in Nuclear and Radiological Legacy Site Management [18] sets out the work of the Expert Group on Legacy Management (EGLM). It notes that legacy sites should be managed in an open and transparent way, addressing the views of relevant stakeholders so as to build confidence in the solutions being developed. It also states that:

- A holistic approach to management and regulation of the hazards and risks is warranted in order to achieve proportionate risk management and overall optimisation.
- Overall optimisation implies the need to consider chemical and other hazards alongside the radiological hazards, adopting proportionate health, safety and risk management strategies and applying corresponding regulatory requirements based on common protection objectives.
- The use of graded assessment methods so as to support and promote proportionate approaches to demonstrating or confirming regulatory compliance in line with the common protection objectives.
- Strategies for the management and regulation of legacy sites should take into account strategies for radioactive waste management and vice versa. This is especially important for legacy sites that involve large volumes of contaminated waste, which incorporate old disposal facilities, or which have contamination in underground structures, for which in-situ disposal may be an appropriate management option.
- It is necessary, and of long-term advantage, to broadly involve all stakeholders in the process.
- A staged process is likely to be needed since it will not be possible to achieve an appropriate end-state in only one step, except in trivial cases.

2.2 CHARACTERISATION AND CONCEPTUAL MODEL

It is not the remit of this guidance document to present detailed approaches to site characterisation and development of conceptual models (CM). However, it is important to highlight the role that both these aspects play in the derivation of a suitable remediation strategy and also in enabling the ONR to determine if the presented solution fits appropriately with the issue presented and if all possible options have been considered from the outset. It is important to note that environmental regulator guidance on the implementation of GRR [8] notes that:

"…irrespective of the stage in their lifecycle, all sites in the first iteration of their SWESC, should be able to present a conceptual site model (CSM). The CSM should be supported by desk-based assessment (as a minimum) of sources, pathways and receptors potentially present at the site and include any interpretive intrusive site investigation information where available. We will expect all nuclear sites to have an up to date CSM, proportionate to the risks and complexity of the site and / or the potential pollutant linkages."

In simple terms, has the operator demonstrated that the problem is well quantified and understood and can they clearly demonstrate how the remediation solution will result in betterment? Regulator expectations for successful LQM at nuclear licensed sites [19] also notes that:

"Site characterisation should be used to establish a conceptual site model which describes the pathways by which contamination from a source could reach local receptors, and the risks posed to those receptors. This conceptual model should also set out baseline conditions against which any subsequent changes can be reviewed and their potential impacts assessed. Where land quality issues are potentially significant, more detailed characterisation of the source term, pathways and receptors may be necessary. Where appropriate and proportionate this may also include the use of models to aid understanding of the geology, hydro-geology, geochemistry and contaminant transport."

The full process is clearly set out in Land Contamination: Risk Management (LCRM) [5], however the characterisation and conceptual model development aspects are covered in Stage 1 (see Appendix B). In all cases, a duty holder would normally start with a Preliminary Risk Assessment (PRA). Additional site characterisation may be required to facilitate further Generic Quantitative Risk Assessment (GQRA) and Detailed Quantitative Risk Assessment (DQRA) dependent upon the complexity of the CM.

The PRA will require the development of the CM. The CM is a clear pictorial representation or description in words which shows clearly the nature of the source, pathways and receptors. This is covered in detail in LCRM, but in broad terms the following should be clearly described:

- **Sources** of contamination i.e. a contaminant or pollutant that is in, on or under the land and that has the potential to cause harm or pollution, lateral and vertical extent and how it spatially relates to surface water, ground water and geological features such as low and high permeability strata. It is also important to demonstrate how any structural elements such as drains and foundations may interact with a source.

- **Pathways** a route by which a receptor is or could be affected by a contaminant and may be further described as a route by which contamination may travel away from the source location. Examples could be travelling through the air as a windborne dust or dissolving into groundwater and travelling laterally or vertically away from the source or entering a surface water drain to be carried towards a surface water course.
- **Receptors** i.e. something that could be adversely affected by a contaminant, for example a person, controlled waters, an organism, an ecosystem, or other receptors such as buildings, crops or animals.

Where all three Source-Pathway-Receptor (S-P-R) components are present, this constitutes an Active Pollutant Linkage (APL) which requires further assessment using the steps set out in [5] to determine if any APLs are Relevant Pollutant Linkages (RPL) and a remedial strategy is required in order to disrupt or 'break' the RPL linkage. A RPL is an APL which is significant in terms of posing an unacceptable level of risk. It is important to fully consider the relationships and interactions between soils and surface/groundwaters within the S-P-R assessment process to fully define the CM and drive the characterisation programme.

The derivation of the CM and the S-P-R and APL/RPL assessments are vital in demonstrating a clear understanding of a source and its behaviour within the surrounding environment. The selection of a remediation strategy should involve 'breaking' the APL by either removing or isolating the source, removing the pathway or protecting the receptor. A combination of these approaches may also be applied.

Therefore, the first step in assessing if a presented remedial solution is appropriate is to ensure that the development of the CM is sound and has been suitably underpinned through characterisation and risk assessment due process.

Site characterisation is likely to be an iterative process which is started well in advance of examining potential remediation options. The CM should drive the design of site investigations to ensure the best characterisation methods are selected and work is focussed upon uncertainties within the CM. Following completion of iterative phases of site characterisation, it is important that any remaining uncertainties within the CM are declared and their potential impacts upon the preferred remediation solution set out so this uncertainty can then be managed.

2.3 STAKEHOLDER ENGAGEMENT

Stakeholder engagement is sited in multiple industry best practice guidance (e.g. [10], [12], [15], [14], [15], [16] etc) as an important aspect of any options assessment related to land quality management and derivation of preferred remedial schemes. If decisions are made in isolation by a duty holder without the appropriate dialogue and engagement, considerable time and effort may be wasted if a preferred management option is identified which is later found to be unacceptable to key stakeholders, such as regulators or for more significant schemes, local communities.

Each remediation technique may have positive and negative impacts. For example, an excavate and dispose technique may result in a significant increase of vehicle movements and the carriage of radioactive materials through populated areas. This may not be acceptable to a local community even if all regulatory and legal aspects are satisfied.

The Joint Regulatory Guidance [19] on LQM states that:

> *"…to ensure achievable, cost effective and acceptable solutions for remediation it is important to identify at an early stage stakeholders with an interest in LQM. Once identified, stakeholders should be engaged in a proportionate way during the development and implementation of LQM plans."*

Early and continued engagement with stakeholders is advocated which should include regulators and be focused on an agreed set of objectives and appropriate hold points.

CIRIA SAFEGROUNDS (2011) W38 'Community Stakeholder Involvement', Version 3 [20] also states that stakeholder involvement is central to the SAFEGROUNDS approach. Key Principle 2 in W29 also states that "…*site owners/operators should involve stakeholders in the management of contaminated land particularly to inform decision making*".

SAFEGROUNDS guidance emphasises the importance of:

- Giving a wide range of stakeholders the opportunity to participate and allowing them to make the decision as to what they wish to be involved in, rather than restricting involvement arbitrarily;
- Beginning early, to build relationships and allow stakeholders to help shape the work programme and the stakeholder involvement plan;
- Allowing people to help frame the questions as well as helping answer them; and
- Considering an ongoing programme of stakeholder involvement covering overall planning and the decision-making process rather than separate involvement initiatives on individual projects.

Compliance with Key Principle 2 does not mean that all stakeholders have to be involved in all decision-making steps for every contaminated land issue on every site. Consultation should be proportionate to the scale of the issue.

The Surf-UK framework [10] provides further reinforcement of the importance of including relevant stakeholders and that their involvement should be proportional to the complexity and context of the problem being discussed.

Generally, the project team, comprising the site owner, whoever is being affected by the contaminated site, the service provider, the regulator(s) and planners are consulted. However, other stakeholders can be influential depending upon the technical complexity of the site and how it is sited within the local community:

- Site users (workers, possibly unions, and other visitors);
- Those with a financial or ownership interest;
- Neighbours (adjacent owners and tenants, local communities and councils); and
- Technical specialists, researchers, non-governmental organisations (NGOs) and pressure groups, particularly for more complicated problems.

The NDA Value Framework [15] encourages wider stakeholder engagement. However, it is recognised that input requires time and effort and hence the balance of participation must be right for any given scenario.

When considering which remediation techniques may be suitable for a given scenario, consideration is required as to how each technique may both positively and adversely impact the range of relevant stakeholders. Therefore, it should be demonstrated that a fit for purpose consultation exercise has been undertaken in order to seek and record stakeholder views and the potential impacts to them of any given technique. Both SNIFFER (Scotland and Northern Ireland Forum For Environmental Research) [21] and NICOLE (Network for Industrially Contaminated Land in Europe) [22] have produced specific guidance on communicating risks from contaminated land to stakeholders.

2.4 RECORD KEEPING

All of the good practice guidance sited in Section 2.1 advocates the keeping of comprehensive records for the duration of operation of any site with respect to the location and nature of contamination within the land and associated controlled waters and in-ground infrastructure.

The Joint Regulatory guidance [19] specifically identifies that records of the following should be made:

- The nature and extent of contamination;
- Processes used for deciding management options and the setting of strategies;
- Remediation that is being or has been carried out; and
- Method for and results of validation of the remediation work.

One of the SAFEGROUNDS Key Principles (Principle 5) is Record keeping. This requires site owners/operators to make comprehensive records about the management of contaminated land, to keep these records, and to update them as necessary. SAFEGROUNDS has also developed a practical guide (CIRIA W21 [23]) on record-keeping which recommends that a Land Quality File (LQF) is set up for each nuclear or defence site so that information about contaminated land can be held in a formalised structure. Equally, transfer of LQM information between operators, including any contractors, should be delivered in a controlled way.

With specific reference to the type of records required when selecting remediation options, Stage 2 of the Environment Agency CLRM [5] process identifies that the following information should be recorded before moving onto to a detailed assessment of the options selected:

- Shortlist of feasible remediation options;
- Summary description for each RPL;
- Any constraints on how options were selected;
- Methods used to collect information;
- Justification for selection of the options - why some were kept and others rejected;
- Caveats and assumptions used during this tier of option assessment.

A clear and traceable process should be presented which demonstrates that all potentially applicable remediation technologies have been considered at the outset. For any which are considered non-viable when compared to key attributes (Section 3.2) the justification behind their removal should be recorded for future reference.

3 LAND QUALITY MANAGEMENT TECHNICAL SELECTION CONSIDERATIONS

3.1 PROCESS

This guidance document does not cover the whole process of characterisation and evaluation by risk assessment of land quality impacts (see Figure **1**). It is intended for use once the decision has been made by a duty holder that a remediation solution is required and where a preferred solution is being assessed.

The following process of evaluation provides an overview of the key components to consider and questions to apply to the assessments made.

3.1.1 Drivers and Objectives

The duty holder may have one or several drivers for carrying out a remediation activity, for example, voluntary remediation to enable re-use of a land area, hazard reduction, environmental protection or to meet site licence conditions, or other regulatory requirement. The driver(s) for any remediation scheme should be clearly stated and the objectives defined. Ultimately, the selected remediation technology and management approach must be demonstrated to be suitable for achieving the objectives defined at the outset and should be proportionate to the priority of the driver(s).

Suitably Qualified and Experienced People (SQEP) need to be involved in defining what the drivers and objectives are for any given scheme. The operator should be able to clearly demonstrate the part played by each SQEP in determining the boundaries of each project by capturing this in a suitable document which can be retained for future reference and to keep the work scope relevant. SQEP may include, for example, those in an Intelligent Customer (IC) role or technical specialists from the supply chain who are capable of making good technical decisions.

3.1.2 Conceptual Model

As stated in Section 2.2, it is not the remit of this guidance document to present detailed approaches to site characterisation and development of conceptual models. However, the determination of a preferred management option for a contaminated land scenario begins with analysing the CM. In order to decide which management techniques to include within the selection process, it is important to understand the exact nature of the source or sources in question, the pathways by which they may disseminate and the receptors which may be affected. Without this first step, potential options may be missed from the outset or relevant attributes inaccurately assessed throughout the selection process. Therefore, it is important to check:

- Whether a clear understanding of the conceptual model has been presented to underpin the selection of a preferred remediation solution;
- That the uncertainties within the CM have been clearly identified and their potential impacts assessed throughout the selection process.

3.1.3 Identification of Long List Options

To prepare for the options assessment process, it is important to identify all possible techniques which might be suitable for any given remediation scenario. The list should be comprehensive and range from ‘do nothing’ to potentially feasible techniques which may be recently developed or new to the market, along-side established methods.

The CIRIA SAFEGROUNDS W28 [12] guidance recommends that a broad range of options should be identified from the minimum to the maximum range on effort. The options should be distinct from each other and are more likely to be identified by those familiar with the situation. CLR11 [4] recommends identification of options relevant to each RPL, however, CIRIA W28 [12] suggests that a more holistic view may be more appropriate.

The long list of options would benefit from technical peer review from specialists and for more strategic options input from relevant stakeholders may be appropriate. It should also be considered that a singular treatment technology used in isolation may not offer a total solution and often a combination of treatments may be necessary. These can be applied in sequence as part of a 'treatment train' to meet the remediation objectives. As part of a holistic remediation strategy, particularly where a site may be complex or remediation may have to be timed to coincide with particular future decommissioning activity, for example, 'holding' technology solutions which serve to temporarily immobilise or contain contamination could form part of the 'treatment train'. Adequate consultation with technical specialists and stakeholders should allow all options which may form part of a 'treatment train' to be identified.

Section 3 and Appendix C contains information and fact sheets for those remediation technologies most likely to be applicable to the UK nuclear sector, although as technology develops and time elapses, other technologies could be presented and considered by operators.

3.1.4 Down-selection to Short List Options

In order to avoid unnecessary time and effort being put into assessing all options on the long-list, the options should be narrowed down to those most likely to be suitable for the given scenario. For any options removed from the process at this stage, the reason(s) behind their removal should be recorded for future reference.

Reasons for removal of options, for example, may include:

- The technology may not meet the safety requirements of a particular site.
- The technology is not at a sufficient readiness level for application at field scale.
- A soil mass to be treated does not meet the minimum volume threshold for the technique to applied.
- Groundwater may be too deep for a treatment method to be applied.
- The geology (e.g. bedrock) may not be suitable for excavation or ex-situ treatment.

The decision to exclude options should not be taken in isolation but should include some level of stakeholder engagement or at least agreement that the exclusions are valid. Before advancing to the option assessment stage, it is therefore, important to assess if all the options removed from the process are reasonable and justified.

For situations where a wide range of options are identified a screening process is advocated by CIRIA W28 [12] using factors such as legal, practicability or gross disproportionality. The screened options taken forward to a short-list should all be capable of being put into practice within the required timeframe.

The OECD NEA [16] also advocates the use of a feasibility study which evaluates different methods to remediate. The feasibility study is essentially a risk management tool carried out to evaluate the likely success of a solution or a selected number of solutions. It identifies the risks, increases financial certainty and provides evidence as to whether an option is workable and realistic from a technical, cost or other perspective. It is equally valuable if it demonstrates that an option is not viable. The feasibility study also identifies requirements and goals that all viable options should meet. Those requirements are then used to screen inadequate options from future evaluation.

3.1.5 Options Assessment

The short-list of options should undergo an option assessment. There are many forms in which an option assessment can be delivered [12] and the selected approach should be suitable for the scale and priority of the problem at hand.

The NDA Value Framework [15] states that "…*the nature of the assessment will depend on the options under consideration, the importance of the assessment and the timescale required for decision-making*."

When carrying out option assessments it is also important that:

- A consistent, systematic and transparent approach is used with clear definitions of the criteria that are being considered as part of the assessment;
- Adequate time is allocated to describe each option and to obtain underpinning information;
- The assessments are evidence based, and the evidence supports the conclusions reached;
- Options are assessed based on consideration of their full life cycle impact;
- Combinations of options (which may vary for each contamination scenario being considered) are considered; and,

- Risks and uncertainties are considered, in particular it is important to understand the consequences if an option does not perform as anticipated and hence whether the risk outweighs the potential benefits from implementation.

It is also important that any assessment undertaken is free from bias, particularly in scenarios where a preferred outcome is identified in advance or if those involved in the assessment may be skewed towards a particular technology. Therefore, there may be significant benefits in including an impartial entity in the process to oversee discussions and record outcomes and to make sure that all participants in the process have had an equal opportunity to put forward their views based upon their own sphere of knowledge and experience.

Regulator expectations for successful LQM at nuclear licensed sites [19] notes that LQM decisions should be informed by an assessment of options for remediation that exist for each land and groundwater contamination source term, taking account of the overall remediation strategy for the site. An appropriate level of stakeholder dialogue should occur early in the process of identifying, screening and selecting remediation options.

Option assessment includes consideration of the:

- Physio-chemical nature and current state of contaminants;
- Actual or potential risks to people and the environment under current conditions;
- Benefits and detriments that implementation of each option would bring;
- Impact that any delay in implementing the option might have upon the spread of contamination;
- Actual or potential risks, and the costs of any option;
- Nature and volume of wastes that would be generated by each option or combination of options within a treatment train, and availability of disposal routes;
- Lifecycle impacts[6] on people and the environment;
- Practical issues of implementation associated with each option;
- Intended site end states (interim and/or final); and
- Extent to which each option addresses any concerns raised by stakeholders.

The outcome of the assessment of remediation options should be a strategy which should form the basis of a prioritised programme of work to implement the selected option.

Important requirements can be summarised as [14]:

- Document and justify the process adopted;
- Demonstrate that the outcome is robust; and,
- Ensure that the level of effort expended is proportionate to the scale of the issue to be resolved.

It is also important to note that no assessment can be used to argue against statutory duties, to justify risks that are intolerable, or to justify what is evidently poor engineering.

3.2 ATTRIBUTES

3.2.1 Introduction

A consistent set of criteria or 'attributes' are required to underpin a meaningful comparison of remediation technology options. There is no 'set list', but all relevant issues of concern should be captured within the list of attributes [12]. The NDA Value Framework [15] is also a useful document as it highlights many of the issues to consider and defines constraints and uncertainty in decision making.

The main categories which criteria are captured within are:

[6] This should consider both immediate impacts (detriments, including cost, and benefits) of action and broader impacts such as longer term effects and impacts of transferring risk elsewhere, the long-term effectiveness and permanence of the options, and the ability of each option to reduce the toxicity, mobility or volume of contamination through treatment.

- Health and Safety;
- Environmental;
- Technical;
- Social and Economic;
- Costs.

These main categories can then be broken down further into sub-categories to reflect all concerns of included stakeholders. Some common attributes which fall within the main categories above are discussed in more detail in the following sections.

3.2.2 Worker Health and Safety

All land and groundwater contamination should be managed in accordance with an appropriate safety case and waste management arrangements, to demonstrate that risks to operating staff, to other persons and to the environment are avoided, so far as is reasonably practicable [15].

If the benefits of resolving a land quality issue through use of a particular remediation technology are outweighed by the potential risks to the workforce, then this would prevent selection of that particular solution.

Safety, and provision of safe working practices, is a requirement within primary legislation. When considering any option, it is a requirement that a risk assessment be carried out to produce safe systems of work and ensure that the risk of accidents and injury to any individual are kept ALARA[7] [15].

Workers on a remediation scheme will need to have the right level of training and experience to implement and maintain a scheme safely. Consideration needs to be given with regard to the likely number of skilled operators which may be available, particularly for a more novel technology or scheme. There may be insufficient time to train enough personnel in some situations to support safe systems of work.

3.2.3 Logistics, Space and Time

The practicalities of physically implementing a remediation scheme should be carefully considered. A solution may be demonstrated to be the best technical solution on paper, however, what should also be considered is the specific location and context in which the scheme must be implemented. Each site is unique, ground conditions and site setting must be reviewed on a case by case basis.

Key questions should be considered, for example:

- What internal or external approvals, whether in terms of licensing, permitting or planning etc are required? This should include consideration of what assessments need to be prepared, how long will this take and is the resource available to do it and what are the timescales for review and approval.

- Is there sufficient road access and egress for delivery of equipment and dispatch of any arisings or waste or will these need to be created?

- Will an 'island site' with its own secure access and egress need to be created for the period of treatment in order to minimise logistical issues?

- Are there any height, width or weight restrictions for large or bulky items which need to be placed on the plot and how would these be mitigated without adverse impact?

- How much room will the treatment technology or process actually require and how will taking up this space affect surrounding operations and traffic routing etc?

[7] The NDA Value Framework notes that ALARA (As Low As Is Reasonable Achievable) is considered to be equivalent to ALARP (As Low As Is Reasonably Practicable) and SFAIRP (So Far As Is Reasonably Practicable).

- Who will be responsible for this space and how will access and egress be managed?

- Is there a suitable location for the welfare of contractors in close proximity to the treatment site, or will new temporary service routes and laydown platforms need to be established?

The timing of the treatment and longevity of the process will also need to be reviewed in terms of activities planned for the wider site and its operations. Would the work clash with any other planned activities such as maintenance or construction or decommissioning phases on an adjacent plot?

In order to understand these issues and to raise the right questions, it is important to involve specialist practitioners with detailed knowledge and experience of the equipment and process to be used. Without this level of understanding, it is easy to make assumptions and miss critical logistical issues. Alongside these specialist practitioners, stakeholders with a detailed knowledge of site operations and future operational plans should be consulted.

3.2.4 Engineering and Geotechnical Aspects

In order to demonstrate that all aspects of a scheme have been considered and in particular potential impacts to site infrastructure and surrounding operations, the nature of any civil and engineering works required to implement should be recorded and considered.

To identify a preferred option, consideration must be given to the following factors:

- Dig depths and dig extents are understood so that current and proposed site levels and backfill engineering requirements are known and factored into the wider assessment. A change of site level could have implications for surrounding operations and the nature of infill could alter the permeability of the ground and provide preferential migration routes from adjacent areas, as well as affecting the local hydrological and hydrogeological regimes.
- The materials balance or deficit for a scheme should be understood as this would influence the generation of excess soil arisings or drive the need for import or re-use of site-won material. Also factors such as laydown areas for waste arisings will need consideration.
- Excavation support requirements (batters, sheet piles etc) for excavations should be understood along with potential ground stability issues. Of particular influence is proximity to features such as critical infrastructure, ageing buildings, site boundaries, party walls, and adjacent roads/water courses. For instance, dewatering can lead to geotechnical changes in the ground.
- Depth to groundwater and dewatering requirements need to be considered as dewatering could potentially lead to ground settlement via the removal of fine sediment from within the soil matrix, drawing in contamination from adjacent areas, as well as requiring treatment and management of the water as it is removed. Particular discharge consents may be required, over and above those already permitted at the site.
- An assessment should also be made if either treatment or removal of obstructions and hard materials, such as foundation footings, service corridors, drain runs etc would be needed to fully implement a solution and if removal of services requires temporary diversions of drainage and other associated services.
- If tanks or pits or basements need to be removed and they have the potential to hold contamination, the risks associated with accidental release of contamination and the mechanism to be used for removal should be enveloped within each associated option.
- The potential for below-ground structures to be sensitive to aggressive treatment chemicals or remediation bi-products is also important to consider.

There may be other engineering or geotechnical aspects to consider depending upon the particular scenario encountered. It is important to understand the full scope of works behind a selected scheme rather than just focusing upon the specific technology itself. A remediation technology solution may on first view seem to have a small engineered footprint, however, the extent of below-ground impacts of activities required to facilitate the solution could have significant impacts.

3.2.5 Sustainability

Three elements of sustainable development are usually considered when assessing the likely impacts and benefits of undertaking any scheme:

- **Environment** – e.g. impacts to air, water, ecology, natural resources, waste generation, intrusiveness, energy consumption.
- **Social** – e.g. impacts on human health and safety, neighbourhoods, communities, local policy and ethics.
- **Economics** – e.g. direct and indirect costs and benefits, land value, employment, life-span of project and associated risks.

SuRF-UK [10] notes that "*…the specific tool used for a sustainable remediation assessment is less important than the process and thought that goes into the assessment. An assessment that considers environmental, social and economic factors from various stakeholder perspectives and which supports a management decision based on a clear and documented process is likely to be more acceptable than one which uses a sustainability assessment tool as a 'black box' and which fails to properly consider or justify input data and assumptions."*

Depending upon the specific remediation scenario and the level of risk associated with the continuing presence of a significant contamination source and RPL, sustainability assessment may be more or less influential upon the decision to select one treatment technology over another.
The input of stakeholders to the selection and assessment of sustainability criteria is critical in capturing all relevant issues and those of most importance to each type of stakeholder, for example, environmental regulator, community group representative or budget holder.

3.2.6 Waste Disposal

Waste management and disposal is an essential component of any remediation scheme and should reflect the requirements set out within the site's LQM plans. The Joint Regulatory Guidance [19] states that LQM plans should avoid the unnecessary generation of waste and that opportunities to minimise the volume of waste arising from LQM should be explored. Within this, wastes may be solid, liquid or gaseous, both radioactive and non-radioactive.

Waste disposal may entail many attribute sub-categories and refer to the waste management hierarchy [24] in terms of applying a comparative assessment between options. For example, removal of the source term to protect groundwater may be viewed as preferential (under other attributes) to leaving a source term in-situ, however, this may generate a significant volume of waste. In-situ alternatives to excavating material for management as waste (e.g. monitored natural attenuation) could therefore be viewed as preferential in terms of waste disposal attributes.

Some remediation technology options may present opportunities for re-use of excavated material, once it has been treated (e.g. sorted, segregated or chemically or biologically treated) under the necessary permits and authorisations. This would prevent the generation of waste requiring disposal and would be seen as beneficial as it is applying the waste management hierarchy.

LQM plans and underpinning remediation activities should be optimised by implementing sentencing arrangements and protocols to exclude or exempt material or waste from regulatory control. Ultimately this will increase the availability of disposal options and make processes easier to manage.

As part of reviewing waste disposal as an attribute, consideration should also be given to each waste stream which will be generated as part of the remediation activities. It should be confirmed that a suitable disposal route either already exists or can be secured by the operator prior to generating waste from the selected process. A clear understanding of all waste streams is therefore required prior to the assessment of options, in order to potentially screen out any techniques which may generate wastes that are problematic to dispose of. Radiological and conventional wastes could be as influential as each other when assessing waste as an attribute and the final destination of each waste should be considered, not just interim solutions such as storage on-site.

The review of waste streams should include both primary and secondary wastes from the process, so that they can both be minimised. By-products from a remediation process may be more problematic to manage and dispose of than the contamination in its original form.

Radioactivity is not destroyed by a treatment process; ex-situ techniques will require eventual disposal of residual radioactive wastes. These waste forms must meet disposal site waste acceptance criteria. Some remediation technologies (e.g. water treatment or sorting decontamination rubble and scrap metal) result in the concentration of radionuclides. By concentrating radionuclides, it is possible to change the classification of the waste, which impacts requirements for disposal. Waste classification requirements, for disposal of residual waste (if applicable), should be considered when evaluating remediation technologies.

3.2.7 Costs

There is limited research which addresses the issue of remediation costs. It is not possible to compare several different sites or scenarios and then derive a generic system to identify which solutions would cost more than others. Costs can only be viewed relative to one another on a case by case basis, as variability of geological, hydrogeological and chemical/radiological factors have a large impact.

There are several elements which need to be considered when estimating lifetime costs for a remediation scheme:

- Purchase of capital equipment;
- Operating and maintenance costs (including energy, treatment chemicals, costs for obtaining permits and other disposable items);
- Labour;
- Disposal of waste, including any processing, treatment, packaging and transport;
- Verification and aftercare (ongoing sampling and maintenance following the main phase of remediation);
- Specialist consultancy and system design costs;
- Insurance costs (for example to cover risk of consequential losses during operation of a remediation system or scheme);
- Management costs, dependent upon the complexity of the scheme and risk level;
- Contingency costs to address unexpected technical challenges and physical constraints.

Consideration of all the costs, which may be involved with implementing a remediation scheme, will be necessary to aid inspectors to make a judgment if the cost presented is both reasonable and proportionate to the derived benefit from implementation.

Remediation costs are also strongly influenced by how stringent the remedial targets are and differences in remedial targets can affect the remediation duration and therefore impact costs. Remedial targets may be linked to the identified end state or interim state, for example, delicensing and re-use for housing would impose more stringent remedial targets for a range of contaminants than an interim state of industrial/commercial use, prior to delicensing. The views and requirements of stakeholders in determining remedial targets are critical to cost evaluation. Documenting the process of deriving remedial targets is important and the discussion around cost versus benefit should be started at this stage.

It may be appropriate to view each scheme in a cost versus benefit framework [25] as it may be possible to remove contamination to increasingly lower levels, however, the costs to achieve each increment of improvement could increase sharply as the difficulty in retrieving the more challenging contamination mass also increases. The costs of a remediation scheme should be proportionate to the level of risk, and care should be taken that targets set are underpinned by science and logical reasoning, rather than simple perception. In some cases, targets can be set for other reasons e.g. to satisfy stakeholders or legislative requirements, or to remove blight, i.e. circumstances can dictate a different approach. Clear communication and explanation of risk is therefore critical between technical specialists and stakeholders to ensure that costs remain proportionate.

No broad conclusions can be drawn that either in-situ or ex-situ treatment methods are more or less costly, or have more variable costs. [27] It was observed that per unit costs generally decrease for higher volumes of material treated (>5,000 m^3), particularly for permeable reactive barriers, ex-situ thermal desorption and soil washing. This is a trend that may be expected as these technologies generally have considerable mobilisation/initialisation costs, making them a more cost-effective option where larger volumes of material require treatment. It was also noted that for a number of remediation techniques, the variance in costs decreases for volumes greater than 5,000 m^3. Economy of scale may play an important part in the assessment of costs and which remediation technologies may be more cost effective on either larger or smaller scale source areas.

3.2.8 Verification and Aftercare

Although the purpose of this guidance document is not to provide detailed information on the verification of remediation, CLR 11 [4] defines verification as "*the process of demonstrating that the risks have been reduced to meet remediation criteria and objectives based on a quantitative assessment of remediation performance*".

The Environment Agency has developed a document which specifically outlines the requirements for verification of land contamination [26]. This document identifies four key stages in the verification process:

1. Developing the remediation strategy – planning verification is an integral part of this process and involves the review of information already available and collected during development of the remediation strategy.
2. Developing the verification plan – including identification of the roles, responsibilities and the sampling approach needed to demonstrate that remediation objectives are satisfied.
3. Implementation of the verification plan, with production and communication of the verification report.
4. Long-term monitoring and maintenance, where needed to satisfy long-term remediation objectives.

Stage one shows how verification must be considered as an integral part of remediation and different remediation technologies will require differing levels of post-implementation care. For example, an excavate and remove scenario will require verification sampling to demonstrate that all material in excess of the remediation target has been removed. Following this point then no further monitoring or aftercare would be required.

However, other technologies such as a pump and treat or monitored natural attenuation may require many years of monitoring following installation or main treatment phase in order to verify that the remedial targets have been met and continue to show either decreasing or stable trends. Should a continuing rising trend, for example, be recorded in monitoring data for a contaminant of interest following a main treatment or installation phase, intervention action may be required to either investigate or resolve the issues.

A monitored natural attenuation solution may at first appear a simple solution with little risk, however, the risk could exist for a long time drawing upon resources (time, cost, energy etc.). This of course depends upon the half-life on the radionuclide contaminants. For some radionuclides the decay rate may be so slow that decay provides no useful benefit. An excavate and remove option may initially appear far more costly and disruptive to ongoing site operations, however, the risk would be removed in the short term.

The consideration of aftercare duration, not just the immediate implementation phase of the options, should therefore be included within the attributes considered for each technology solution. The views of the stakeholder group should be considered when evaluating the impacts of aftercare, as a clear vision of exactly what verification for each remediation option, or treatment train, practically involves and how verification will materially be achieved will be critical in correctly evaluating this attribute.

Timescales for decommissioning and for site operation are also a key factor in determining a preferred option, as some options may need to be ruled out if the aftercare requirements stretch beyond the intended lifetime of the site in question.

4 REMEDIATION TECHNIQUES

4.1 INTRODUCTION

In order to provide ONR with some background understanding of common remediation techniques which may be presented to their inspectors as a preferred management strategy, Remediation Technique Profiles (RTP) have been generated and presented in Appendix C. The RTPs contain technique descriptions, their drawbacks and benefits and in which situations they may be suitable to apply.

There are other technical resources which contain information on a wide range of remediation techniques used in the context of the wider UK land management market such as the Defra Research Project Final Report, Defra Project Code SP1001 - Contaminated Land Remediation, November 2010 [27]. This was a project organised by CL:AIRE looking primarily at conventional rather than radiological contamination. A wide range of consultants and technology vendors were involved in the information gathering exercise to identify techniques used in the UK, how commonly they were applied, limiting factors and relative costs. Historically the Environment Agency produced Remedial Action Treatment Data Sheets (RATDS) [28] describing technologies based on effectiveness, durability, practicability and cost. The RATDS described were representative of techniques that the Environment Agency considered to be applicable to remediation of both soil and groundwater, considering their commercial availability and track record in England and Wales in 2001. It was intended that as new techniques became available and their applicability was demonstrated (e.g. through the CL:AIRE Programme) the set of presented data sheets would be updated and augmented. Expectations have changed since then and good practice guidance is now more usually produced by representative industry or sector bodies in the UK.

There are two main genres of application for remediation techniques. The first is in-situ methods which are those that take place in the subsurface, without excavation of the contaminated soil or abstraction of groundwater. The second is ex-situ techniques, which are those that are applied to excavated soil, or treatments of contaminated water or gaseous emissions that take place at the surface. The main advantage of ex-situ techniques, compared with in-situ, is that contaminants, being brought up to the surface, are made more accessible to treatment processes and therefore, the verification of process performance is also typically simpler as the treated materials are easier to access and sample [27].

The RTPs within this document aim to highlight factors related to applicability and constraints specifically for addressing radiological contamination or co-located contamination scenarios, rather than the conventional scenarios discussed in other guidance documents.

The RTPs selected and presented in the following section are considered to be those most commonly used in the UK [27] and which are most likely to be presented, either individually or in sequence to remedy radiological or co-located radiological and chemical contamination.

4.2 REMEDIATION TECHNIQUE OVERVIEW MATRIX

Remediation technologies may be suitable for a wide range of applications or for a more singular purpose. It is important to understand in which situations a particular technology should be considered. To provide a reference overview of applicability, a simplified matrix table is presented below in Table 1. This identifies if a technology is used to treat soil or water or both, if it can be used in-situ or ex-situ or both, and, if it can remove either radiological or chemical or both types of contamination.

Within the UK, it may also be applicable to apply 'holding technologies' which do not necessarily treat or remove contamination but temporarily hold the contamination in-situ until a later date where its final treatment or removal may be more achievable e.g. during a main phase of site decommissioning. Examples of these technologies are also contained within the matrix table so that they may be further understood by users of this guidance document. The matrix table is intended to direct the reader to the applicable RTPs for the scenario and CM that has been presented to them and to support challenge to the operator if seemingly viable options have not been included in the options assessment or have been ruled out of the assessment at long list stage without adequate justification. The overview matrix is not intended to be used as a selection tool, more to provide information and to set potential options into context.

Table 1 Simple Remediation Technique Overview Matrix

Remediation Category	Remediation Technique	In-situ	Ex-situ	Soil	Water	Radiological	Chemical	Time (Years)	Relative Cost (£)	Maturity (M)	Interim or Final
Containment	Capping	✓	X	✓	X	✓	✓	<1	£	MMMM	I/F
	Vertical In-ground Barrier	✓	X	✓	✓	✓	✓	>10	£-££	MMM	I/F
	Permeable Reactive Barrier	✓	X	X	✓	?	✓	>10	££	M - MM	F
Biological	Bioremediation	✓	✓	✓	✓	?	✓	0.5-3	£	M	F (chemical)
	Monitored Natural Attenuation	✓	X	X	✓	✓	✓	1-30	£-££	MMMM	I/F
Physical / Chemical	Solidification/stabilisation	✓	✓	✓	X	✓	✓	<0.5	££	MMMM	F
	Soil washing/flushing (in-situ)	✓	X	✓	X	?	✓	1-3	££	M	F
	Excavate and Separate	X	✓	✓	X	✓	✓	<0.5	£+ - ££	MMMM	F
	Soil Washing (ex-situ)	X	✓	✓	X	?	✓	<0.5	££+	M	F
	Ion Exchange	X	✓	X	✓	✓	✓	>10	££	MMM	F
Temporary Containment	Hydraulic Barriers	✓	X	X	✓	✓	✓	>10	£	MMM	I
	Redox Stabilisation	✓	X	✓	✓	✓	✓	>10	££	MM	I

Key	
✓	Proven technique and extensively used in the UK.
?	A possible technique, not proven or widely used in the UK but implemented globally with limitation.
X	Technique not suitable.
Years	The indicative lifecycle timespan from implementation to close out. Can only be confirmed on a case by case basis and provided for general indication only. Information taken from [29]
£	Costs of lifecycle of remediation technology relative to each tabulated option. Can only be provided on a case by case basis and provided for general indication only. Information taken from [29] £ Low, £+ Low to Medium, ££ Medium, ££+ Medium to High.
M	Indicates the level of maturity of a technology for radiological remediation. Information taken from [33] and [36]. M – immature, MMMM very mature.
I/F	I indicates a technology is generally used as an interim holding technology to manage a risk or temporarily improve a condition, F indicates a technology presents a final solution as it removes contamination and I/F indicates if a technology is used in both situations.

In some cases, a technology may be mature and proven commercially in the field, whereas, other technologies may have been more recently developed and although proven to be technically viable at lab scale, are not yet widely proven at field scale. This is indicated within the RTPs, however, as time passes since publication of this guidance document, maturity levels may need to be updated for some technologies to reflect their ongoing development.

Whichever maturity level a technology has reached by the time it is presented for application; it still needs to be demonstrated scientifically that it will function as expected when applied to a particular site. This is often demonstrated through treatability studies or pilot trials run either in a laboratory or in the field. Such trials can be used to prove that a technology is viable under expected field conditions or to determine what the critical control parameters will need to be maintained at (e.g. pH, temperature etc.). This process may also help to confirm that assumptions used to estimate by-products or waste materials are confirmed by demonstrating types and volumes produced and in which phases of operation. In proximity to sensitive infrastructure or buildings, impacts to geotechnical properties of the ground can also be observed.

Research has been undertaken in the past, for example, such as that presented in CIRIA C662 [29] where Table A2.1 provides a treatment technology screening matrix which sets out basic information on the availability of remedial technologies at the time the guidance was published, gives guidance on which are applicable to the various types of contaminant and indicates the key issues for determining their suitability in various situations. References were also included for further reading.

4.3 OTHER REMEDIATION TECHNIQUES AND INFORMATION SOURCES

There are other remediation technologies which may have been used globally but have not yet been implemented in the UK as the risk driver is absent or the costs would be disproportionate. However, their use globally may have been appropriate due to the magnitude of either the spatial scale or risks to receptors (for example, in situations such as management of extreme impacts of disaster events such as at Fukushima Daiichi in Japan).

These globally used technologies are briefly summarised, for information, in Appendix D and are presented to give a view of global activities and advances which could start to impact the UK market in years to come.

A further useful resource, not only for 'other' remediation technologies, but also for more examples of the use of UK applicable techniques is the United States Environmental Protection Agency (EPA) library of 'All Publications on Technologies for Cleaning Up Contaminated Sites'[8]. This contains many papers and resource guides summarising the science and technology of a wide variety of remediation techniques and also provides specific information on approaches used for radiological contamination in the American Regulatory regime and commercial market.

Volume 11 of the Federal Remediation Technologies Round Table [30] in Appendix D, identifies the specific sites, technologies, contaminants, media, and year published for 393 case studies. Volume 11, covers a wide variety of technologies, including full-scale remediations and large-scale field demonstrations of soil, groundwater, and acid rock drainage treatment technologies. The examples which relate to radioactivity are dominated by physical separation and sorting. Containment with barriers and caps and solidification and stabilisation are also used. Field scale demonstrations of vitrification, soil flushing and reactive barriers are also documented.

Remediation Technologies Screening Matrix and Reference Guide, 4th Edition [31] was produced with the purpose of providing enough information to allow the reader to use the guide, in combination with other references, to efficiently proceed from identifying a contaminated site toward communicating and recommending suitable site remediation technologies to environmental regulators. Section 2.9 specifically addresses radionuclides and identifies that common solutions for soils are solidification and stabilisation, vitrification and excavation, sorting and off-site disposal. Common solutions for groundwater treatment were identified as precipitation/flocculation, filtration and ion exchange. Table 3.2 of this document also provides a comprehensive Treatment Technologies Screening Matrix which includes radionuclides as a category of treatment. The table also provides the American perspective on relative overall cost and performance of each technology. However, this may not be directly transferrable to the UK market and typical UK conceptual models presented. A copy of this table is provided in Appendix D. What it clearly shows is that there are only limited options where either above average (two options) or average (five options) performance could be anticipated.

[8] https://www.epa.gov/remedytech/all-publications-technologies-cleaning-contaminated-sites

The EPA, in 2007 produced a Technology Referencing Guide for Radioactively Contaminated Media [32]. This Technology Reference Guide was designed to help site managers, Remedial Project Managers, On-Scene Coordinators, their contractors and others to identify and understand technologies that are potentially useful in the remediation of radioactively contaminated media. The Guide is primarily targeted at Superfund or 'CERCLA' sites (the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 as amended by SARA, the Superfund Amendments and Reauthorization Act of 1986).

The Guide provides basic information on technologies and references to further information sources. Each technology profile provides process descriptions, operating principles, performance and cost data, target contaminants, applicable site characteristics, and other features relevant for each technology.

Consideration must be made to site specific characteristics (soil properties, hydrogeology, geochemistry, etc.), the half-lives / decay rate of the radionuclides present, type of radiation of the radioactive materials (alpha, beta, or gamma), radioactive concentration, other waste characteristics (depth and horizontal distribution, presence of multiple radionuclides or mixed waste, etc.), proximity of the waste to populations, available resources, handling required and level of personal protective equipment, and treatment costs.

The guide emphasises that disposal of extracted and concentrated radioactive material is a key part of the selection process and must be considered near the beginning of the decision process and that a succession of remedial measures ('a treatment train') would likely be employed at most sites to respond to various types of site contamination. Treatment trains can reduce the volume of materials that need further treatment and/or remediate multiple contaminants within a single medium. A treatment train, for example, might include soil washing, followed by solidification and stabilisation measures, and land encapsulation.

The IAEA, through ENVIRONET (the IAEA Network of Environmental Management and Remediation) have produced several reports from global contributors on environmental remediation. Lessons Learned from Environmental Remediation Programmes [33] documents learning from experience through applying a variety of remediation techniques across the world. It should be noted that the costs presented in the text are indicative and local and national factors will play a role in eventual costs. The IAEA under their CONNECT platform[9] also offer remediation training courses.

[9] https://nucleus.iaea.org/sites/connect/Pages/default.aspx

5 LEARNING FROM INDUSTRY

Learning from industry in the remediation technique selection process has been gathered from review of case studies and the workshop held in February 2020. Key points are summarised below:

- The selection of a remediation technique is only a small part of a long process which includes development of a conceptual site model, site characterisation, interpretative reporting and risk assessment etc. Knowledge management is key – record keeping throughout the decision and design process as well as part of implementation and validation is critical. Equally, limitations in measurements, or tools and equipment used, needs to be documented and understood otherwise weaknesses in the conceptual model can be overlooked.
- Remediation approaches can vary widely depending upon project specific drivers. For instance, remediation for near-term delicensing may be different to some form of safe and secure stewardship, where a final solution may not be implemented for several decades. In this instance, techniques which allow a situation to be maintained or held in status-quo (rather than techniques which actually remove the contamination), may become more relevant.
- Remediation option comparison and selection typically follows a multi-attribute decision analysis process of long list screening and short list assessment, generally involving a range of technical representatives. It may also involve external stakeholders.
- Typically, remediation solutions need a clear example of UK deployment to be considered credible.
- Options assessment can be an iterative process where options initially identified as preferred may not be practicable and where further assessment and consideration may then be required.
- Land quality issues can be relatively low risk compared to other site hazards. As such, funding availability may be low and land quality related works may be opportune or related to regulatory compliance. Equally, the remediation technique decision-making may be dominated by waste management needs and practical constraints such as space available, fragile infrastructure or issues of disruption to other site operations or ecologically sensitive habitats. Operator decisions on approaches can be influenced by the perceived current or future availability of support services in the supply chain including aspects such as framework contractors available and commercial engagement mechanisms.
- Overly rigorous success criteria and target setting in relation to remediation schemes can be a barrier in itself to successful delivery. Equally, information which provides a preliminary awareness to those involved in decision making is vital as it prompts appropriate questioning and highlights when to seek professional help.
- It can be helpful, as part of the remediation process, to get all the relevant regulators together in one room as each will have different priorities and there may need to be a 'trade-off' between the objectives of each stakeholder to achieve an outcome which meets all expectations.
- The end state is critical to consider in any given remediation scenario. Several interim states may be required to facilitate ongoing operation or decommissioning, rather than reaching the required end state in one single step and this needs to be considered in the development of a complete remediation strategy.
- ONR Inspectors should have an overview of both decommissioning and remediation programmes in their early planning stages, as decommissioning activities, such as removal of structures, may remove some of the protections afforded to receptors by exposing or mobilising contamination which could potentially have been dealt with, at least partially, in advance of the decommissioning activity to achieve betterment.
- ONR interaction is 'minimal' with regard to land management and therefore is mainly driven by the environmental regulator. Several sites highlighted a lack of ONR engagement on land quality issues.
- Early and active engagement, driven by the ONR, in land quality management discussions would add significant value to the process of deriving and underpinning remediation solutions. It would give opportunity to discuss and mitigate points of contention or to clarify interpretation of guidance. Greater involvement in the decision process by ONR would also provide a greater depth of understanding of the potential management and remediation solutions to be developed over time and lessons learned to be disseminated through the organisation.

6 SUMMARY

There is a well-documented process to follow to assist a site operator to identify a preferred remediation technology for any given scenario. The regulatory regime, within which the process needs to be applied, is also well established with a clear framework around expectations with regard to protection of human health and the environment. It is therefore possible for an operator or site owner to present a technically underpinned and well-thought-out solution to remedy radiological and co-located contamination and for the ONR to critically follow that process through and identify any steps which may not have been adequately addressed.

What is clear, from literature review of the UK market as well as global regulatory regimes and best practice guidance, is that mature technology options for radiological remediation technologies are limited and although several more solutions may have been proven to function on a laboratory or small field pilot scale or on specific projects globally with non-comparable conceptual site models, they have not been proven effective within the framework of a live, large-scale remediation project within the UK.

Proportionality of any scheme in balancing resources versus risk is critical in reaching a mutually agreeable solution between regulators, operators/owners and stakeholders. Decisions need to be underpinned by science and assessment of risk, rather than unduly influenced by perception. This approach should result in the right level of remediation being delivered to meet the objectives agreed at the outset of a scheme.

Stakeholder dialogue is a key component of setting objectives for a remediation scheme and early discussion and involvement is advised. This is advocated in numerous guidance and best practice documents and evidence of stakeholder involvement in making key decisions should be provided as part of any presented preferred remediation option.

7 REFERENCES

[1] IAEA (2018). IAEA Safety Glossary, Terminology Used in Nuclear Safety and Radiation Protection, 2018 Edition

[2] ONR (2014). Safety Assessment Principles for Nuclear Facilities, 2014 Edition, Revision 0

[3] ONR (2018). Nuclear Safety Technical Assessment Guide: Land Quality Management. Ref. NS-TAST-GD-083 Revision 1, November 2018

[4] Environment Agency: Model Procedures for the Management of Contaminated Land, CLR11, 2014

[5] Environment Agency, Land contamination: risk management, June 2019 (updated December 2019)

[6] Department for Business, Energy & Industrial Strategy (2018). Amending the Framework for the Final Stages of Nuclear Decommissioning and Clean-up. Government response to consultation, October 2018

[7] Scottish Environment Protection Agency (SEPA), Natural Resources Wales and the Environment Agency (2019). Implementing GRR in a proportionate manner. Version 1 - November 2019

[8] SEPA, Environment Agency and NRW (2018). Management of radioactive waste from decommissioning of nuclear sites: Guidance on Requirements for Release from Radioactive Substances Regulation. Version 1.0: July 2018

[9] CL:AIRE (2011). The Definition of Waste: Development Industry Code of Practice, Version 2, March 2011

[10] Sustainable Remediation Forum UK (SuRF-UK) A Framework for Assessing Sustainability of Soil and Groundwater Remediation, 2010.

[11] International Organisation for Standardisation: ISO 18504 Soil Quality – Sustainable Remediation, 2017

[12] CIRIA (2009) W28 – SAFEGROUNDS: Guide to the comparison of contaminated land management options, 2009

[13] CIRIA (2009) W29 – SAFEGROUNDS: Good practice guidance for the management of contaminated land on nuclear-licensed and defence site. Version 2, 2009

[14] Nuclear Industry Safety Directors Forum (2010). Best Available Techniques (BAT) for the Management of the Generation and Disposal of Radioactive Wastes Good Practice Guide, Issue 1, December 2010

[15] Nuclear Decommissioning Authority: The NDA Value Framework, 2016

[16] OECD NEA (2014). Nuclear Site Remediation and Restoration during Decommissioning of Nuclear Installations, NEA No. 7192, OECD 2014

[17] OECD NEA (2016). Strategic Considerations for the Sustainable Remediation of Nuclear Installations, NEA No. 7290, OECD 2016

[18] OECD NEA (2019). Challenges in Nuclear and Radiological Legacy Site Managements – Towards a Common Regulatory Framework, NEA No. 7419, OECD 2019

[19] ONR, the Environment Agency, Natural Resources Wales and the Scottish Environment Protection Agency (SEPA) (2014). Regulatory Expectations for Successful Land Quality Management at Nuclear Licensed Sites, June 2014

[20] CIRIA W38 (2011) – SAFEGROUNDS: Community stakeholder involvement - A report prepared within the SAFEGROUNDS project, Version 3, 2011

[21] SNIFFER (2010) Risk Communication Booklet, Communicating understanding of contaminated land risks, 2010.

[22] NICOLE (2004) Communication on contaminated land, 2004.

[23] CIRIA W21 (2007) – SAFEGROUNDS: Good practice guidance for land quality records management for nuclear-licensed and defence sites, 2007

[24] Defra (2011) Guidance on applying the Waste Hierarchy, 2011

[25] Environment Agency (1999) Cost Benefit Analysis for the Remediation of Land Contamination, R&D Technical Report P316, 1999 (INFO-OA-2h)

[26] Environment Agency (2010) Verification of remediation of land contamination, Report: SC030114/R1

[27] Defra (2010) Research Project Final Report, Defra Project Code SP1001 - Contaminated Land Remediation, November 2010.

[28] Environment Agency (2001) Remedial Action Treatment Data Sheets, 2001 (INFO OA-1c).

[29] CIRIA C662 (2004) Selection of remedial treatments for contaminated land, A guide to good practice, 2004

[30] Federal Remediation Technologies Roundtable (2007) Abstracts of Remediation Case Studies – Volume 11 August 2007

[31] Federal Remediation Technologies Roundtable (2002) Remediation Technologies Screening Matrix and Reference Guide, 4th Edition, 2002

[32] EPA (2007), Technology Referencing Guide for Radioactively Contaminated Media, EPA 402-R-07-004, 2007

[33] IAEA (2014) Nuclear Energy Series, Lessons Learnt from Environmental Remediation Programmes No. NW-T-3.6, 2014

8 DISTRIBUTION

Person	Organisation	Media
[redacted]	ONR	Electronic
[redacted]	ONR	Electronic
[redacted]	ONR	Electronic
[redacted]	RadEcol	Electronic
[redacted]	TUV-SUD Nuclear Technologies	Electronic
Technical Secretary	NIGLQ	Electronic

APPENDIX A – ORGANISATIONS ENAGED IN GUIDANCE DEVELOPMENT

The following organisations attended the February 2020 workshop where the guidance was discussed:

Atomic Weapons Establishment
CL:AIRE
Dounreay Site Restoration Ltd
Environment Agency
Low Level Waste Repository Ltd
Magnox Ltd
Ministry of Defence
Natural Resources Wales
Nuclear Decommissioning Authority
Nuclear Technologies
Office for Nuclear Regulation
RadEcol Consulting Ltd
Scottish Environment Protection Agency
Sellafield Ltd
URENCO Nuclear Stewardship Ltd

A draft of the document was also distributed around all members of the Nuclear Industry Group on Land Quality for comment.

APPENDIX B – REGULATORY GUIDANCE

B.1 REGULATORY GUIDANCE ON LAND QUALITY MANAGEMENT

The ONR was established as a statutory Public Corporation on 1 April 2014 under the Energy Act 2013. Other legislation that underpins the legal framework for nuclear industry regulation by the ONR includes:

- Health and Safety at Work Act 1974 (HSWA). Employers are responsible for ensuring the safety of their workers and the public.
- NIA 1965. A site cannot have a nuclear plant unless the user has been granted a site licence by ONR. Only a corporate body can hold such a licence.
- Ionising Radiations Regulations 2017. Provides for protection of workers in all industries from ionising radiations and by the general health and safety regulation which ONR also enforces at nuclear sites.
- Nuclear Industries Security Regulations 2003. ONR Civil Nuclear Security and Safeguards (CNSS) conducts its regulatory activities, approving security arrangements within the industry and enforcing compliance under the authority of these regulations.

The ONR Safety Assessment Principles (SAPs) for nuclear facilities [B1] set out principles concerned with the safe management of radioactively contaminated land ('RL') on nuclear licensed sites. It notes that ONR treats radioactively contaminated land and emplaced radioactive material as accumulations of nuclear matter, unless they are, or arise from, authorised disposals. The principles apply both to the ongoing control and remediation of contaminated land and to activities undertaken in preparation for achieving the site's final end state. They need to be applied in a proportionate manner. It also notes that the environmental regulators are responsible for the regulation of disposals on, and from, licensed sites in accordance with the appropriate environmental regulation and that the principles therefore need to be applied in a manner that is in accordance with the Memoranda of Understanding with the relevant environmental regulator. This includes the production of joint guidance as necessary to manage working arrangements in key areas where there are joint regulatory activities.

Within the SAPs, there are nine 'RL' principles:

- **RL1:** A strategy should be produced for the control and remediation of any radioactively contaminated land on the site.
- **RL2:** Steps should be undertaken to identify any areas of radioactively contaminated land on or adjacent to the site.
- **RL3:** Arrangements should be in place to ensure that leaks and escapes giving rise to radioactive land contamination are promptly identified and controlled.
- **RL4:** Radioactively contaminated land should be characterised to facilitate its safe and effective control and remediation.
- **RL5:** Radiological surveys, investigation, monitoring and surveillance of radioactively contaminated land should be carried out such that its characterisation is kept up to date.
- **RL6:** A plan should be prepared and implemented for the safe control and remediation of radioactively contaminated land and should be subject to appropriate stakeholder engagement.
- **RL7:** Arrangements should be made and implemented for recording and preserving information needed for the safe and effective control and remediation of radioactively contaminated land now and in the future.
- **RL9:** A safety case should be provided to demonstrate the safety of the plan for managing radioactively contaminated land and its associated control and remediation activities. The safety case should be kept up to date as the work progresses.

- **RL8:** Radioactively contaminated land should be remediated and controlled as appropriate before any construction of new facilities upon it.

The IAEA [A2] broadly define the term contamination as radioactive substances on or within a material where their presence is unintended or undesirable. The term contamination refers only to the presence of radioactivity and gives no indication of the magnitude of the hazard involved. Equally, the term is not meant to include residual radioactive material remaining at a site after the completion of decommissioning. It is therefore reasonable to conclude that the term should not be used where radioactivity can be excluded from relevant legislation, for instance where [B3]:

- Activity concentrations meet the relevant exemptions values;
- Naturally-occurring radionuclides occur in their normal setting or location, unless they have been processed or used for their radioactive, fertile or fissile properties or originate from a Naturally Occurring Radioactive Material (NORM) industrial activity;
- Artificial radionuclides which are present throughout the environment occur, for example as a result of atmospheric weapons tests and accidents;
- The radionuclide content is attributable to a lawful disposal, i.e. where no further act of disposal is foreseen, for example, discharge of liquid or gaseous waste to the environment or final closure of a solid waste disposal facility.

The ONR Nuclear Safety Technical Assessment Guide (TAG) on 'Land Quality Management' [B4] sets out, as noted above, that the ONR has vires for regulating radioactively contaminated land on nuclear sites in GB, this includes instances where radioactive and non-radioactive contamination co-exist. In this, radioactively contaminated land and groundwater are considered by ONR to be accumulations of nuclear matter. ONR may also be involved in instances where radioactive contamination of land has migrated off a licensed site. Vires for non-radioactively contaminated land and groundwater (metals, solvents, hydrocarbons etc) in a nuclear site context reside with the relevant environmental regulator or in some cases, at least initially, with the local authority.

Joint ONR and environmental regulator expectations for successful LQM at nuclear licensed sites [B5] states that:

> *"LQM refers to the prevention of land and groundwater contamination, and the remediation (including control and monitoring) of radioactive and non-radioactive contamination on the surface of the ground, in the ground and in groundwater. Therefore, LQM includes management activities that should occur irrespective of whether or not any contamination exists. If there is contamination then LQM activities should include the implementation of proportionate remediation options intended to meet standards that will ultimately not require further specific regulatory controls on the site and will not preclude other beneficial re-use of the land."*

It goes on to note that:

> *"…where contamination exists, proportionate remediation is undertaken to avoid, so far as is reasonably practicable, risks to human health, safety and the environment for present and future generations."*

In terms of demonstrating proportionate remediation, licensees and operators are expected to have a robust strategy for LQM with a LQM plan that addresses issues holistically and takes due account of radioactive and non-radioactive substances. The strategy and plan should be systematic and the approach to their development and management should be fully integrated and iterative. For example, operators should:

- Prevent new land contamination, so far as is reasonably practicable;
- Understand the land quality and contamination characteristics of the site, so as to inform decisions on LQM;
- Assess the options for LQM taking due account of sustainable development;
- Identify and prioritise LQM activities;
- Apply the waste management hierarchy;

- Avoid the creation of radioactive wastes in forms which may foreclose options for safe and effective long-term waste management;
- Ensure sufficient and competent resources are allocated to implement LQM activities;
- Engage with stakeholders (including the regulators) from an early stage;
- Develop the safety case / radioactive and non-radioactive waste management arrangements for LQM;
- Ensure that risks are as low as reasonably practicable (ALARP) / as low as reasonably achievable (ALARA) (or otherwise minimised as appropriate for non-radioactive contamination); and
- Maintain fit-for-purpose land management records and manage relevant knowledge appropriately.

The ONR TAG on 'Decommissioning' [B6] notes that the Licensee is to propose and justify the precise format of a decommissioning programme; nonetheless it should include defined end state criteria (and the methodology for subsequently confirming that these criteria have been achieved) and establish that this is an optimised outcome. It also notes that as a site moves into decommissioning and implements plans to reach its desired end state, LQM will take on greater importance (including a greater drive for remediation). Ultimately a nuclear site licence may be surrendered by the licensee. Currently for this to happen, the ONR has to give written notice that in its opinion, there has ceased to be any danger from ionising radiations from anything on the site. This is the so called, 'no danger' criterion and relates to an annual risk of death of 1 in a 1,000,000.

It is important to note that GB environmental regulators require RSR permitted operators under the GRR [B7] to develop an optimised waste management plan (WMP) of how radioactive waste (including emissions to the environment and land management) will be managed. It also requires a site-wide environmental safety case (SWESC). This is the overall safety argument that demonstrates that the environment is protected and that the protection of people is optimised, both in terms of radiological exposure and any chemically hazardous or polluting properties associated with that radioactive waste disposal (or discharge). This should include assessment of the radiological risk to public and non-human biota associated with any residual contamination that is planned to be left in the ground. The GRR applies over the lifetime of any nuclear site.

Internal guidance from the environmental regulators on the implementation of the GRR [B8] recommends a proportionate approach, i.e. a graded approach in which the level of control exercised is commensurate with the level of risk to people and the environment associated with the activity being controlled. It notes that the regulators should aim to jointly monitor the degree to which sites are consistent with the following key elements:

- Operators should have in place a robust Land Quality Management Plan (LQMP), which identifies the level of available (existing) information on both radioactive and non-radioactive areas of contamination across the site, and identifies any further work required to improve characterisation and understanding;
- A clear strategy for land quality should be in place and agreed with regulators and local stakeholders (e.g. identification of gaps in desk-study, site characterisation or monitoring information as well as conceptual site model maturity);
- The operators should have sufficient arrangements capable of ensuring that all reasonably practical measures are taken to prevent contamination and to ensure that existing contamination is managed to mitigate safety and environmental risks;
- Operators should consider proportionate clean-up options (depending on the identified risks to people / environment) where contamination exists. The selected options should ensure regulatory standards can be achieved.

The LQMP and land quality strategy should be core components of an operator's SWESC. Equally, if incidents such as leaks or spills have occurred, plans for characterising and dealing with contaminated structures, land and groundwater should be developed and maintained, with such plans being captured in the site's WMP. Any contamination remaining after clean-up of land and groundwater should be fully characterised and recorded and these records maintained in the WMP for reference in later stages of the site's lifecycle [B8]. An operator's activities in these areas should involve early engagement with the relevant environmental regulator and not just the ONR.

Sites that also come under other environmental regulations, for instance related to chemical industry activities, that have an 'Installations Permit' (or similar), will also have to prepare a site closure plan that will be required prior to permit surrender. This must show that there is no pollution risk, including from conventional contaminants in the ground (including groundwater).

There is also guidance from the Environment Agency on risk management in the context of LQM [B9]. This guidance for sites in England (referred to as 'Land Contamination Risk Management', LCRM) is based on the 'Model Procedures for the

Management of Land Contamination - Contaminated Land Report' ('CLR11') [B10]. The scope, framework and purpose of LCRM remains the same as that of CLR11. The Environment Agency published the updated guidance[10] in June 2019 and asked for feedback from the industry over the following six months to December 2019 with the intention of republishing in early 2020 to coincide with the withdrawal of the current CLR11. The LCRM guide is intended for use in a range of regulatory and management contexts such as voluntary remediation, planning, assessing liabilities or under the Part 2A contaminated land regime. Note, different guidance may apply in Scotland and Wales.

The key principles in the new English guidance are to be used to:

- Assess the risks;
- Make appropriate decisions;
- Take action where necessary.

There are three stages to be followed:

- **Stage 1** – Risk Assessment (RA), there are three stages to follow in order to identify issues which require a suitable management strategy to be derived –
    - Preliminary risk assessment (PRA) - first tier of RA that develops the outline conceptual model (CM) and establishes whether there are any potentially unacceptable risks.
    - Generic quantitative risk assessment (GQRA) - carried out using generic assessment criteria and assumptions to estimate risk.
    - Detailed quantitative risk assessment (DQRA) - carried out using detailed site-specific information to estimate risk.
- **Stage 2** – Options Appraisal (OA), there are 3 tiers to follow –
    - Identify feasible remediation options.
    - Do a detailed evaluation of options.
    - Select your final remediation options.
- **Stage 3** – Remediation, there are 3 tiers to follow –
    - Develop a remediation strategy (RS).
    - Remediation and verification.
    - Long-term monitoring and maintenance, if required.

This guidance document provides, in the following sections, information on key aspects of Stage 2 which need to be considered when evaluating remediation techniques for their suitability and practicality of application. The key aspects discussed within this guidance can also be influential upon developing the detailed implementation strategy within Stage 3 Remediation and should be clearly addressed within Stage 2 in order to provide confidence to the environmental regulator that the preferred strategy is likely to be successful at the point of validation.

B.2 APPROACH TO OPTIMISATION

Under RSR as described above, operators should show that their LQM strategy (including any remediation actions proposed) represents BPM in Scotland under the Environmental Authorisations (Scotland) Regulations 2018 and BAT in England and Wales under the Environmental Permitting (England and Wales) Regulations 2016 (EPR 16). That is that radiological risks are shown to be ALARA, i.e. they are 'optimised' where optimised can be described as [B11]:

> *"…keeping the magnitude of individual doses, the likelihood of exposure and the number of individuals exposes as low as reasonably achievable taking into account the current state of technical knowledge and economic and social factors".*

The ONR TAG on 'Guidance on the Demonstration of ALARP' [B12] identifies that nuclear licensee or duty holders have a legal requirement to reduce risks so far as is reasonably practicable (SFAIRP). In this, the terms SFAIRP and ALARP are considered as synonymous. The requirement for risks to be ALARP is fundamental and applies to all activities within the scope of the HSWA. In simple terms, it is a requirement to take all measures to reduce risk where doing so is reasonable. In most

[10] https://www.gov.uk/guidance/land-contamination-how-to-manage-the-risks

cases this is not done through an explicit comparison of costs and benefits, but rather by applying established relevant good practice and standards. It goes on to note that affordability is not a legitimate factor in the ALARP argument, though the cost of implementing the improvement is and that:

> *"The ALARP argument needs to consider all the types of risk that are relevant, not just the nuclear / radiological ones, and where these conflict with one another, ensure that an appropriate overall balance is achieved in regard to their management."*

Given the different terminology used in different legislation and the requirement for licensees to meet all their duties, the term "optimisation" is used in the ONR TAG 'Decommissioning' [B13] to refer to the level of protection that meets all the legal requirements of ALARP, BAT, BPM etc. Optimisation is also the term used in the IAEA Safety Fundamentals [B14] where Principle 5 states "*Protection must be optimised to provide the highest level of safety that can reasonably be achieved.*"

Consequently, it is important that, during optioneering studies carried out by the licensee to establish the BPM or BAT option, adequate consideration is given to health and safety aspects so that an overall ALARP solution that balances health, safety and environmental aspects is reached in an optimised manner. Such a balance should consider:

- The number of people (workers and the public) who may be exposed to radiation;
- The likelihood of their incurring exposures;
- The magnitude and distribution of radiation doses received;
- Radiation risks arising from foreseeable events;
- Economic, social and environmental factors;
- Using good practices and common sense to avoid radiation risks as far as is practical in day to day activities.

In respect of decommissioning, there are some specific aspects of optimisation that ONR might expect to be addressed as part of a licensee's arrangements to comply with LC35. The precautionary principle should be applied to the uncertainties that often need to be managed during decommissioning. Health and Safety Executive (HSE) guidance on reducing risks and protecting people [B15] notes that the process of assessing risks needs to take account of the possibility of uncertainty. Uncertainty is a state of knowledge in which, although the factors influencing the issue are identified, the likelihood of any adverse effects or the effects themselves cannot be precisely described. It further notes that the precautionary principle describes the philosophy that should be adopted for addressing hazards subject to high scientific uncertainty and rules out lack of scientific certainty as a reason for not taking preventive action. That is, decisions should take into account uncertainties and where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing cost-effective measures to prevent potential harm to people and the environment.

The precautionary principle should be invoked where there is good reason, based on empirical evidence or plausible causal hypothesis, to believe that serious harm might occur, even if the likelihood of harm is remote and where it is impossible to evaluate the conjectured outcomes with sufficient confidence. It is important to note that the precautionary principle is most applicable to serious or large-scale threats to society and has limited meaning at low doses (e.g. annual effective dose less than 100 μSv).

The ONR TAG on ALARP [B16] states that operators should also seek to protect future generations at least as well as we seek to protect the present one. Although it could be argued that the next few generations may gain some indirect benefit, the uncertainty of how they will view the risks left to them (and indeed the uncertainty of any benefits further into the future) argues for a precautionary approach and hence a particularly stringent demonstration that risks are indeed ALARP. It is therefore important that the operator makes particular efforts to demonstrate that risks to future generations are at least consistent with the levels of risk that would be accepted as adequate protection for the present generation.

Another important aspect relates to the potentially long timescales involved, and hence the increased importance of economic, social and environmental factors such as sustainable development and long-term environmental damage.

B.3 APPENDIX REFERENCES

[B1] ONR (2014). Safety Assessment Principles for Nuclear Facilities, 2014 Edition, Revision 0

[B2] IAEA (2018). IAEA Safety Glossary, Terminology Used in Nuclear Safety and Radiation Protection, 2018 Edition

[B3] BEIS, DEFRA, Welsh Government and Department of Agriculture, Environment and Ritual Affairs (2018). Scope of and Exemptions from the Radioactive Substances Legislation in England, Wales and Northern Ireland. Guidance Document, 2018

[B4] ONR (2018). Nuclear Safety Technical Assessment Guide: Land Quality Management. Ref. NS-TAST-GD-083 Revision 1, November 2018

[B5] ONR, the Environment Agency, Natural Resources Wales and the Scottish Environment Protection Agency (SEPA) (2014). Regulatory Expectations for Successful Land Quality Management at Nuclear Licensed Sites, June 2014

[B6] Decommissioning Nuclear Safety Technical Assessment Guide NS-TAST-GD-026 Revision 5, September 2019

[B7] SEPA, Environment Agency and NRW (2018). Management of radioactive waste from decommissioning of nuclear sites: Guidance on Requirements for Release from Radioactive Substances Regulation. Version 1.0: July 2018

[B8] Scottish Environment Protection Agency (SEPA), Natural Resources Wales and the Environment Agency (2019). Implementing GRR in a proportionate manner. Version 1 - November 2019

[B9] Environment Agency, Land contamination: risk management, June 2019 (updated December 2019)

[B10] Environment Agency: Model Procedures for the Management of Contaminated Land, CLR11, 2014

[B11] SEPA (2019). Satisfying the Optimisation Requirement and the Role of Best Practicable Means. RS-POL-001, May 2019, Version 2.0

[B12] ONR (2019). Guidance on the Demonstration of ALARP (As Low As Reasonably Practicable). Nuclear Safety Technical Assessment Guide, NS-TAST-GD-005 Revision 10, Dec 2019

[B13] ONR (2019). Decommissioning. Nuclear Safety Technical Assessment Guide. NS-TAST-GD-026 Revision 5, Sept 2019

[B14] IAEA (2006). IAEA Fundamental Safety Principles: Safety Fundamentals no. SF-1. IAEA Vienna, 2006

[B15] HSE (2001). Reducing Risks, Protecting People (R2P2) - HSE's Decision-Making Process, 2001

[B16] ONR (2019). Guidance on the Demonstration of ALARP (As Low As Reasonably Practicable). Nuclear Safety Technical Assessment Guide, NS-TAST-GD-005 Revision 10, Dec 2019

APPENDIX C - REMEDIATION TECHNOLOGY PROFILES

CONTAINMENT

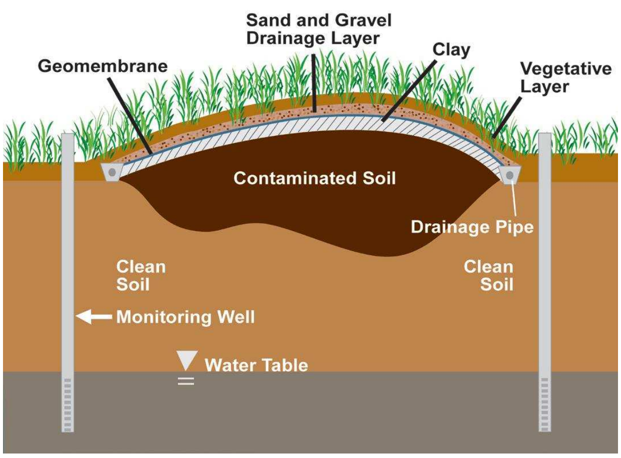
Technique	Capping			
Type, media	**Applicable contaminants**	**Technology maturity (M-MMMM)**	**Costs (£ to ££££)**	**Final or Interim Solution**
Containment, soil	All mobile contaminants, all classes of radioactive waste	MMMM	£	F / I

Technology

The use of capping to contain contaminated soils is well established within the UK. The technology is applicable to soils impacted with both radioactive and non-radioactive contaminants. A series of impermeable membranes are installed over the contaminated soils preventing rainwater or winds from dispersing the contaminant and often to also act as a shield for other site users. Using this technique does not treat the contamination and it is effectively disposed of in place. Capping reduces rainwater infiltration, reducing vertical groundwater flow and preventing an increase in plume geometry. Capping could be used as a temporary solution with contamination removed at a more suitable stage within a decommissioning lifecycle.

Implementation

Caps can be made from a number of different materials layered on top of one another to meet technical requirements or specifications. Materials used may include synthetic geomembranes (high density polyethylene), asphalt, cement, and natural low permeability materials such as clay. Generally, a combination of these are used for optimum containment. In addition to the engineered cap; ground cover and vegetation are often used to maintain cap integrity; this also has aesthetic benefits. Whilst the main objective of capping is preventing rainwater or wind from disturbing and dispersing the contaminant, caps have the added benefit of not letting a contaminant reach the surface. This may be most applicable to volatile gases or the cap may be used as shielding from radioactive decay. The thickness of the cap should be sufficient to provide adequate shielding from the radionuclides present.
During the installation of the cap a good quality assurance system is needed and consideration to settlement and the impact of settlement to cap integrity and durability is required. To mitigate, surcharging (preloading) of soils should be considered to accelerate any settlement prior to construction to prevent any structural weaknesses (e.g. slumping, desiccation cracks) or imperfections (e.g. to welded seems in any geomembranes used), otherwise the cap may not correctly function to the desired specification or for the desired time. A set of groundwater monitoring wells are also usually required as part of the design in order to demonstrate correct functionality of the cap during operation. In addition, water management should be considered; caps can be large areas that will need an effective drainage and water collection system.



Cross Section of Cap with Several Layers[1]

Grasses Growing on Cap of Hazardous Waste[1]

Constraints
Access: Construction requires full access to the area of impacted soils and a perimeter area to ensure the cap has suitable coverage to work effectively. **Site conditions**: The conditions must be suitable for the chosen technique; temperature, precipitation and subsidence can all negatively impact the integrity of the cap. The cap prevents precipitation vertically mobilising contaminants, however, if there is considerable shallow groundwater flow, the cap may be ineffectual as lateral migration will disperse contaminants wider than the capped area. If there is known to be a high water table, the use of capping will be inappropriate. **Sustainability (waste, energy, amenity impacts):** No additional wastes are produced. This is considered a low energy technique. Once in place there may be impacts to the capped land as this will have restrictions on future use. **Timescales**: Capping is relatively quick to implement providing the surface of the site can be readily accessed. Capping only covers the contamination in-situ, it does not provide any treatment to affected soils. Contamination is left to either naturally attenuate or decay and is effectively immobilised. **Durability:** The durability of a cap can vary dependant on the climate. Greater levels of rainfall may erode the surface soils more quickly reducing the longevity. Erosion of the cap surface can be combatted by initially adding more layers to the cap. If being used for a remedy for radiological contamination, the design life must be suitable for the decay rate of the specific radionuclide(s) present.
Aftercare
Ongoing monitoring of groundwater quality down gradient for the duration post installation is usually required to demonstrate correct functioning. Monitoring of the surface condition of the cap should be carried out to a defined protocol to ensure that there is no degradation or puncture to any impermeable layer. The combination of monitoring and inspection can be used to demonstrate capping is still appropriate. Specific care needs to be taken to avoid slumping, ponding, inadvertent site development, surface erosion, unplanned vegetative growth, and wildlife activity (e.g. burrowing animals) in the capped area. Institutional controls are usually required to prevent disturbance or access to the capped area into the future. Consideration should be given to end state uses as the capped contamination will remain in-situ and this will likely affect site licence/permit surrender.
Guidance
EPA (2007), Technology Referencing Guide for Radioactively Contaminated Media, EPA 402-R-07-004, 2007 EPA Citizens Guide to Capping, EPA 542-F-12-003, 2012 Federal Remediation Technologies Roundtable (2002) Remediation Technologies Screening Matrix and Reference Guide, 4th Edition, 2002 CIRIA C662 (2004) Selection of remedial treatments for contaminated land, A guide to good practice, 2004

[1] Image reproduced from 'EPA A Citizen's Guide to Capping, EPA 542-F-12-003, 2012' with permission from Linda Fiedler

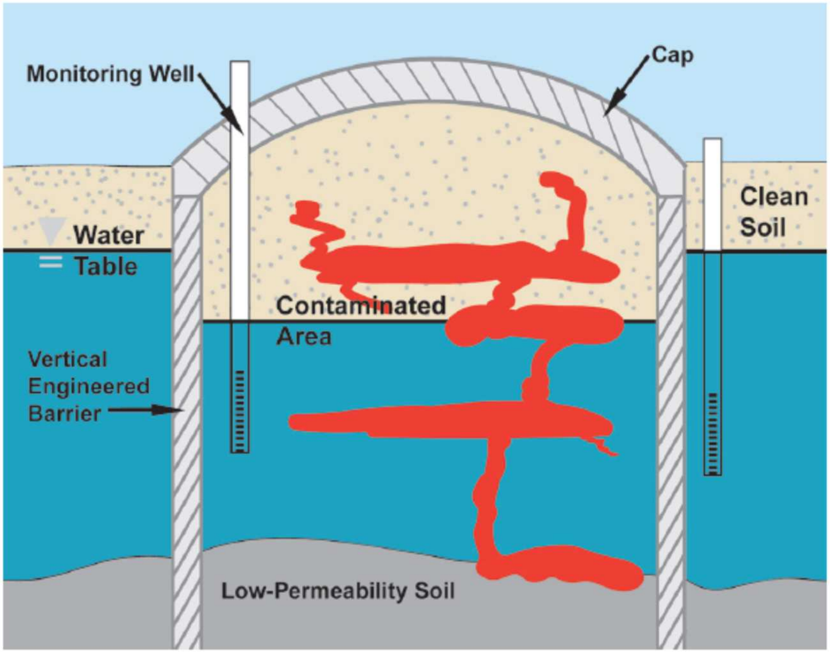
Technique	Vertical In-Ground Barriers			
Type, media	**Applicable contaminants**	**Technology maturity (M-MMMM)**	**Costs (£ to ££££)**	**Final or Interim Solution**
Containment, soil and groundwater	All mobile contaminants, all classes of low level radioactive and mixed waste	MMM	£ - ££ (Dependent upon depth and method of installation)	F / I

Technology

Vertical in-ground barriers are constructed using low permeability material, usually bentonite clay slurry, grout or piles, to contain the lateral migration of mobile contaminants in groundwater or used in conjunction with a cap to fully contain impacted soils. Their use is well established in the UK remediation sector to contain a variety of conventional mobile contaminants. Their main advantage being a well understood and easy to implement engineering solution. Additional containment can be provided by the inclusion of a membrane installed in parallel to the slurry walls, thus thickening the barrier. There are long-term implications of contamination remaining in place. For example, inadvertent human intrusion once institutional control has been removed.

Implementation

Bentonite walls, typically around 1m thick, can be installed to depth of up to 25m. Shallow walls can be installed using conventional excavation plant to dig a trench which is backfilled with bentonite slurry as it is dug. The technique has the benefit of the trench being self-supporting and therefore not requiring any temporary support. An alternative method is to inject grout into the ground under pressure using a suitable array of injection wells to form a 'grout curtain'. An imperative requirement for the system is that the wall/grout curtain must adequately key into a low permeability layer such as a clay. Bentonite is delivered to site in dry form, hydrated and mixed with cement to form a pumpable slurry. The mix of bentonite and cement can be varied according to site conditions. The use of just bentonite or small quantities of cement will create a flexible barrier able to accommodate some ground movement. Higher cement content will increase the material strength, but at the expense of increased brittleness and a reduction in the ability of the barrier to tolerate ground movement. Piled barriers may also be considered as an alternative to grout or a slurry and are usually formed using sheet piles mechanically driven into the ground to the required depth using percussion.



Vertical in Ground Barrier Cross Section[1]

Constraints
Access: Construction requires full access to the length of the wall and room for plant to dig a trench, inject grout or install piles. **Site conditions:** The ground conditions must be suitable for the chosen technique. Bentonite slurry walls require ground that can be excavated, grout injection requires sufficient soil permeability to ensure that a continuous barrier is formed, and piles require ground suitable to allow installation to depth with no significant in-ground obstructions. Slurry walls require level topography and consideration needs to be given to the management of groundwater levels as installation can alter the groundwater regime. The presence of construction rubble and large cobbles can be problematic to installation. **Timescales:** In ideal ground conditions the installation of slurry walls can be quite quick as this technique has wide application in engineering under a wide variety of site-specific conditions. **Sustainability (waste, energy, amenity impacts):** No waste is generated as the contaminants are immobilised in-situ. The energy and amenity impacts are low once the barrier(s) is constructed, however, if implementation using driven piles, this will create excess noise and vibration, which may affect sensitive plant and infrastructure. **Durability:** The vulnerability of in-ground barriers to degradation due to ground chemistry needs to be considered in the design. Certain chemicals are known to affect the 'setting' of bentonites (e.g. dense non aqueous phase liquids) and may cause desiccation and cracking over time. Barriers need to be protected from damage throughout their operational life, however, limited breaches of slurry walls will 'heal' due to the flexibility of the clay.
Aftercare
Monitoring of groundwater quality down gradient for a period after installation is usually required to demonstrate correct functioning. Barriers need to be protected from break by future excavation works and bentonite slurry walls need to be kept hydrated. Ongoing institutional control is likely to be required as the contamination remains in-situ. As contaminants are left in-situ consideration will need to be given to ongoing use of the site and future delicencing requirements.
Guidance
ICE, CIRIA, BRE and DETR. 1999. Specification for the construction of slurry trench cut-off walls as barriers to pollution migration EPA, Technology referencing Guide for Radioactively Contaminated Media, EPA 402-R-07-004, 2007 EPA A Citizen's Guide to Vertical Engineered Barriers, EPA 542-F-12-022, 2012 IAEA. Remediation of sites with dispersed radioactive contamination, Technical Reports Series: No.424, 2004 CIRIA C662 (2004) Selection of remedial treatments for contaminated land, A guide to good practice, 2004

[1] Image reproduced from 'EPA A Citizen's Guide to Vertical In Ground Barriers, EPA 542-F-12-022, 2012' with permission from Linda Fiedler

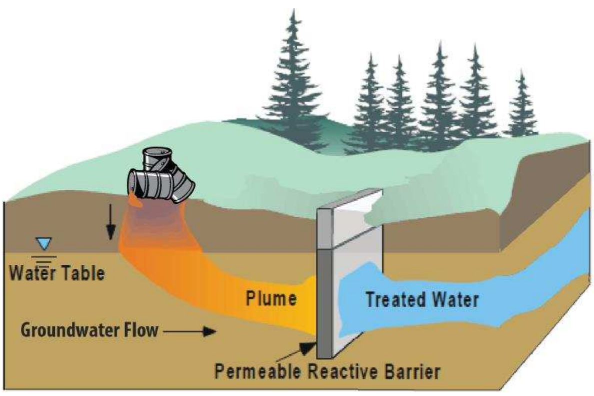
Technique	Permeable Reactive Barriers			
Type, media	**Applicable contaminants**	**Technology maturity (M-MMMM)**	**Costs (£ to ££££)**	**Final or Interim Solution**
Containment, groundwater	Volatile and semi-volatile organic compounds, metals and recently radionuclides (principally uranium and strontium but caesium, technetium, and cobalt also noted)	M-MM (For radiological contamination. Very mature technology for non-radiological contamination)	££	F

Technology

Permeable reactive barriers, also known as passive treatment walls, are installed in the subsurface across the flow path of a radionuclide-contaminated groundwater plume, allowing the groundwater to passively flow through the wall while prohibiting the movement of the radionuclides. This is accomplished by employing treatment agents within the wall such as chelators (ligands specific for a given radionuclide), sorbents (such as peat, bone char phosphate, apatite, activated carbon, or zeolites) and reactive minerals (such as limestone). The radionuclides are retained in a concentrated form by the barrier material. In the UK, this technology has been primarily used to remediate groundwater containing halogenated and non-halogenated volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs), as well as metals. In the USA, it has also been deployed to treat radionuclides. The two common technologies are: Continuous wall – uses a reactive treatment zone across the width of contamination plume (below groundwater level), Funnel and gate – low permeability barriers or drain systems channel (the funnel) contaminated groundwater flow to a permeable reactive zone (the gate). This technique could be combined with bioremediation for co-located contamination using additional additives and adjustments to the barrier design.

Implementation

A permeable reactive barrier is built by excavating a trench perpendicular to the groundwater flow path and backfilling it with the reactive materials, which can be mixed with sand to increase permeability. Typical permeable reactive barriers are installed to depths of up to 25m with either backhoes in combination with sheet piling or slurry trenches for deeper excavation. Other methods for installation include deep soil mixing (mixing the reactive material with soil using augers, similar to in-situ solidification techniques), jet grouting (injection of a mixture containing reactive material), and vibrating beam (driving an I-beam to depth and withdrawing while injecting a reactive slurry in the resulting void space). An ideal site would have uniform permeability, low levels of dissolved solids, poorly buffered groundwater and a shallow aquitard to key the barrier. Consideration should be given to maintaining accessibility, there may be practicality issues overtime replacing reactive media within the barriers.



Permeable Reactive Barrier Treating a Groundwater Plume[1]

Construction of a Permeable Reactive Barrier[1]

Constraints
Access: Enough space for large earth moving plant to be deployed across the width of the plume. **Site conditions:** Laboratory and field trials would be needed to ascertain suitability of the technique and optimum media composition. High levels of dissolved oxygen or dissolved minerals could result in clogging and biomass build-up. Less useful in areas with numerous underground utilities or structural obstructions. **Timescales:** Could take several years to implement depending upon complexity, groundwater velocity, solubility of contaminant and half-life etc, therefore, this technology is not applicable if there is a need for rapid attainment of remediation goals. **Sustainability (waste, energy, amenity impacts):** Installation would create noise, dust, and a nuisance due to large excavation plant and the ongoing waste stream generated as new reactive media is placed into the barrier and old media removed. Low energy once established as natural processes drive the technology. Area of barrier would have restricted access/use due to ongoing maintenance of system. **Durability:** Permeable reactive barriers for non-nuclear contamination is an established technique and is able to treat a wide range of contaminants. Advantages include it being in-situ, there is no loss in groundwater, low operational costs, barriers should last many years and the site can still be used whilst barriers are in place. **Limitations:** Barriers could become blocked. Heavy rain may cause groundwater to rise behind the barrier causing water to flow around it. Installation costs could become prohibitive as treatment depth increases. Long term presence of barrier could affect site end state objectives and impact surrender of site licence/permit.
Aftercare
Reactive media may need replacing during treatment process creating secondary waste streams. Downgradient monitoring of groundwater will be required during operational life to demonstrate functionality of the scheme. Institutional control will be required around the barrier to ensure integrity and facilitate maintenance inspections. There may be long term implications as the contamination remains in place until passing through the reactive barrier.
Guidance
Permeable Reactive Barriers for Inorganic and Radionuclide Contamination. Bronstein, K. EPA 2005 (Website accessed 27/01/2020) CL:AIRE Treatability Bulletin TrB 2 – Permeable Reactive Barriers. November 2011 Reclamation Of Contaminated Land (Modules in Environmental Science) – Nathanial C.P and Bardos R.P - Wiley & Sons. May 2004 EPA (2007), Technology Referencing Guide for Radioactively Contaminated Media, EPA 402-R-07-004, 2007 EPA A Citizen's Guide to Permeable Reactive Barriers, EPA 542-F-12-015, 2012 CIRIA C662 (2004) Selection of remedial treatments for contaminated land, A guide to good practice, 2004

[1] Image reproduced from 'EPA A Citizen's Guide to Permeable Reactive Barriers, EPA 542-F-12-015, 2012' with permission from Linda Fiedler

BIOLOGICAL

Technique	Bioremediation			
Type, media	**Applicable contaminants**	**Technology maturity (M-MMMM)**	**Costs (£ to ££££)**	**Final or Interim Solution**
Biological, soil and groundwater	Hydrocarbons and chlorinated solvents, or reduction in solubility for radionuclides	M (for radiological contamination)	£	F

Technology

Bioremediation of radionuclides in soil and groundwater utilises microbes (bacteria, plants and fungi) to catalyse chemical reactions that alter the properties of radionuclides in terms of solubility (mainly by reducing their oxidation state or lowering valence). This reduces their mobility and their bioavailability to sensitive receptors (also referred to as biotransformation). The reduction of Uranium (VI) from its soluble form to insoluble Uranium (IV) and Technetium (VII) to less soluble Technetium (IV) has been demonstrated using bacteria and fungi in experiments and pilot studies in the United States. (Technology Reference Guide for radioactively contaminated media, 2007 and Lloyd and Renshaw 2005).

The use of bioremediation is widely used to remove hydrocarbon and chlorinated solvent contaminants by decomposition to non-hazardous compounds, however, radionuclides are not removed but can be converted into more stable forms. Bioremediation can be achieved by using in-situ and ex-situ methods and optimum conditions for the microbes to flourish can be achieved by bio-stimulation and bioaugmentation. The former involves supplying additional nutrients, oxygen and moisture to stimulate microbial functionality in the soil and the latter involves the addition of prepared (sometimes genetically engineered) microbes to carry out the remediation and is often carried out with bio-stimulation. This technology is most likely to be used in conjunction with other solutions within a treatment train.

Implementation

In-situ

In-situ bioremediation uses flushing systems of injector wells, recovery wells (with submersible pumps) and monitoring wells. The injected water wells are inured with microbial nutrients and dissolved oxygen (this technique is also called biosparging). This technique is best suited where the contamination is from near surface to about 20m depth.

Ex-situ

Excavated soil is either placed as windrows (parallel rows of soil) or as a biopile. Both techniques need to be in sited on an impermeable bunded surface to prevent contamination of soils below. The former is turned and tilled to increase aeration and nutrients and microbe cultures can be added. Biopiles are static and nutrients, oxygen, water and microbe cultures added via pipes. This method is only practical where the soil to be treated is near surface and only a few metres deep. Once the soil is deemed to have been remediated it could be re-used.

Constraints

Access: In-situ will only require enough space for the placement of injection and recovery wells and pumping and treatment systems. These may be placed around existing site infrastructure. Ex-situ will require a large unobstructed treatment area with a secure boundary which could limit its suitability on sites with restricted space.

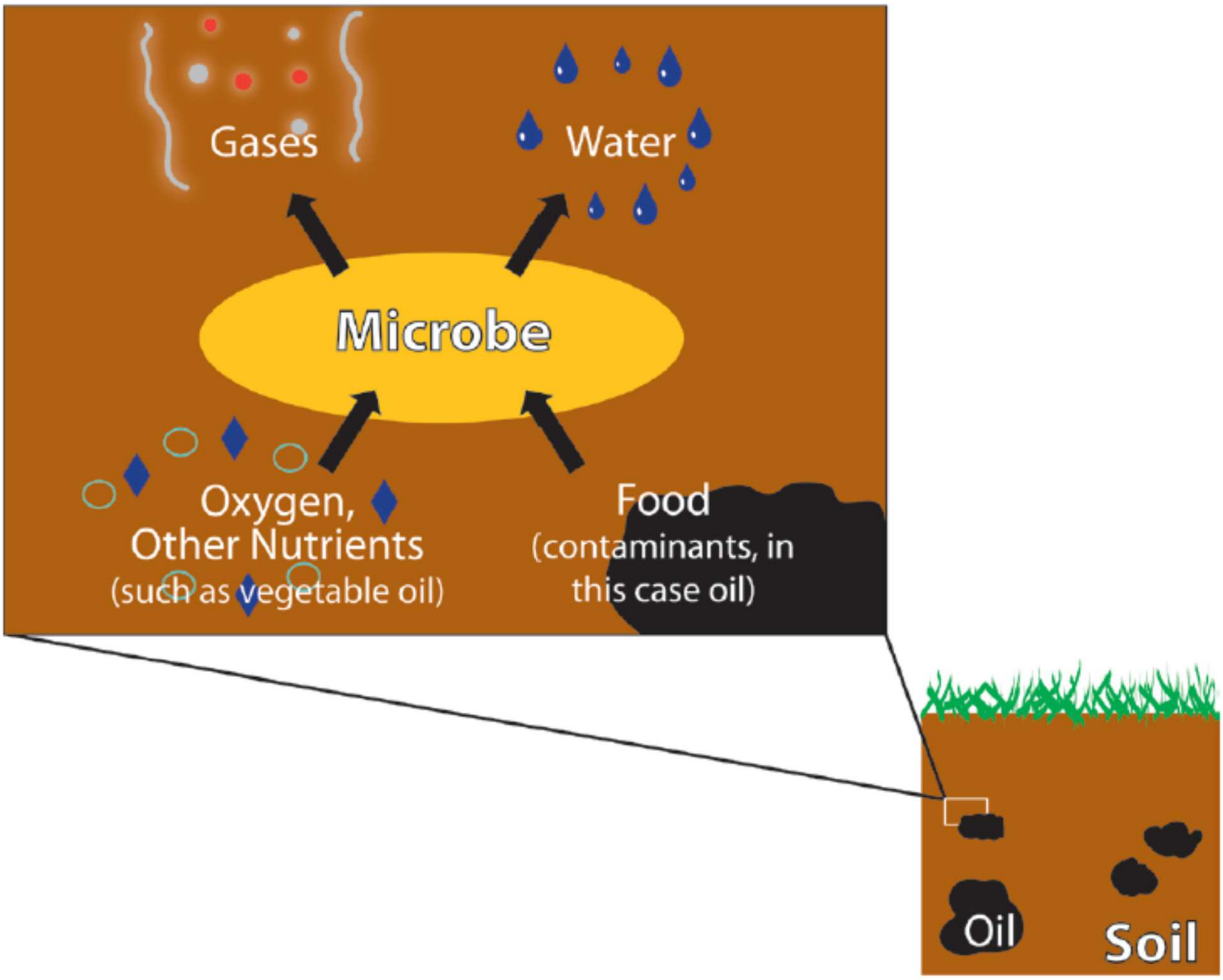
Site conditions: Conditions must be compatible with supporting the required microbes without excessive intervention or use of additives. Cohesive materials such as clays would be difficult to treat both in-situ and ex-situ.

Sustainability (waste, energy, amenity impacts): No additional wastes are produced, the microbes become part of the soil and are unlikely to impact disposability. The energy inputs are not considered high.

Timescales: Could range from months to years depending upon the range of contamination present. Trials would be required to optimise conditions (presence of competing anions, heavy metals, organic compounds etc.) prior to full implementation.

Durability: Re-oxidation and thus the remobilisation of reduced radionuclides by other microbial metabolism and abiotic mechanisms may occur. For in-situ treatment, rebound of contamination levels may occur from low permeability strata as bound contamination is slowly released.

Limitations: Site conditions are highly specific, and bioremediation is likely to be a step in a process rather than the whole solution for radiological remediation.



Bioremediation of oil contamination[1]

Aftercare
Constant monitoring of subsurface conditions (pH, temperature, nutrients present) will be needed and in-situ techniques will need ongoing monitoring of groundwater quality during and a period after treatment to demonstrate success. Ex-situ soil requires ongoing sampling for maintaining good conditions for microbes and to demonstrate the process is occurring as predicted.

Guidance
Technology Reference Guide for Radioactively Contaminated Media – EPA-402-R-07-004. October 2007 Bioremediation of radioactive waste: radionuclide-microbe interactions in laboratory and field-scale studies. Lloyd JR and Renshaw JC. Elsevier Ltd. May 2005 Federal Remediation Technologies Roundtable (2002) Remediation Technologies Screening Matrix and Reference Guide, 4th Edition, 2002 A Citizen's Guide to Bioremediation. EPA 542-F-12-003. September 2012

[1] Image reproduced from 'A Citizen's Guide to Bioremediation. EPA 542-F-12-003. September 2012' with permission from Linda Fiedler

Technique	Monitored Natural Attenuation			
Type, media	**Applicable contaminants**	**Technology maturity (M-MMMM)**	**Costs (£ to ££££)**	**Final or Interim Solution**
Biological, groundwater	All mobile contaminants could be considered (chemical and radiological)	MMMM	£-££	F / I

Technology

This technique is the nearest approach to 'do nothing' as no intervention is activated, however, the status of contamination behaviour does still require constant and rigorous monitoring. Contaminants are left in-situ for natural processes to reduce the contamination. These natural processes may be physical, biological or chemical. Natural processes in the subsurface can reduce radionuclide contaminant concentrations over time to acceptable levels as natural radioactive decay occurs. Although radionuclides cannot be biodegraded, microbial action can transform the chemical state of the radioactive contaminants and modify their solubility and mobility. Monitored Natural Attenuation (MNA) involves allowing these processes to reduce radioactivity levels while conducting long-term monitoring to confirm that the contaminant reduction is occurring at rates consistent with meeting clean-up objectives. Evaluation of suitability requires modelling, evaluation of radionuclide reduction rates and pathways, and prediction of concentrations at down gradient receptor points. MNA is not applicable if a plume is expanding or migrating or if there are imminent site risks present. It may be implemented alongside removal of a soil source by other remedial technologies designed to artificially speed up physical/biological/chemical degradation.
MNA might be an attractive option whilst extended institutional control and security are still in place, or if a plume extends beneath critical buildings and infrastructure, which limits other more intrusive options.

Implementation

When evaluating MNA as a remedial option, sufficient evidence must be given to demonstrate that the contaminant plume is exhausted, shrinking or stable, and that there is no risk that the contaminant will adversely impact any identified receptors.
Generally, MNA is an appropriate remediation technique when:

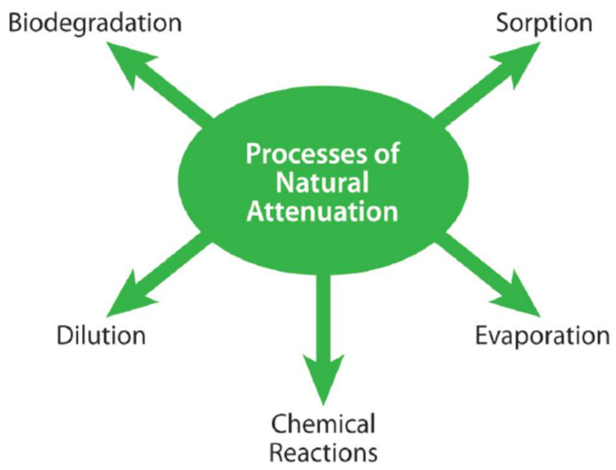
- It can be demonstrated it is protective of the receptors;
- Long-term treatment is needed and appropriate;
- The future evolution of the plume is understood;
- It is economic;
- An appropriate monitoring programme can be put in place;

The desired clean-up objectives are stable and acceptable.

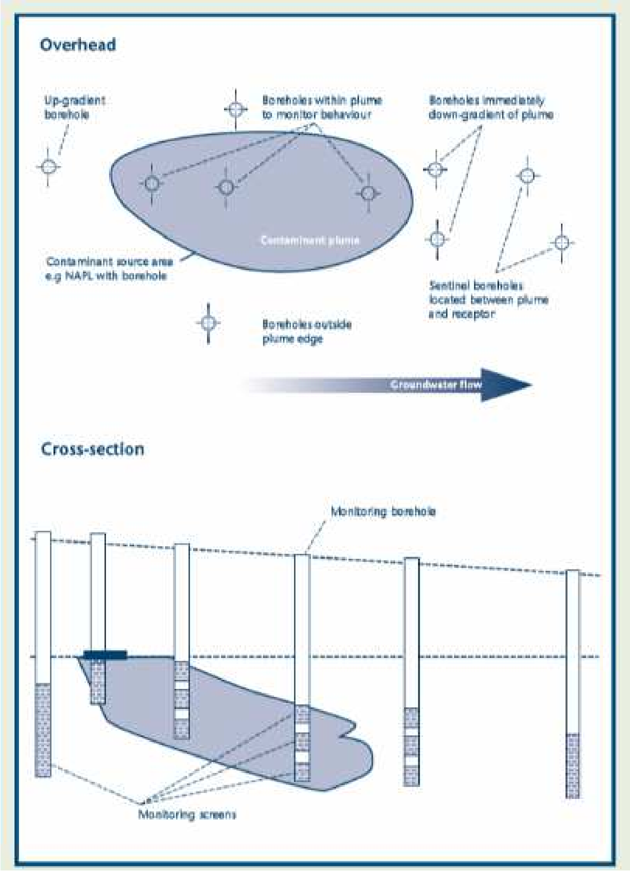
If there is uncertainty as to the ability to continually monitor the site and any natural attenuation processes occurring there into the future, then other remediation techniques should be selected. In order to implement MNA a network of appropriately designed groundwater monitoring wells need to be carefully constructed up-gradient, within the plume centreline, to the margins of the plume and at agreed sentinel points downgradient of the plume fringe. Regular monitoring and sampling are required to observe trends in concentrations of the key contaminants. Although radionuclides with short half-lives and immobile, short-lived daughter products could be favourable target contaminants for this process (e.g. tritium with no daughter products), MNA might not be applicable for radionuclides with longer half-lives and/or more toxic and mobile daughter products.

Constraints

Access: No particular access is required to the contaminated area other than to allow adequate placement of monitoring wells and for monitoring purposes. Wells must be protected from damage for long periods of time.
Site conditions: The physical properties of the contaminated medium, the continued presence of the contamination source, geochemical conditions (e.g. redox, dissolved oxygen, nutrients), the presence of microbes able to degrade contaminants, site geological heterogeneity and site hydrogeology are all critical.
Sustainability (waste, energy, amenity impacts): This technique has minimal impacts, low energy use and does not produce large volumes of waste. The only materials that will require disposal are samples obtained during routine monitoring and any consumable sampling equipment.
Timescales: These will vary depending on the radiological characteristics of the contaminant, but MNA will usually take several years following implementation, so is not suitable where a quick remedy is required.
Durability: Provided adequate modelling and assessment has been undertaken, the process is usually demonstrated to be successful over a long period of time, with little maintenance required other than to ensure wells continue to function correctly.



Monitored Natural Attenuation Mechanisms[1]



Contains public sector information licensed under the Open Government Licence v3.0, Ref: Environment Agency, 2004

Aftercare
This technique uses time to allow natural processes to attenuate the contamination, therefore, any instruments or wells used to monitor must be well maintained. In addition, the contaminated area should also be maintained as any change could affect the plume. Contaminants are not actively removed during implementation of this process only allowed to decay over time. This may have impacts on further land uses until such time as remedial targets are met and this will need to be considered in terms of meeting site end state conditions.
Guidance
Environment Agency (2004): Mobilising Natures Armoury – Monitored Natural Attenuation, Dealing with pollution using natural processes, 2004 EPA, Technology referencing Guide for Radioactively Contaminated Media, EPA 402-R-07-004, 2007 EPA A Citizen's Guide to Monitored Natural Attenuation, EPA 542-F-12-014, 2012 Federal Remediation Technologies Roundtable (2002) Remediation Technologies Screening Matrix and Reference Guide, 4th Edition, 2002 CIRIA C662 (2004) Selection of remedial treatments for contaminated land, A guide to good practice, 2004

[1]Image reproduced from 'EPA A Citizen's Guide to Monitored Natural Attenuation, EPA 542-F-12-014, 2012' with permission from Linda Fiedler

PHYSICAL / CHEMICAL

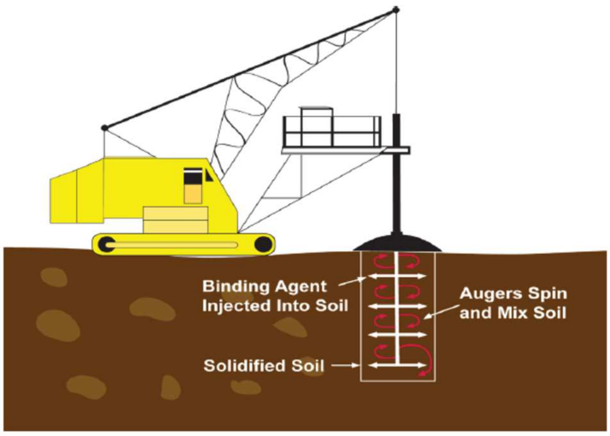
Technique	Solidification/Stabilisation			
Type, media	**Applicable contaminants**	**Technology maturity (M-MMMM)**	**Costs (£ to ££££)**	**Final or Interim Solution**
Physical/chemical, soil	All mobile contaminants considered and all classes of radioactivity	MMMM	££	F

Technology

Solidification/stabilisation (S/S) of contaminated material involves the use of additives to reduce the availability and mobility of contaminants within the contaminated material, usually resulting in a monolithic mass with high structural integrity. Specifically, stabilisation involves a chemical change in which the contaminants are converted into a less mobile form, and solidification involves a physical change in which they are bound within a solid matrix. Some additives used can have both these effects. Portland cement is an example of this and is the most commonly used additive for S/S. The technique can be used both in-situ (e.g. by injecting a treatment into the ground) and ex-situ (e.g. by excavating material for mixing above ground) and can be effective in treating a wide variety of contaminants simultaneously.

Implementation

In-situ methods involve the injection of the additives directly into the contaminated ground and these may then be physically mixed e.g. with an auger. Ex-situ techniques involve the removal of the contaminated material and the mixing of this with the additives externally, the resulting mixed material will then require disposal. Ex-situ methods allow for more control of the mixing process as it can be adjusted if the composition of the retrieved material changes. In-situ methods do not allow for this and require the correct mixing parameters to be set at the start. Radioactive waste has a long history of management using ex-situ techniques. S/S is most often used for land contaminated with inorganic constituents. Often it is the only practical solution to the treatment of materials contaminated with heavy metals and the use of cement as the additive is particularly effective. Additives are generally cementitious or chemical and include both inorganic (e.g. lime, gypsum) and organic (e.g. bitumen, thermoplastics) additives. Organic additives are less common given their increased cost over inorganic alternatives. Compatibility testing of cementing and solidifying agents with contaminants is required. Where contaminants extend below the water table, the ground may require de-watering prior to treatment. Another consideration is changes in volume that may result from the addition of S/S additives e.g. the addition of cementing agents can increase the volume of the solidified/stabilised mass by 30-50%. This could impact sensitive infrastructure. It is important to test method through bench and field scale trials.



In-situ solidification/stabilisation[1]

Injection of Binding Agents[1]

Constraints
Access: For in-situ S/S full access is required across the contaminated area. For ex-situ S/S partial access for local, staged excavation is required, as excavated material can be treated elsewhere. **Site conditions:** Different additives are available for different soil types, with grain size, pore size and permeability being factors to consider. Soils with a high clay content can be problematic to treat with S/S as it is more difficult to achieve uniformity in mixing. Cement based techniques are best suited to highly porous, coarse-grained, materials in permeable matrices. Chemical treatment is better suited to fine-grained soil with small pores. In-situ treatment for both cement and chemical not suitable if waste masses are thin, discontinuous, and at or near the surface. The S/S mass should remain above the water table to reduce the potential for future leaching of the contaminants. **Sustainability (waste, energy, amenity impacts):** In-situ no wastes are produced unless dewatering required, which could generate water management and disposal issues. Ex-situ there will be an arisings waste stream for disposal. This is considered a low energy technique. Prolonged site works may be needed to remove soils or to treat in place. **Timescales:** Full characterisation of the contaminated land is required to ensure the correct additive is used and to delineate layering. Development trials will be required to ensure that it is optimised. For in-situ S/S the equipment required will likely be limited to an excavator, mixing heads and an additive batch plant. Treatment is likely to take months rather than years. **Durability:** Depending on the additives used, the durability of the final products will be variable. In the long term, the effects of weathering, groundwater infiltration and physical disturbance associated with uncontrolled future land use will affect the integrity of the material where it remains in-situ. Some organic materials present within the soil mass may also inhibit the performance of the solidifying agent over time.
Aftercare
For in-situ treatment, monitoring of groundwater quality down gradient for a period after treatment is usually required to demonstrate correct functioning of the S/S material. Appropriate barriers/signage will be required to mark the area preventing future excavation or construction. If carried out in-situ the contaminants are simply immobilised and would need to be considered within the final end state and would likely affect site licence/permit surrender.
Guidance
Stabilization and Solidification of Contaminated Soil and Waste: A Manual of Practice, Edward Bates and Colin Hills. EPA (2007), Technology Referencing Guide for Radioactively Contaminated Media, EPA 402-R-07-004, 2007, EPA A Citizen's Guide to Solidification and Stabilisation, EPA 542-F-12-019, 2012 Federal Remediation Technologies Roundtable (2002) Remediation Technologies Screening Matrix and Reference Guide, 4th Edition, 2002 CIRIA C662 (2004) Selection of remedial treatments for contaminated land, A guide to good practice, 2004

[1] Image reproduced from 'EPA A Citizen's Guide to Solidification and Stabilisation, EPA 542-F-12-019, 2012' with permission from Linda Fiedler

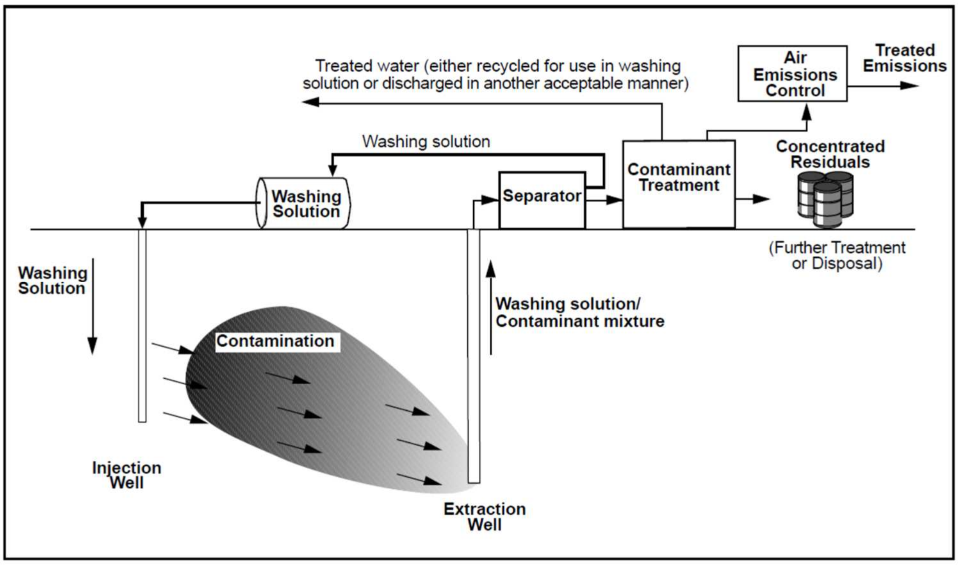
Technique	Soil Washing / Flushing (In-situ)			
Type, media	**Applicable contaminants**	**Technology maturity (M-MMMM)**	**Costs (£ to ££££)**	**Final or Interim Solution**
Physical/chemical, soil	All mobile contaminants, limited application to radionuclides (predominantly uranium)	M	££	F

Technology

In-situ soil washing / flushing involves the injection or spraying of water onto contaminated soils, allowing the water to dissolve the contaminants in-situ and then collecting the water in trenches or wells for treatment. There is limited use of this technology in-situ globally and it is yet to be fully developed and tested for the UK.

Implementation

Extensive modelling is required to understand the groundwater model to ensure adding water does not mobilise the contaminant in an unexpected direction. Once established the contaminated area is covered in an aqueous solution (often treated groundwater) or it is injected into the ground or sprayed over the ground and allowed to infiltrate. Commonly, the water used is treated with additives including: acids (soil leaching), alkalis, chelating agents, surfactants and organic solvents (solvent flushing). The purpose of this flushing solution is to solubilise or mobilise contaminants into an aqueous solution, to stimulate in-situ biodegradation, and/or to stimulate in-situ redox reactions. After flushing, the solution is recovered using wells or trenches and is treated at the surface to remove contaminants using a water treatment plant. The water may then be returned to the aquifer (possibly after being conditioned), discharged to the ground or to sewer, subject to regulatory requirements. Effectively a pump and treat system is established to retrieve the wash / flush water.
The target contaminant group for soil flushing is inorganics including limited soluble radioactive contaminants. The technology can be used to treat volatile and semi-volatile organic compounds, fuels, and pesticides, but it may be less cost-effective than alternative technologies for these contaminant groups. The addition of environmentally compatible surfactants may be used to increase the effective solubility of some organic compounds; however, the flushing solution may alter the physical/chemical properties of the soil system. The technology offers the potential for recovery of metals and can mobilise a wide range of organic and inorganic contaminants from coarse-grained soils, resulting in a net deterioration to the environment. Soil washing will generally not be cost effective for sites with less than 5,000 tons of contaminated soil. The potential of washing the contaminant beyond the capture zone and the introduction of surfactants to the subsurface can concern regulators. The technology should be used only where flushed contaminants and soil flushing fluid can be contained and recaptured.
Above ground separation and treatment costs for recovered fluids can drive the economics of the process.



In-Situ Soil Flushing Process Overview[1]

Constraints
Access: Dependent upon the flushing methodology, large areas may be required over the source to facilitate flushing. Sufficient access is needed to position wells and flush collection plant needed to remove treated waters for ongoing discharge or disposal. **Site conditions:** The site needs to be suitable from a geology/hydrogeology aspect, this is to be defined in the Conceptual Site Model. Consideration should be given to groundwater protection when injecting and removing treatment liquors, with potential for adverse impacts to groundwater chemistry well quantified and tested using bench and field scale pilot trials. This method is more successful with sandy or gravelly soils with little to no humus (total organic carbon less than 10%) and with low cation exchange capacities (less than 8 meq/l). Soil washing is generally not effective for soils with high proportions (>40%) of clay and silt. Soil washing appears to work best for soils contaminated with low-level radioactivity. Limitations include: • Low permeability or heterogeneous soils are difficult to treat. • Surfactants can adhere to soil and reduce effective soil porosity. • Reactions of flushing fluids with soil can reduce contaminant mobility. **Sustainability (waste, energy, amenity impacts):** This technique will generate secondary wastes in the form of flush/wash waters requiring separation, treatment and final disposal. Treatment area will have restricted access and ongoing use, energy requirement is moderate as flushing and retrieval system in constant operation. **Timescales**: The length of time to remediate may depend on the ground water flow but would usually take a few years rather than months to complete. **Durability:** The contamination is removed from the environment and is therefore a long-term solution with no maintenance costs following main phase application.
Aftercare
Requires on going monitoring to ensure that there are no remaining mobile contaminants and to demonstrate success of the methodology. Verification is key to understanding to what extent the soils have been remediated and that rebound of contamination levels does not occur.
Guidance
EPA, Technology referencing Guide for Radioactively Contaminated Media, EPA 402-R-07-004, 2007 IAEA. Remediation of sites with dispersed radioactive contamination, Technical Reports Series: No.424, 2004 Federal Remediation Technologies Roundtable (2002) Remediation Technologies Screening Matrix and Reference Guide, 4th Edition, 2002 CIRIA C662 (2004) Selection of remedial treatments for contaminated land, A guide to good practice, 2004 Soil Washing Treatment Trials at UKAEA, Presented to WM Conference 2000 by M. Pearl

[1]Image reproduced from 'EPA A Citizen's Guide to In-Situ Soil Flushing, EPA 542-F-96-006, 1996' with permission from Linda Fiedler

Technique	Excavate and Separation			
Type, media	**Applicable contaminants**	**Technology maturity (M-MMMM)**	**Costs (£ to ££££)**	**Final or Interim Solution**
Physical/chemical, soil	Wide range of contaminants detectable in-situ. Radionuclides emitting detectable gamma and beta but unsuitable for radionuclide which are hard to detect in-situ such as technetium and tritium.	MMMM	£+-££ (dependant on scale of operation)	F

Technology

This process separates radioactive particles from clean soil particles once the impacted soil has been mechanically removed from the ground. The simplest application involves screening and sieving soils to separate finer fractions (silt and clay) from coarser fractions of the soil. Since most contaminants tend to bind, either chemically or physically, to the fine fraction of a soil, separating this fine fraction can concentrate the contaminants into a smaller volume of soil for treatment or disposal. Soil excavation and separation is generally the first step of all ex-situ remediation methods; isolating the soil and removing it from the ground to allow for treatment. Any construction material components, if clean and structurally suitable for re-use, are normally crushed for structural fill. Natural soils would normally be separated where practical into granular soil and cohesive soil for further treatment where necessary. Excavated soils are often screened using in-line radiation detection equipment suitable for assessing containers (bags or drums) or in conjunction with a conveyor belt system. Detectors normally rely on the gamma emissions but systems can also be designed to detect beta emissions.

Implementation

Desk studies and ground investigations are recommended to characterise the ground. Knowledge of the primary radioactive contaminants is necessary. Soil cannot be properly sorted for unknown radioactive contaminants. Conventional excavation equipment and operators can be used to remove the impacted soil from the ground whereupon large debris is removed before processing. The large fractions may then be crushed prior to being put through the detection process so that they meet the parameters of the scanning methodology. Portable detection systems can be used for on-site nuclear assay of waste materials along with handheld radiation detectors. Detectors may also be mounted onto buckets of excavation machinery and help to screen material at the point of extraction. For material undergoing separation and sorting, or awaiting treatment, properly managed laydown areas incorporating run-off prevention measures (Visqueen membranes and bunds) are required, along with plant processing areas, such as picking stations, dewatering plant, vibration sieves and crushers. Effective excavation and segregation will reduce the amount of soil that requires further treatment or disposal, produces a more homogenous material suitable for treatment and identifies material that is suitable for reuse as engineering fill. Reducing the amount of soil needing further treatment or disposal will reduce overall costs. The sentencing of large quantities of soil to landfill (especially ones that accept hazardous and radiologically contaminated waste) is expensive and can be a nuisance to site neighbours, with large vehicles frequently travelling to and from the site. These factors must be considered and strict measures will need to be in place to minimize noise, dust and vapour emissions from the works. Any soils removed from site will normally need to be replaced with clean imported or site-won material.

Soil is Excavated and Covered with Plastic Tarps[1]

Worker Collects Soil Samples to Verify Site is Clean[1]

Constraints
Access: Sufficient real estate needed, including areas to be excavated and areas for processing equipment and laydown of soil. **Site conditions**: Ideally, crushers and picking stations should be on flat, stable free draining ground. Multiple gamma emitting radionuclides may make in-situ detection and separation challenging. Thick vegetation and root systems may inhibit soil separation. Screening for conventional contaminants such as asbestos would be required. Any metal, timber, non-biodegradable items (e.g. plastics), and construction material (e.g. brick, concrete and asphalt) would also need to be separated. **Sustainability (waste, energy, amenity impacts):** The process may identify multiple waste streams for segregation. The energy requirements are considered low. Prolonged site excavations, crushing, sorting and transport will create noise and dust. **Timescales**: This depends on the volume of soil needed to be processed but would generally take weeks to months to complete. **Durability:** Removing contaminated soil is a permanent solution. Clean and treated soil can be backfilled, if suitable, reducing the amount of imported fill needed.
Aftercare
None.
Guidance
A Citizen's Guide to Excavation of Contaminated Soil. EPA 542-F-12-007. September 2012 Land remediation and waste management guidelines – SEPA. Accessed 24/01/2020 https://www.sepa.org.uk/media/28317/land-remediation-and-waste-management-guidelines.pdf EPA (2007), Technology Referencing Guide for Radioactively Contaminated Media, EPA 402-R-07-004, 2007 Federal Remediation Technologies Roundtable (2002) Remediation Technologies Screening Matrix and Reference Guide, 4th Edition, 2002 CIRIA C662 (2004) Selection of remedial treatments for contaminated land, A guide to good practice, 2004

[1] Image reproduced from 'EPA A Citizen's Guide to Excavation of Contaminated Soil, EPA 542-F-12-007, 2012' with permission from Linda Fiedler

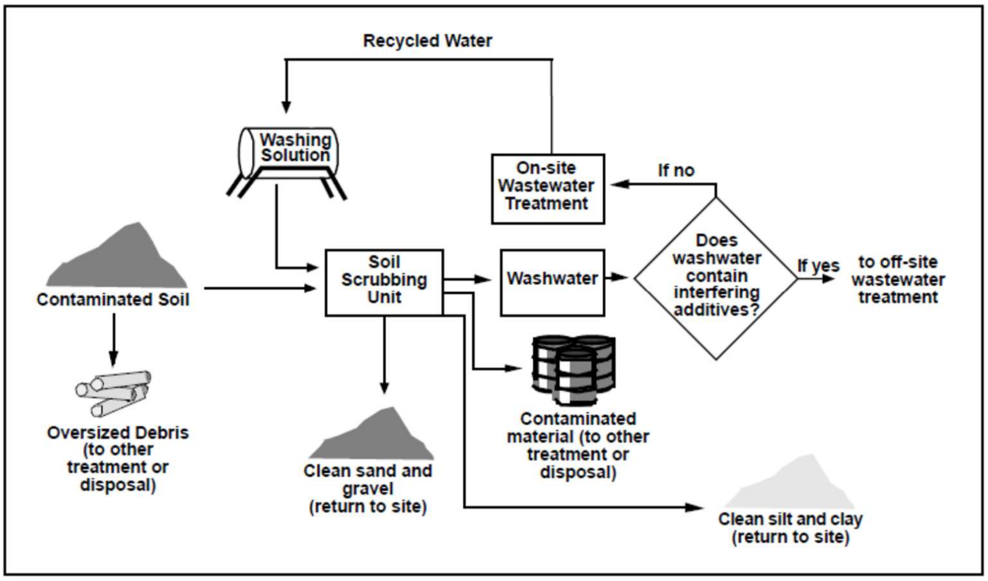
Technique	Soil Washing (Ex-situ)			
Type, media	**Applicable contaminants**	**Technology maturity (M-MMMM)**	**Costs (£ to ££££)**	**Final or Interim Solution**
Physical/chemical, soil	All mobile inorganic and organic contaminants and a range of radionuclides (e.g. uranium, radium, thorium, caesium, plutonium, technetium and strontium)	M	££+	F

Technology

Soil washing is the process whereby contaminated soils are excavated to an above ground treatment plant and mixed with water, to produce a slurry. This washing process can be undertaken with or without the addition of surfactants to the water depending on the chemistry of the contaminant. Finer clay particles, to which contaminants are bound, and coarser clean soil particles are then separated by a scrubbing machine. Any remaining contaminants are suspended or dissolved in the wash while the coarser material is scrubbed to remove surface contamination. The contaminated soil or slurry can then be treated further or disposed of, while the clean soil can be returned to its original location or used elsewhere as backfill. Soil washing must be used with other treatment technologies, such as precipitation, filtration and/or ion exchange. Many trials and pilot sites have been established in the US but the technology has not been widely applied in the UK to radiological contamination.

Implementation

Initially the contaminated soils need to be excavated and removed from the source area. Once removed the soils will need to be suitably stored pending transfer to the washing facility. Once at the facility, the washing process can commence. Water is mixed with contaminated soil and debris to produce a slurry feed. This feed enters through a scrubbing machine which removes the contaminated fine soil particles (silts and clay) from granular soil particles. Contaminants are generally bound more tightly to the fine soil particles and not to larger grained sand and gravel. The separation processes can include screening to divide soils into the coarse and fine fractions and dissolving or suspending contaminants in the wash. The sand and gravel fraction is usually passed through an abrasive scouring or scrubbing action to remove surface contamination. The fine fraction can be separated further in a sedimentation tank, sometimes with the help of a flocculating agent through precipitation, filtration or ion exchange. The output streams of these processes consist of clean granular soil particles, contaminated soil fines, and process/wash water, all of which are tested for contamination. Soil washing is effective only if the process transfers the radionuclides to the wash fluids or concentrates them in a fraction of the original soil volume. This fraction and wash water may need further treatment prior disposal to meet specifications of final disposal facility.



Soil Washing Process Overview[1]

Constraints
Access: While the exaction work is ongoing to remove the soils, full access to the site is needed. In addition, unless the soil is removed from site when excavated, site will need some space to store the material appropriately. **Site conditions:** Soil washing is most effective when the contaminated soil consists of less than 25% silt and clay and is at least 50% larger particles of sand and gravel. In addition to this, soil washing is most effective in soils where there is total organic carbon less than 10%. Excavation from the surface must also be practicable and be above the groundwater table. **Sustainability (waste, energy, amenity impacts):** Wash liquors may require separate disposal to any remaining contaminated soils and may prove challenging to dispose of. The ongoing process shall require moderate energy consumption. Excavation works to remove the soils will generate noise and dust. **Timescales:** Characterisation, bench and field trials will be required to determine how the inventory may respond during the washing process; however, large volumes of soil can be treated within months rather than years. **Durability:** Contamination is bulk removed from the land making this a very effective technology.
Aftercare
Once it has been demonstrated that all required source material has been removed there is no aftercare required.
Guidance
EPA, Technology referencing Guide for Radioactively Contaminated Media, EPA 402-R-07-004, 2007 IAEA. Remediation of sites with dispersed radioactive contamination, Technical Reports Series: No.424, 2004 Federal Remediation Technologies Roundtable (2002) Remediation Technologies Screening Matrix and Reference Guide, 4th Edition, 2002 CIRIA C662 (2004) Selection of remedial treatments for contaminated land, A guide to good practice, 2004

[1] Image reproduced from 'EPA A Citizen's Guide to Soil Washing, EPA 542-F-96-002, 1996' with permission from Linda Fiedler

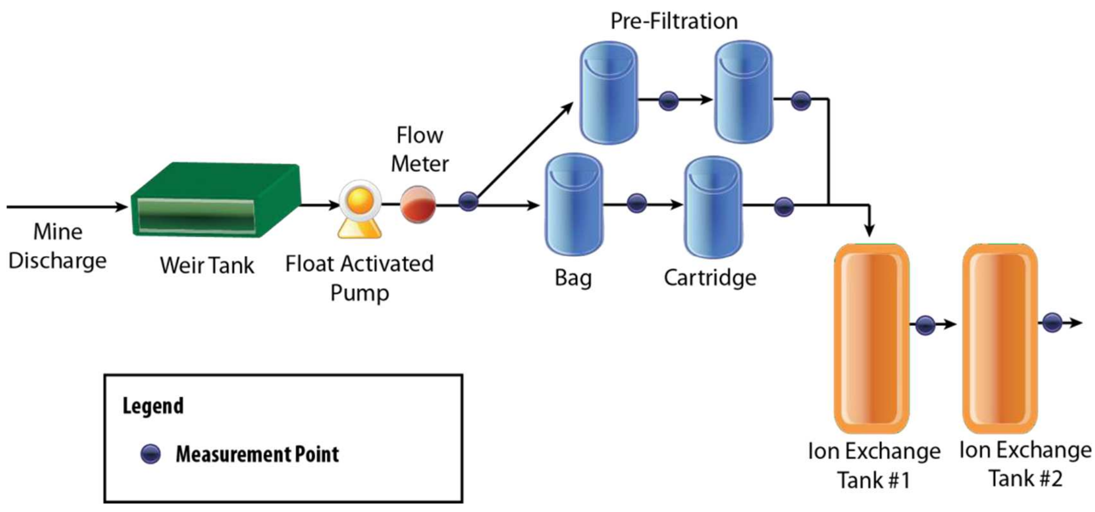
Technique	Ion Exchange			
Type, media	**Applicable contaminants**	**Technology maturity (M-MMMM)**	**Costs (£ to ££££)**	**Final or Interim Solution**
Physical/chemical, groundwater	Soluble inorganic contaminants and wide range of radionuclides (such as: radium, uranium, strontium, plutonium, caesium and tritium)	MMM	££	F

Technology

Ion exchange is a chemical separation process that removes dissolved metals and other inorganic chemicals from contaminated groundwater. Ion exchange is commonly used for the removal of both natural (e.g. Uranium and Radium) and man-made (e.g. Caesium, Strontium and Technetium) radionuclides. Ion exchange works by replacing radionuclides in a waste stream with relatively harmless ions from a synthetic resin or natural zeolite. If the electrochemical potential of the contaminant ion is greater than that of the harmless 'exchangeable' ion, then the exchange ion goes into solution and the contaminant ion binds to the resin. Resins must be periodically regenerated or replaced. Ion exchange significantly reduces contaminant mobility by immobilizing it in the exchange media but does not affect the radiotoxicity of the contaminant itself. It is most effective when the waste stream is in the ionic form; non-ionic waste streams or waste streams with suspended solids must be pre-treated. The concentrated radioactivity removed from the resin, and spent resin itself, must be treated, stored, or disposed of.

Implementation

Wells are required from which the contaminated ground water is extracted. The liquid is pumped through ion exchange units comprising of columns or beds, containing the exchange resin beads. The effectiveness of the ion exchange process depends on a number of factors including the contaminant concentration, flow rate and the resin's selectivity and exchange capacity. Pre-treatment e.g. filtering and pH adjustment, or removal of competing ions, is usually necessary. If more than one radioactive contaminant is present, more than one resin may be required. Monitoring is undertaken to record and control the relevant factors and determine when ion exchange resin bed requires regeneration/replacement. The concentration of radiological contaminants collected on the resin will affect the classification of the wastes resulting from this process.



Overview of Ion Exchange Process[1]

Constraints
Access: To treat contaminated ground water a plant comprising of suitable pumps, pre filters and ion exchange columns etc, will be required. Such equipment is often modular minimising the construction work required at site and may be as simple as the pumping of prefiltered water through barrels containing the resin. It may also be located away from the area of contamination and connected to the wells via pipework. **Site conditions**: The effectiveness of the process depends on the radiological contaminants present and also any contaminants that may hinder the process. Pre-treatment is possible to remove solids/oils that may clog the exchange column, or organics and competing ions, that could interfere with the removal of the target contaminant. Oxidants in the waste stream can damage the ion exchange resin. **Sustainability (waste, energy, amenity impacts):** This technique requires use of resins to capture contamination. These resins need to be periodically changed and disposed of so final disposal routes need to be secured and accounted for in any optioneering. It should be noted that spent ion exchange resins are considered to be a problematic waste. The physical impacts and energy demands are relatively low and zeolites are cheaply obtained. **Timescales**: A period of characterisation and development will be necessary to determine whether the technique can be implemented. Given the potential variability in groundwater conditions and contaminants it is likely that a bespoke plant will be required with associated bench and field scale pilot trials to prove the design. **Durability:** Since contaminants are removed from land, this technology is very effective in the long-term.

Aftercare
Monitoring of local groundwater will be required to show that the ion exchange plant is having the desired impact on overall groundwater contamination. Once a resin is 'spent' and it is no longer performing its function it must either be regenerated or replaced. Replacement is often preferable to regeneration as the radioactivity has been sequestered within the ion exchange resin and a further liquid waste stream is not generated.

Guidance
EPA (2007), Technology Referencing Guide for Radioactively Contaminated Media, EPA 402-R-07-004, 2007 Federal Remediation Technologies Roundtable (2002) Remediation Technologies Screening Matrix and Reference Guide, 4th Edition, 2002 CIRIA C662 (2004) Selection of remedial treatments for contaminated land, A guide to good practice, 2004

[1] Image reproduced from 'EPA Referencing Guide to Treatment Technologies for Mining-Influenced Water, EPA 542-R-14-001,2014' with permission from Linda Fiedler

TEMPORARY CONTAINMENT

Technique	Hydraulic Barriers			
Type, media	**Applicable contaminants**	**Technology maturity (M-MMMM)**	**Costs (£ to ££££)**	**Final or Interim Solution**
Containment, groundwater	All mobile contaminants	MMM	£	I

Technology

Hydraulic Barriers are constructed from a series of wells installed at suitable distance to one-another to form an effective containment boundary. The wells are located down gradient of a contamination plume. As groundwaters are pumped to above ground temporary containment, through the wells, the draw of the pump forms an effective barrier which contaminated groundwaters do not migrate beyond. This contains the plume, rather than treating it, but prevents it from spreading to pollute sensitive receptors. The technique works similarly to a pump and treat technique without the treat element.

Implementation

This remediation technique involves the installation of one of more wells to contain a contamination plume. The wells need to be installed down gradient of the plume migration at a suitable distance from the source. This distance will vary dependant on the geometry of the plume and shall be underpinned by the conceptual site model. It is important to note that the ground model should be fully understood before the drilling of any new wells. If a well is too shallow it will be ineffective. A well could also penetrate an impermeable layer in the geology, such as a clay, potentially accelerating the plume dispersion. Once installed the wells are used to extract groundwaters using submersible pumps. Waters are pumped to ground level drawing surrounding waters to the well. As the system continues to pump, contaminated waters are drawn towards the well for extraction. The plume waters are prevented from passing the barrier and are instead removed. The system can be operated remotely and thus not unnecessarily expose workers to potential hazards. The system will require ongoing monitoring to ensure correct operation and samples of groundwater from beyond the hydraulic barrier will need to be collected to demonstrate the effectiveness of the system.

Constraints

Access: Initially required to install wells, potentially over a large area dependant on how dispersed the plume is. Space will be necessary to store the water drawn up through the wells for the duration of pumping operations. Access will also be required to well heads to perform routine maintenance.
Site conditions: The ground conditions must be suitable for the chosen technique. There needs to be suitable groundwater flow to maintain optimum pumping rates. An assessment of potential impacts to surrounding structures will be needed to confirm that removal of fines or drawdown of water levels will not contribute to ground settlement or stability issues.
Timescales: The drilling of new wells can be relatively quick ranging from a few days to a few weeks dependant on the local site rules and the depth and number of wells required. The implementation may last for a few years to several decades.
Sustainability (waste, energy, amenity impacts): Low energy to install the system of wells, with some drilling arisings to dispose. Although low impact, operation and maintenance of the pumps will be ongoing for potentially a number of years, and so energy usage may accumulate. A receipt area for the extracted groundwater will be required and for any groundwater not meeting discharge specifications, a disposal route will be required which may become unsustainable if the system is operated over a long period of time.
Durability: Once installed, monitoring wells remain functional for decades with correct maintenance of pumps and protective headworks.

Aftercare

Monitoring of groundwater quality down gradient for a period after installation is usually required to demonstrate correct functioning of the system, and periodic monitoring after this to confirm it remains effective.

Guidance

EPA, Technology referencing Guide for Radioactively Contaminated Media, EPA 402-R-07-004, 2007
IAEA. Remediation of sites with dispersed radioactive contamination, Technical Reports Series: No.424, 2004

Technique	Redox Stabilisation			
Type, media	**Applicable contaminants**	**Technology maturity (M-MMMM)**	**Costs (£ to ££££)**	**Final or Interim Solution**
Containment, soil and groundwater	Redox sensitive metal/radionuclide contaminants (particularly Tc, Np, U and Pu)	MM	££	I

Technology

The mobility of metals and radionuclides changes under different redox and pH conditions (redox changes the oxidation state of the radionuclide, resulting in a less mobile form)The injection of aqueous solutions of appropriate redox buffering agents or reactive gasses (e.g. hydrogen sulphide or sulphur dioxide diluted in an inert gas) into the contaminated zone, to enhance attenuation, can temporarily reduce the mobility of a contaminant until such time as a permanent remedial solution can be implemented. Technology is often used in situations where treatment is otherwise difficult, such as in fractured rock. The treatment can fix contamination to soil solids and result in reduced concentrations and mobility to groundwater.

Implementation

The first stage of implementation would be a treatability study to demonstrate the effectiveness of a selected redox buffering agent in the site specific environment, prior to full scale implementation. The redox stabilisation solution would be introduced in-situ, through injection wells into the contaminated area. Further groundwater monitoring wells would be required outside of the treatment area for monitoring to demonstrate the reduction in mobility and hence migration of contaminants. Ongoing analysis of redox and pH conditions will be required to balance the injection process. Redox stabilisation can be locally enhanced by adding additional sorption sites to soils by the addition of clay or zeolites within the contaminated area.

Constraints

Access: Initially required to install wells, potentially over a large area dependant on how dispersed the contamination is. Space will be required on an ongoing basis for a surface injection and control system and access will also be required to well heads to perform routine maintenance and sampling activities.
Site conditions: The ground conditions must be suitable for the chosen buffering solution and it must have adequate sorption geochemistry.
Timescales: The drilling of new wells can be relatively quick ranging from a few days to a few weeks dependant on the local site rules and the depth and number of wells required. The implementation may last for a period extending over ten years, depending upon fluctuating geochemical conditions.
Sustainability (waste, energy, amenity impacts): Long term sustainability is uncertain due to competing geochemical processes. This is considered to be a low energy process (though total energy usage will accumulate if operated over an extended period), with minimal visual impact and loss of amenity space.
Durability: Once installed, injection and monitoring wells can remain functional for decades with correct maintenance of pumps and protective headworks.

Aftercare

Monitoring of groundwater quality down gradient of the area of contamination is required to demonstrate correct functioning and redox and pH balance within the system. Continual monitoring of redox and pH indicators is required to adjust and maintain optimum conditions.

Guidance

EPA, Technology referencing Guide for Radioactively Contaminated Media, EPA 402-R-07-004, 2007
IAEA. Remediation of sites with dispersed radioactive contamination, Technical Reports Series: No.424, 2004
Hu QH, Zavarin M, Rose TP. Effect of reducing groundwater on the retardation of redox-sensitive radionuclides. Geochem Trans. 2008;9:12. Published 2008 Dec 12. doi:10.1186/1467-4866-9-12

APPENDIX D - OTHER REMEDIATION TECHNOLOGIES AND FRTR TABLE 3.2

OTHER REMEDIATION TECHNOLOGIES

Remediation Technique	Brief Description	Application
Physical Containment		
Cryogenic Barrier	Cryogenic barriers involve the freezing of contaminated soils to create an ice barrier around the contaminated zone, confining contaminated groundwater and therefore reducing the mobility of radionuclides on the site; this is achieved by inserting freezing pipes in an arrangement around the contaminated zone. Cryogenic barriers rely on the presence of groundwater within the soil to freeze and form an ice barrier; therefore, the moisture content of the soil must be considered in the implementation of this technique. High volumes of water in the subsurface may increase the costs of implementing a cryogenic barrier to freeze a larger volume of water. Cryogenic barriers are best used to immobilise radionuclides in soluble forms. On-going refrigeration is required to maintain the barrier and therefore increased energy/power may be required in cases where there are higher ambient temperature conditions. Cryogenic barriers have the advantage of being deployable within a few months once a refrigeration plant has been installed on site. Additional benefits are that they can be deployed on sites with ground movement/subsidence due to their ability to be repairable in-situ. Provided refrigeration is maintained, cryogenic barriers do not weaken or degrade over time. The contamination is left immobilised within the subsurface. This will have implications for future land uses, for example, should the site wish to delicence. This is more likely to be used as a temporary holding, or short-term, solution as once the refrigeration units are switched off, the contamination would be remobilised.	Cryogenic barriers are effective in the containment of short-lived radioactive contaminants due to the energy intensive process of continual refrigeration. Full scale demonstrations of cryogenic barriers have been demonstrated in the USA. The system was demonstrated to be economically sustainable and physically reliable for 20-50+ years, therefore becoming an effective treatment for short-lived radionuclides such as tritium.

Remediation Technique	Brief Description	Application
Land Encapsulation	Land encapsulation is an in-situ technique that uses a combination of capping and in- situ sub-surface barriers (e.g. linings or grouted walls) to effectively isolate the contaminants in the ground. This can be implemented by excavating the disposal area, lining it with an impermeable liner and backfilling the excavated contaminated land. This can be done at the original location or another site. The method can be effective for 10s to 100s of years, provided the capping and the barriers are effectively maintained. The process is effective for both radioactive and chemical contaminants. Liners used in land encapsulation often form two or more composite layers, for example a geomembrane and a compacted soil layer, with a leachate collection system located above and between the liners. Clays can also be used in land encapsulation (for example bentonite and smectite) as these have the advantage of being both impermeable and able to bind hazardous cations. Another method used in land encapsulation is the in-situ emplacement of subsurface impermeable barriers through jet grouting; this has been demonstrated in the U.S. at the Hanford Site and at the DOE's Brookhaven National Laboratory. Once the encapsulation and capping have been established there are no energy requirements, apart from ongoing monitoring to demonstrate continued performance of the containment. The use of another site may have wider impacts to the environment as waste materials may need transporting large distances. The contamination is left in-situ for the duration of the implementation of this technique and the regulatory implications of disposing of contamination in this way need to be fully understood along-side impacts to final site end states and site licence/permit surrender.	Both capping and land encapsulation are mature, well understood technologies that have been used in the containment of radioactively contaminated land and radioactive waste on a number of nuclear licensed sites and landfill sites permitted to accept radioactive waste; for example, the Low Level Waste Repository (LLWR), Lillyhall Landfill Site, Clifton Marsh Landfill Site.
Chemical Separation		
Adsorption	Adsorption is an ex-situ technique for treating ground water. The groundwater is pumped through a series of vessels containing an adsorbent. Dissolved contaminants in the groundwater are adsorbed by sticking to the surface / within the pores of the adsorbent media. Adsorbents used include granular activated carbon, alumina, forager sponge and lignin absorption/sorptive clay. Carbon adsorption systems are common; activated carbon often being used in the cleaning of drinking water. Carbon adsorption systems are usually set up as a series of continuous flow columns. Pre-treatment to remove suspended solids is generally required to prevent fouling and reduction of through	Activated carbon is a well-established treatment for removing organic compounds and is offered commercially by a number of different companies, however, their use in removing inorganic compounds is not widespread.

Remediation Technique	Brief Description	Application
	flow. The granular carbon will require replacing periodically, this is indicated by an increase in the number of contaminants in the effluent. Secondary wastes are potentially generated during implementation, contaminated reagents will need replacing.	
Chemical Precipitation	Chemical precipitation is an ex-situ technique that can be used to treat extracted groundwater contaminated with soluble radionuclides. A chemical precipitant is added to the contaminated water which causes the contaminant to become insoluble and come out of solution. The contaminant can then be removed by a combination of filtration, clarification and coagulation. The resulting sludge containing the precipitated radionuclides will require further processing for disposal. The method can be performed in a batch or continuous process. Typically used precipitants include carbonates, sulphates and sulphides. The precipitants may need to be removed from the treated groundwater prior to discharge. If the ground water contains a combination of different contaminants, then several different stages of precipitation may be required. Some radionuclides e.g. cobalt and technetium, will also require additional stages, such as chemical reduction. Implementation of this technology will have a high energy requirement. The decision to run a batch or continuous processes should consider waste streams. Disposal limits at the waste receiver may dictate how to optimally operate and bench and field pilot trials will be critical in determining the optimum operating parameters.	The method has been shown to be successful in the treatment of uranium and radium at a number of sites in the US.
Solvent Extraction	Solvent Extraction is an ex-situ technique that separates hazardous contaminants from soils, sludges, and sediments. The contaminants dissolve and concentrate within the solvent which is then removed for processing. Solvent extraction can be used as a standalone remediation technique or can be used in combination with other techniques such as solidification/stabilisation or soil washing. Applicable solvents include complexing agents, organic solvents, and mineral acids. Solvent extraction involves excavating soil and mixing it with the solvent in a mixing tank (the use of water alone as a solvent is known as Soil Washing). When the contaminants have been sufficiently extracted, the solvent can be separated from the soil and either distilled in an evaporator column or removed from the leachate as a	Large debris will require removal before processing. Multiple solvents may need to be used in cases where multiple different contaminants are present. Mineral acids, such as sulphuric, hydrochloric or nitric acid, can dissolve large proportions of the soil matrix, in addition to the contaminants, and therefore may not be suitable for certain sites. Low permeability and

Remediation Technique	Brief Description	Application
	precipitate. In either case, the resulting product will require disposal. The soil may be sufficiently clean after the process to be returned to its original location. Acid extraction is suitable for the removal of heavy metals. Organic solvent extraction can be used on organically bound metals and organic contaminants. Physical separation prior to treatment may optimise the process as contaminants are often associated with the finer material. The process will have high energy cost and may produce multiple waste streams for separate disposal.	heterogeneous soils can be hard to treat.
Supercritical Fluid Extraction	Supercritical fluid extraction is a novel ex-situ technique which uses the special properties of supercritical fluids to remove organic contaminants from contaminated soils. A supercritical fluid is formed when an element reaches its critical point; this is defined as the temperature and pressure at which the liquid and gaseous phases merge. At this point the element has both liquid and gaseous properties and so is referred to as a fluid. These properties include a high material density, like a liquid, allowing for a high capacity for solutes, but with a large diffusivity and low viscosity, like a gas, allowing the fluid to easily pass through media. This allows the supercritical fluids to quickly permeate a matrix (e.g. the soil), dissolve an organic compound, and transfer it out quickly. By lowering the temperature and pressure in the treatment vessel, the contaminants can then come out of solution. Carbon dioxide is particularly useful as a supercritical fluid as it has large changes in properties for relatively small changes in temperature and pressure. It is also non-toxic and non-combustible. This process will have high energy demands and likely require the construction of a bespoke facility.	This method has been used in trials by the US Department of energy to remove organic materials from mixed waste, allowing for subsequent disposal of the waste. They have also proposed adding a complexing agent to the supercritical fluid, to allow for the extraction of metallic radionuclides.
In-situ Gaseous Reduction	In-situ gaseous reduction involves the injection into the ground of a low concentration of reactive gas, such as hydrogen sulphide or sulphur dioxide, diluted in an inert gas. When the gas encounters redox-sensitive contaminants in the ground, such as uranium, the oxidation state of the radionuclide is reduced, and it becomes less mobile. The gas mixture is injected at a central well and then removed at other wells outside of the contaminated area using a vacuum. The gas will preferentially follow the most permeable pathways, and so contamination in areas of lower permeability may not be treated. This process will require novel plant to be set up on site and operated for a period of time.	Laboratory scale trials of this technique have been undertaken in the US and shown a ~50% immobilisation of uranium and technetium (separate trials). A field trial has been performed on non-radioactive chromium.

Remediation Technique	Brief Description	Application
Elektrokinetic	The application of a low intensity direct current via electrode pairs situated within the contaminated ground mobilises charged ions and water via a number of processes causing them to migrate towards the electrodes. The contaminants can then be collected at the electrodes. The technique works particularly well for metals. The process can be performed in-situ by installing electrodes directly into the ground or in can be done ex-situ on soil piles, or soil within large containers. The electrodes can be arranged within an array, so the electric field applied covers the whole area of treatment. Relatively large areas can be treated at a time. The power can be supplied by an AC generator coupled with a DC converter. The contaminants can be removed at the electrode via a number of techniques such as electroplating the electrodes or pumping off the groundwater containing the concentrated contamination. This technique shall have a high energy demand and will require permits to set up electrodes on site.	The technique works best on fine grained material such as clay. The water content of the land must be greater than ~10% to be effective, though additional fluid can be added if required. Buried services and metal ores can disrupt the electric field.
Physical Separation		
Membrane Filtration	Membrane filtration refers to either micro filtration, or reverse osmosis, and are ex-situ techniques for the treatment of contaminated water. Micro filtration removes suspended radionuclides from contaminated water by passing the water through a thin membrane with small pore size which intercepts the suspended radionuclides. Complexing agents may be used first to increase the size of the molecules associated with the contaminants to enhance the process. Reverse osmosis uses a selective semi-permeable membrane which allows water through but concentrates the dissolved radionuclide ions on the contaminated liquid side of the membrane. High pressure is required to overcome the normal osmotic potential. Pre-treatment of the contaminated water is often required for both techniques to reduce the chance of damage to, or fouling of, the membranes. The techniques may be used in combination with each other, or, as part of a series of other processes. In either case additional waste will be generated e.g. filter cake or liquid concentrate.	A number of trials using these techniques have been performed by nuclear operators. The techniques are in commercial use in the US to reduce the concentration of radionuclides (uranium and radium) in public drinking water.

Remediation Technique	Brief Description	Application
Flotation	Flotation separates radionuclide contaminant fractions of the soil. It is used to reduce the amount of soil required to be disposed of. The mechanism works by passing small air bubbles through a soils and water slurry, to which the contaminated particles then adhere to. The bubbles and contaminants form a foam which is transported to the surface. The foam is then mechanically skimmed from the surface where it can be treated further or disposed of. After dewatering and drying, the clean soil can then be returned to the excavation area. Once excavated and removed from site, floatation agents and contaminated soil are placed into a large industrial mixer. There the flotation process commences with the addition of water. Whilst 'mixing' a foam raises the contamination to the surface. This foam contains soil fines and is removed for treatment and/or disposal. The remaining soil and water are separated, with the water recycled back into the process. Remaining soils are to be tested to be classed as clean.	At present this technology is mainly at a laboratory bench stage for radioactively contaminated soils. However, the technology is widely used in the mining industry for heavy metals.
Magnetic Separation	Magnetic separation is a novel ex-situ process that uses magnetic fields to separate contaminants from contaminated liquids/slurries. One process uses the fact that uranium and plutonium are paramagnetic, meaning that they are slightly magnetic in the presence of a magnetic field, and this magnetism increases with the field strength. A magnetic field is applied externally to a suitable matrix, such as steel wool, which the contaminated liquid is passed through. The paramagnetic elements will then adhere to the matrix and so be removed from the liquid stream. The success of this techniques is variable, and often results in much non-radioactive material also being removed. A further proprietary technique uses iron particles coated with ion exchange resin. These are mixed with the contaminate liquid and the radionuclides are adsorbed onto the coated particles. These can then be separated using a magnetic field in a similar way to the process above. This process requires large amounts of energy to supply the magnetic field.	Bench scale trials have been performed in the US for paramagnetic separation. The proprietary process of using iron particles coated with ion exchange resin has been applied in field trials.
Stabilisation/Solidification		
Thermal Vitrification	Vitrification involves heating contaminated material to extremely high temperatures (>1000°C), then cooling to form a solid, glassified mass that contains and traps the radioactive contaminants. Vitrification processes can be performed both in-situ and ex-situ.	Ex-situ vitrification is usually only used for small volumes of high activity waste. Therefore, its applicability to

Remediation Technique	Brief Description	Application
	In-situ vitrification uses an electric current to melt soil or other media at extremely high temperatures. Radionuclide contaminants become immobilised within the vitrified glass, which is chemically stable, leach resistant and durable. In-situ vitrification volatises and destroys organic pollutants, breaking them down into their element components. Volatile radionuclides are also released. A vacuum hood is usually placed over the treatment area to collect off gases. These can then be treated prior to release. Traditionally, in-situ vitrification uses a square array of four graphite electrodes; electrical power is supplied to the electrodes through flexible conductors; a starter path of graphite flakes and glass frit is placed between them and as the electrical current is established, the starter path heats up and the surrounding soil melts. Once the soil melts, it too becomes electrically conductive, melting more soil. The electrode array is then lowered progressively as the melt grows to the required treatment depth. Ex-situ vitrification can use a range of different furnaces to heat the contaminated material and additional material (e.g. glass beads) can be added to improve the quality of the resulting waste product. The molten glass can be drained from the furnace into containers. Pending solidification these will require disposal. The process will require large amounts of energy to provide heat suitable to melt the wastes. When operated in-situ complex plant will need to be mobilised.	contaminated land in a UK context will be limited.
Biological		
Phytoremediation	Phytoremediation is an in-situ remediation method. The natural ability of plants is utilised to extract, accumulate, store and/or degrade organic, inorganic and radionuclide contaminants. Once the vegetation has grown to an optimum size it is harvested and disposed of. The process of growth and removal can then be repeated as necessary. This technique does not treat or dispose of the contaminant, just moves it from the soil into the biomass of the chosen plant. This technology can be used for a range of contaminants, radioactive and conventional, as the plant will uptake localised contaminant laden groundwaters. This technique may be utilised to treat shallow soils, soil water and runoff via a number of mechanisms: • Phytoextraction – the use of plants which can take up and store high concentrations of contaminants (called hyperaccumulators). The process separates the contaminants from the soil through the roots	Considerations would include the depth of contaminant. As the roots are required to provide an uptake mechanism, the technique only works to limited to depth. Phytoremediation is suitable for use in cases of extensive wide-spread contamination where other remediation methods would not be cost effective or practicable.

Remediation Technique	Brief Description	Application
	• Phytovolatisation – the contaminant is separated from the soil, translocated through the plant and transpired through the leaves • Phytosabilisation – takes place within the roots and root zone of plants and immobilises the contaminants by preventing their migration • Phytocontainment – the use of plants to establish a cover layer on sites to reduce the migration of contaminants and to restrict the availability of contaminants to humans by minimising surface erosion, runoff, dust generation and skin contact. To utilise this technique a suitable crop needs to first be chosen. There are a wide range of crops to select from; each crop better or worse suited dependant on the contaminant of concern: radionuclides, heavy metals, inorganics or organics. The two main areas of consideration are on vertical depth and lateral coverage of the rooting system of the selected plants categorised into anchor plants, shrub plant or creeping plant. This choice may be informed by the depth of contamination and the size of plume. Before planting there may need to be a period of site preparation, for example: weeding of existing grasses, introduction of clean soil to allow for growth and/or liming to obtain neutral pH condition. This technology is best suited to sites with lower levels of contamination and can proceed slowly. Contaminants are likely to also be toxic for the plant material, gross contamination may kill the plants. The technique is also limited to shallow contamination as the limit of effectiveness is to the depth of the roots. Thus, it is not suitable for grossly contaminated sites planning a fast remediation programme. Plants most suited for phytoremediation have a high growth rate, widely distributed root systems; effective accumulation of target contaminants and effective translocation of accumulated contaminants from roots to shoots, tolerance of the toxic effects of the target contaminants, are easy to cultivate and harvest, and have repulsion to herbivores to avoid food chain contamination.	
Enhancement		
Hydrofracturing Enhancements	Hydrofracturing enhancement is an in-situ technique which uses the injection of high-pressure water into wells to create cracks, or fissures, in low permeability or over consolidated sediments. The fissures are then filled with a porous media (e.g. sand), so that they do not close, allowing fluids to travel through them. The technique is an *enhancement* used alongside other remediation techniques. For example, the pathways now available within the ground can be used to transport nutrient fluids to enable bioremediation, or, used to transport ground water for treatment ex-situ.	Hydraulic fracturing has a long history of use in the petrochemical and water well industries. Its application to land remediation is relatively novel and new.

Remediation Technique	Brief Description	Application
	The technique is not suitable in ground that is susceptible to seismic activity. It is also not possible to precisely control where water and sand will travel within fissures, thus, there is a risk that new pathways may be formed allowing the contaminants to spread.	
Main References for Further Reading		
EPA (2007), Technology Referencing Guide for Radioactively Contaminated Media, EPA 402-R-07-004, 2007 Federal Remediation Technologies Roundtable (2002) Remediation Technologies Screening Matrix and Reference Guide, 4th Edition, 2002 CIRIA C662 (2004) Selection of remedial treatments for contaminated land, A guide to good practice, 2004		

FRTR TABLE 3.2

TABLE 3-2: TREATMENT TECHNOLOGIES SCREENING MATRIX

Rating Codes
● Above Average
◑ Average
○ Below Average
N/A - "Not Applicable"
I/D - "Insufficient Data"
◇ - Level of Effectiveness highly dependent upon specific contaminant and its application

	Development Status	Treatment Train	Relative Overall Cost & Performance: O&M	Capital	System Reliability & Maintainability	Relative Costs	Time	Availability	Nonhalogenated VOC's	Halogenated VOC's	Nonhalogenated SVOC's	Halogenated SVOC's	Fuels	Inorganics	Radionuclides	Explosives
Soil, Sediment, Bedrock, and Sludge																
3.1 In Situ Biological Treatment																
4.1 Bioventing	●	●	●	●	●	●	◑	●	●	◇	●	○	●	○	◇	○
4.2 Enhanced Bioremediation	●	●	○	◑	◑	●	◑	●	●	●	●	◇	●	◇	◇	●
4.3 Phytoremediation	●	●	●	●	○	●	○	◑	◑	◑	◑	◇	◑	◑	○	○
3.2 In Situ Physical/Chemical Treatment																
4.4 Chemical Oxidation	●	●	○	◑	◑	◑	●	●	◑	◑	○	◑	○	◇	○	◑
4.5 Electrokinetic Separation	●	○	○	◑	◑	○	◑	◑	◑	◑	◑	◑	○	●	◑	○
4.6 Fracturing	●	◑	◑	○	◑	◑	◑	●	◑	◑	◑	◑	◑	○	○	○
4.7 Soil Flushing	●	●	○	◑	◑	◑	◑	●	●	●	◑	◑	◑	●	○	○
4.8 Soil Vapor Extraction	●	○	○	◑	●	●	◑	●	●	●	○	○	●	○	○	○
4.9 Solidification/Stabilization	●	●	◑	○	●	●	●	●	○	○	◑	◑	○	●	●	○
3.3 In Situ Thermal Treatment																
4.10 Thermal Treatment	●	○	○	○	●	◑	●	●	●	●	●	●	●	○	○	○
3.4 Ex Situ Biological Treatment (assuming excavation)																
4.11 Biopiles	●	●	●	●	●	●	◑	●	●	●	◑	◇	●	◇	○	○
4.12 Composting	●	●	●	●	●	●	◑	●	◑	◑	◑	◇	●	○	○	●
4.13 Landfarming	●	●	●	●	●	●	◑	●	◑	◑	●	◑	●	○	○	◇
4.14 Slurry Phase Biological Treatment	●	○	○	○	◑	◑	◑	●	◑	●	●	◇	●	◇	○	●
3.5 Ex Situ Physical/Chemical Treatment (assuming excavation)																
4.15 Chemical Extraction	●	○	○	○	◑	◑	◑	●	◑	◑	●	●	◑	●	◑	○
4.16 Chemical Reduction /Oxidation	●	◑	◑	○	●	◑	●	●	◑	◑	◑	◑	◑	●	○	◑
4.17 Dehalogenation	●	◑	○	○	○	○	◑	◑	○	●	○	●	○	○	○	◑
4.18 Separation	●	◑	○	◑	●	◑	●	●	◑	◑	◑	◑	○	◑	○	○
4.19 Soil Washing	●	○	○	○	●	◑	●	●	◑	◑	◑	◑	◑	◑	○	○
4.20 Solidification/Stabilization	●	●	◑	○	●	●	●	●	○	○	◑	◑	○	●	●	○
3.6 Ex Situ Thermal Treatment (assuming excavation)																
4.21 Hot Gas Decontamination	○	●	○	○	●	●	●	◑	○	○	○	○	○	○	○	○
4.22 Incineration	●	●	○	○	◑	○	●	●	●	●	●	●	●	○	○	●
4.23 Open Burn/Open Detonation	●	●	○	○	●	●	●	●	○	○	○	○	○	○	○	●
4.24 Pyrolysis	●	●	○	○	○	○	●	●	◑	◑	●	●	◑	○	○	○
4.25 Thermal Desorption	●	●	○	○	◑	◑	●	●	●	●	●	●	●	○	○	●
3.7 Containment																
4.26 Landfill Cap	●	●	◑	○	●	●	○	●	◑	◑	◑	◑	◑	◑	○	◑
4.27 Landfill Cap Enhancements/Alternatives	●	●	◑	○	●	●	○	●	◑	◑	◑	◑	◑	◑	○	◑
3.8 Other Treatment																
4.28 Excavation, Retrieval, Off-Site Disposal	●	●	●	●	●	◇	●	●	◑	◑	◑	◑	◑	◑	○	◑
Ground Water, Surface Water, and Leachate																
3.9 In Situ Biological Treatment																
4.29 Enhanced Bioremediation	●	●	○	◑	◑	●	◇	●	●	◇	●	◇	●	◇	○	◑
4.30 Monitored Natural Attenuation	●	●	○	◑	◑	●	◇	●	●	◑	◑	◑	●	○	○	○
4.31 Phytoremediation	●	●	●	●	○	●	○	◑	◑	◑	◑	◑	◑	◇	○	○
3.10 In Situ Physical/Chemical Treatment																
4.32 Air Sparging	●	●	●	●	●	●	●	●	●	◑	◑	◑	●	○	○	○
4.33 Bioslurping	●	◑	●	●	◑	●	◑	●	◑	◑	●	●	●	◑	○	○
4.34 Chemical Oxidation	●	●	○	◑	◑	◑	●	●	◑	◑	○	◑	○	◇	○	◑
4.35 Directional Wells (enhancement)	●	●	◑	○	◑	◑	◑	●	◑	◑	◑	◑	◑	◑	○	◑
4.36 Dual Phase Extraction	●	○	○	○	◑	◑	◑	●	●	●	●	●	●	○	○	○
4.37 Thermal Treatment	●	○	○	○	◑	◑	●	●	◑	●	●	●	●	○	○	○
4.38 Hydrofracturing Enhancements	●	◑	●	●	●	◑	◑	●	◑	◑	◑	◑	◑	◑	○	◑
4.39 In-Well Air Stripping	●	◑	◑	○	◑	◑	○	●	◑	◑	◑	○	◑	○	○	○
4.40 Passive/Reactive Treatment Walls	●	●	◑	○	●	◑	○	●	●	●	●	●	◑	◇	○	●
3.11 Ex Situ Biological Treatment																
4.41 Bioreactors	●	●	◑	○	◑	●	◑	●	●	●	●	◇	●	○	○	●
4.42 Constructed Wetlands	●	●	◑	○	◇	◑	◇	○	◑	◑	◑	◇	◑	●	○	●
3.12 Ex Situ Physical/Chemical Treatment (assuming pumping)																
4.43 Adsorption/ Absorption	●	●	○	◑	◑	○	○	●	◑	◑	◑	◑	○	●	◇	○
4.44 Advanced Oxidation Processes	●	◑	○	○	◑	◑	○	●	●	●	●	●	●	◇	◇	●
4.45 Air Stripping	●	◑	○	◑	●	●	○	●	●	●	○	○	○	○	○	○
4.46 Granulated Activated Carbon/Liquid Phase Carbon Adsorption	●	◑	○	◑	●	◑	○	●	●	●	●	●	●	◇	○	◇
4.47 Groundwater Pumping/Pump & Treat	●	◑	○	○	●	○	○	●	◑	◑	◑	◇	◑	◑	○	◑
4.48 Ion Exchange	●	◑	○	○	●	◑	○	●	○	○	○	○	○	●	◑	○
4.49 Precipitation/Coagulation/Flocculation	●	◑	◑	○	●	◑	○	●	○	○	○	○	○	●	◑	○
4.50 Separation	●	◑	○	○	●	○	●	●	●	●	●	●	●	◇	◇	○
4.51 Sprinkler Irrigation	●	●	●	●	●	○	○	●	●	●	○	○	○	○	○	○
3.13 Containment																
4.52 Physical Barriers	●	●	◑	○	●	●	○	●	●	●	●	●	●	●		●
4.53 Deep Well Injection	●	●	●	●	◑	●	○	●	◑	◑	◑	◑	◑	◑	◑	◑
3.14 Air Emissions/Off-Gas Treatment																
4.54 Biofiltration	●	N/A	●	●	◇	●	●	○	●	◇	◇	◇	●	○	I/D	◇
4.55 High Energy Destruction	○	N/A	I/D	I/D	○	◑	I/D	◑	●	●	●	●	●	◑	I/D	○
4.56 Membrane Separation	○	N/A	I/D	I/D	○	◑	I/D	◑	●	●	◑	◑	◑	○	I/D	◑
4.57 Oxidation	●	N/A	●	●	●	●	I/D	●	●	●	●	●	●	○	I/D	◑
4.58 Scrubbers	●	N/A	◑	○	●	●	I/D	●	○	○	○	○	○	●	I/D	I/D
4.59 Vapor Phase Carbon Adsorption	●	N/A	●	●	●	●	I/D	●	●	●	●	●	●	◑	I/D	●

TABLE 3-1: DEFINITION OF SYMBOLS USED IN THE TREATMENT TECHNOLOGIES SCREENING MATRIX

Factors	● Above Average	◑ Average	○ Below Average	Other
Development Status Scale status of an available technology	Implemented as part of the final remedy at multiple sites, well documented, understood, etc.	Has been implemented at full scale but still needs improvements, testing, etc.	Not been fully implemented but has been tested (pilot, bench, lab scale) and is promising	◇ Level of Effectiveness highly dependent upon specific contaminant and its application/ design
Treatment Train Is the technology only effective as part of the treatment train?	Stand-alone technology (not complex in terms of number of media/treatment technologies, maybe one "routine" technology in addition)	Relatively simple (two-car train or so), and well understood, widely applied, etc.	Complex (more technologies, media to be treated, generates excessive waste, etc.)	
Relative overall cost and performance: **O&M** Operation and Maintenance Intensive	Low degree of O&M intensity	Average degree of O&M intensity	High degree of O&M intensity	
Capital Capital Intensive	Low degree of capital investment	Average degree of capital investment	High degree of capital investment	
System Reliability /Maintainability The expected range of demonstrated reliability and maintenance relative to other effective technologies	High reliability and low maintenance	Average reliability and average maintenance	Low reliability and high maintenance	N/A "Not Applicable"
Relative Costs Design, construction, and operations and maintenance (O&M) costs of the core process that defines each and pre-and post-treatment	Low degree of general costs relative to other options	Average degree of general costs relative to other options	High degree of general costs relative to other options	I/D "Insufficient Data"
Time Time required to clean up a "standard" site using the technology — in situ soil	Less than 1 year	1-3 years	More than 3 years for in situ soil	
ex situ soil	Less than 0.5 year	0.5-1 year	More than 1 year for ex situ soil	
groundwater	Less than 3 years	3-10 years	More than 10 years for water	
Availability Number of vendors that can design, construct, and maintain the technology	More than 4 vendors	2-4 vendors	Fewer than 2 vendors	
Contaminants Treated Contaminants are classified into eight groups: - Nonhalogenated VOCs - Halogenated VOCs - Nonhalogenated SVOCs - Halogenated SVOCs - Fuels - Inorganics - Radionuclides - Explosives	Effectiveness Demonstrated at Pilot or Full Pilot or Full Scale	Limited Effectiveness Demonstrated at Pilot or Full Scale	No Demonstrated Effectiveness at Pilot or Full Scale	Same as above

APPENDIX E – CASE STUDY

SELLAFIELD LTD WINDSCALE TRENCH MANAGEMENT

Background and Context

Sellafield is located on the coast in West Cumbria, England and at present covers 6 square kilometres and is home to more than 200 nuclear facilities. Details below have been adapted from [E1] with further input from Sellafield Ltd [E2].

The Sellafield site began in 1941 when it was developed as a Royal Ordnance Factory for the production of trinitrotoluene (TNT). TNT production ceased at the end of the Second World War and the site was cleared in 1946. In 1947, the site was acquired by the government as the location for Britain's plutonium production plant. The area developed for this purpose is now called the Separation Area and incorporates an area of approximately 31 hectares. In the early 1950s, the world's first civil nuclear power generation reactors (Calder Hall) were constructed on the opposite side of the River Calder from the Separation Area and site development and expansion has continued since that time. With the exception of a prototype reactor built in the 1960s, this later expansion has largely been for the purpose of reprocessing spent nuclear fuel and the temporary storage of solid and liquid reprocessing wastes prior to vitrification, encapsulation and storage.

Land Quality Issues

The Windscale Trenches within the Separation Area were the main onsite disposal facility for solid radioactive wastes in the 1950s. They are unlined trenches that are thought to contain wastes that would be considered low level waste (LLW) today. There are no disposal records and so estimates of inventory have been made based upon factors such as the analysis of site processes and related contemporary documents, anecdotal evidence, and logical reasoning. Much of the original radioactive inventory is thought to be tritium associated with furnace liners and filters disposed following the Windscale fire; however, other fission products and actinides are also thought to be present and asbestos and solvents are amongst the probable non-radiological components of the inventory. There is also a reasonable possibility that small amounts of short-lived ILW may have been disposed.

There is uncertainty regarding the exact dimensions of the Trenches, but the plan area is approximately 7,000 square metres and the depth is approximately 5 metres. The Trenches are above the water table in the surrounding superficial deposits, which is at approximately 8 metres below ground level, and the sandstone bedrock underlying the site is approximately 25 metres below ground level and classified as a major aquifer.

The trenches were covered in the 1950s and by the 2000s, around 40-50% of the area thought to be associated with the Trenches has been partially reprofiled (to enhance surface drainage) and capped with tarmac. The tarmac composition was optimised to provide a loading surface for vehicle access and materials storage but is also thought to offer a substantial barrier against rainwater infiltration.

The remaining "uncapped" areas of the Trenches are either vegetated or simply covered with hardcore/tarmac, put in place for operational reasons without specific regard for protection of the Trench wastes.

In addition to the wider drivers for action from the perspective of Sellafield Ltd (i.e. to identify, reduce and manage liabilities and develop robust management plans), important drivers for the demonstration of optimisation in the management of the Trenches arose from the regulatory context.

Key regulatory considerations were Nuclear Site Licence Conditions 32 (accumulation of radioactive waste) and 34 (leakage and escape of radioactive material and radioactive waste), as well as environmental regulatory requirements, including those relating to the Groundwater Directive. Such considerations meant that, even though offsite risks were considered to be low, the potential for uncontrolled release of contaminants from the wastes to the unsaturated zone and groundwater beneath the Trenches required the identification of an appropriate, proportionate management strategy to control their migration.

Remediation Options Considered and Approach to Option Comparison

In 2011 a Best Available Techniques "BAT" assessment for the interim management of the Windscale Trenches was undertaken. This involved a two-day workshop that included representatives from the Sellafield Ltd project team, senior

Sellafield Ltd management representatives, and other internal stakeholders. Representatives from Cumbria County Council, Copeland Borough Council, the West Cumbria Sites Stakeholder Group, Sellafield Ltd's independent land quality Peer Review Panel, the Environment Agency and the ONR were also in attendance.

The assessment process followed a systematic approach and the Nuclear Industry Sector Directors Forum (NISDF), 2010 BAT 'Nuclear Industry Code of Practice' (NICoP) was used [3], mapping key differentiators between options to identified criteria of interest. The assessment included the business needs of Sellafield Ltd to identify, reduce and manage liabilities and develop robust management plans and the regulatory requirement to demonstrate optimisation in the management of the Trenches. Key considerations were Nuclear Site Licence Conditions 32 and 34, as well as environmental regulatory requirements, including those relating to the Groundwater Directive.

The following management options were assessed during the workshops:

- No change to current arrangements;
- Improved near surface management (Enhanced or Complete Cap);
- In-situ stabilisation;
- Groundwater pumping or treatment, or groundwater barriers;
- Partial or complete excavation followed by waste treatment and storage and/or disposal;
- Further characterisation.

The high-level criteria for assessment were agreed as follows:

- Environmental impact
    - Including aspects related to protecting against expansion of the waste store and impacts to groundwater; potential impacts to members of the public; generation of secondary wastes; resource use; management of the site working environment, etc.
- Health and safety
    - Conventional and radiological hazards to site workers and the public.
- Technical performance and practicability
    - Confidence in ability to implement and to achieve the required technical performance; interactions with other site strategies and operations, and related constraints; timeframes for implementation; potential for benefit to other site operations; etc.
- Socio-economic impacts and security.
- Cost.

Rationale for the Preferred Option

The BAT assessment reached consensus that an enhanced cap was the optimised approach to implement prior to the future determination of the End State when decommissioning operations are completed in the area. That is, that an Interim End State was decided.

During subsequent design work, it became clear that the installation of a cap to meet current landfill specifications would present numerous challenges, the main one being the disruption to site operations which could impact projects to reduce major site hazards. The cost of constructing a cap to the landfill specification, not including any costs associated with delays/disruption or waste disposal, was estimated to be in the order of £4,000,000. The likely disruption to site and the cost were thought to be disproportionate. The assessment findings where therefore reviewed.

A subsequent BAT assessment was undertaken, the output of which was agreed in 2013. This concluded that the preferred management option was to leave the waste in-situ and improve the capping to further reduce the infiltration of rainwater. The design solution for this was to extend the existing tarmac cap (and associated drainage system), over areas of the Trenches that are currently uncovered to provide protection against infiltration. This was agreed as the optimised outcome as it:

- Reduced the environmental impact of the Trenches;
- Improved the efficiency of high hazard reduction projects;
- Increased the future operational value of the area;

- Imposed minimal constraints on future remediation options;
- Reduced the impact on current operational needs of the area; and,
- Did not unreasonably foreclose longer-term options.

The strategy also negated the need to excavate the trenches and prevented disruption to the site and made available valuable resources which could be used on the high hazard reduction projects. Similarly, it avoided the use of a full cap and the impact of an increase in waste volume and the associated environmental risks, reduced capital outlay and allowed for future use of the area. It also set a benchmark for future studies - better understanding for all stakeholders on the issue of contaminated land and how it ranks against other Sellafield Site hazards.

The management strategy for the trenches ensures the risk stays acceptable and does not unreasonably foreclose longer-term options.

Current Situation

Physical works commenced in 2013 and the project was complete in four years.

Appendix References

[E1] IAEA (2014) Nuclear Energy Series, Lessons Learnt from Environmental Remediation Programmes No. NW-T-3.6, 2014

[E2] Sellafield Ltd (2014). Land Quality Strategic Decision. “How should the material in the Windscale Trenches be managed, and is active intervention required, now and in the long term?” (PA17 SO3), 24th November, 2014

[E3] Nuclear Industry Safety Directors Forum (2010). Best Available Techniques (BAT) for the Management of the Generation and Disposal of Radioactive Wastes Good Practice Guide, Issue 1, December 2010