IAEA Nuclear Energy Series

No. NW-T-3.6

Basic Principles

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LESSONS LEARNED FROM ENVIRONMENTAL REMEDIATION PROGRAMMES

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world''.

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FOREWORD

One of the IAEA's statutory objectives is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world." One way this objective is achieved is through the publication of a range of technical series. Two of these are the IAEA Nuclear Energy Series and the IAEA Safety Standards Series.

According to Article III A.6 of the IAEA Statute, the safety standards establish "standards of safety for protection of health and minimization of danger to life and property". The safety standards include the Safety Fundamentals, Safety Requirements and Safety Guides. These standards are written primarily in a regulatory style, and are binding on the IAEA for its own programmes. The principal users are the regulatory bodies in Member States and other national authorities.

The IAEA Nuclear Energy Series comprises reports designed to encourage and assist R&D on, and application of, nuclear energy for peaceful uses. This includes practical examples to be used by owners and operators of utilities in Member States, implementing organizations, academia, and government officials, among others. This information is presented in guides, reports on technology status and advances, and best practices for peaceful uses of nuclear energy based on inputs from international experts. The IAEA Nuclear Energy Series complements the IAEA Safety Standards Series.

Environmental remediation in the context of legacy radiological contamination is increasingly being carried out in IAEA Member States. Significant experience and expertise already exist around the world as nuclear and associated facilities close and move through decommissioning and environmental remediation phases. Remediation technologies have been researched and developed and fine tuned as they have been rolled out, either in relatively small scale projects, or on larger international scales. What lessons can be learned from these projects?

It is clear that the decision to adopt a particular remediation strategy for a location is highly site specific and strongly depends upon local physical (e.g. geological or hydrogeological), technical (e.g. the nature and chemistry of the contamination) and non-technical (e.g. interested parties) factors. Nevertheless, there are some common experiences that can be drawn from these projects. These are collected in this publication to guide decision makers on how best to apply this information to future projects. This report reviews the relevant accumulated experience and relates this to the principal engineering designs and strategies employed.

The report was prepared with the assistance of international experts and in collaboration with S. Fesenko of the IAEA Environment Laboratories. The IAEA officer responsible for this publication was H. Monken Fernandes of the Division of Nuclear Fuel Cycle and Waste Technology.

CONTENTS

SUMMARY

Several remediation projects have been developed to date, and experience with these projects has been accumulated. Lessons learned span from non-technical to technical aspects, and need to be shared with those who are beginning or are facing the challenge to implement environmental remediation works. This publication reviews some of these lessons.

The key role of policy and strategies at the national level in framing the conditions in which remediation projects are to be developed and decisions made is emphasized. Following policy matters, this publication pays attention to the importance of social aspects and the requirement for fairness in decisions to be made, something that can only be achieved with the involvement of a broad range of interested parties in the decision making process. The publication also reviews the funding of remediation projects, planning, contracting, cost estimates and procurement, and issues related to long term stewardship.

Lessons learned regarding technical aspects of remediation projects are reviewed. Techniques such as the application of cover systems and soil remediation (electrokinetics, phytoremediation, soil flushing, and solidification and stabilization techniques) are analysed with respect to performance and cost. After discussing soil remediation, the publication covers issues associated with water treatment, where techniques such as ‘pump and treat’ and the application of permeable barriers are reviewed.

Subsequently, there is a section dedicated to reviewing briefly the lessons learned in the remediation of uranium mining and processing sites. Many of these sites throughout the world have become orphaned, and are waiting for remediation. The publication notes that little progress has been made in the management of some of these sites, particularly in the understanding of associated environmental and health risks, and the ability to apply prediction to future environmental and health standards.

The publication concludes by raising key points such as the requirement to develop a national or even regional prioritization of remediation measures in order to spend limited resources with the highest effect. It is noted that remediation objectives will ideally be defined a priori, i.e. before the design of any technical solution, and it is crucial to recognize that remediation activities are not just determined by radiological or health risks. In many cases, other factors will prevail in the definition of the adopted strategy, and public perception will always be a key driver.

1. INTRODUCTION

1.1. BACKGROUND

Remediation, as defined by the IAEA, means any measures that may be carried out to reduce radiation exposure from existing contamination of land areas through actions applied to the contamination itself (the source) or to exposure pathways to humans [1]. In the past, several activities of nuclear fuel cycles and military programmes were developed without the existence of consistent regulations, and many of these activities did not take into account potential impacts on the environment. Therefore, it was later necessary to put remediation activities into place to reduce potential or ongoing exposures to members of the public derived from contaminated land and water resources.

As a consequence of the above, several remediation projects have been developed worldwide, and experience has been accumulated. At the same time, the IAEA has been encouraged by its Member States to develop documents that address various aspects of radioactive contamination. Some of these publications are included in Table 1, together with rather general documents that do not necessarily focus on cleanup and remediation, but which address overarching principles and guidelines.

These publications cover topics related to contaminated sites: characterization, technical and non-technical factors relevant for the selection of a preferred remediation strategy and options for the cleanup of contaminated groundwater, as well as planning and management issues. In addition, a number of other IAEA publications dealing with related aspects have been compiled under different IAEA projects. They include publications on the remediation of uranium mill tailings, the remediation of dispersed contamination with mixed radiological and non-radiological contamination, the decontamination of buildings and roads, and the characterization of decommissioned sites. Limitations in funds available for remediation, as well as difficult and protracted remediation projects, are increasingly drawing attention towards the use of (monitored) natural attenuation as a core strategy. Planners and managers may want to use these publications to gain an insight into the process chain from shutdown and decommissioning to remediation and post-closure. Long term phases make use of potential synergies to their particular site specific conditions.

The present report complements these publications by providing an overview of the accumulated experience — the lessons learned — from remediation projects worldwide. This publication is not intended to be a guide, and remediation implementers are urged to seek further information when structuring a strategy for the implementation of remediation works. However, it aims to provide initial elements that can aid the preparation of a remediation plan. This publication does not focus on remediation following accidents.

1.2. PURPOSE OF THE PUBLICATION

The purpose of this publication is to provide those in charge or involved in remediation projects with practical information regarding the experiences and lessons learned from remediation projects.

1.3. SCOPE AND STRUCTURE OF THE PUBLICATION

This publication focuses on the remediation of sites affected by operations related to the nuclear fuel cycle, with an emphasis on the remediation of uranium mining and milling sites. However, the information made available is also useful to the so called NORM (naturally occurring radioactive material) sites. The publication begins by discussing non-technical aspects emphasizing the need for available policies and strategies that will be relevant to frame the overall remediation works at the national level. It then focuses on socioeconomic aspects of environmental remediation works, and subsequently it discusses general planning and managerial aspects of remediation programmes. Technical aspects of remediation works are then reviewed. Finally, a general overview on the remediation of uranium mining and milling sites is presented. The publication ends with overall conclusions.

TABLE 1. RELEVANT TOPICAL PUBLICATIONS PRODUCED BY THE IAEA IN THE FIELD OF ENVIRONMENTAL REMEDIATION

Safety	Management	Databases	Technology	Special topics
Management of Radioactive Waste from the Mining and Milling of Ores [2]	Factors for Formulating Strategies for Environmental Restoration [3]	A Directory of Information Resources on Radioactive Waste Management, Decontamination and Decommissioning, and Environmental Restoration Data as of June 1995 [4]	Technologies for Remediation of Radioactively Contaminated Sites [5]	Extent of Environmental Contamination by Naturally Occurring Radioactive Material (NORM) and Technological Options for Mitigation [6]
Monitoring and Surveillance of Residues from the Mining and Milling of Uranium and Thorium [7]	Characterization of Radioactively Contaminated Sites for Remediation Purposes [8]	Design Criteria for a Worldwide Directory of Radioactively Contaminated Sites (DRCS) [9]	Technical Options for the Remediation of Contaminated Groundwater [10]	The Long Term Stabilization of Uranium Mill Tailings [11]
Remediation Process for Areas Affected by Past Activities and Accidents [12]	Compliance Monitoring for Remediated Sites [13]		Site Characterization Techniques Used in Environmental Restoration Activities [14]	Applicability of Monitored Natural Attenuation at Radioactively Contaminated Sites [15]
Release of Sites from Regulatory Control on Termination of Practices [16]	Non-technical Factors Impacting on the Decision Making Processes in Environmental Remediation [17]		Remediation of Sites with Dispersed Radioactive Contamination [18]	Integrated Approach to Planning the Remediation of Sites Undergoing Decommissioning [19]
	Management of Long Term Radiological Liabilities: Stewardship Challenges [20]		Remediation of Sites with Mixed Contamination of Radioactive and Other Hazardous Substances [21]	

2. LESSONS LEARNED CONCERNING NON-TECHNICAL ASPECTS OF REMEDIATION PROGRAMMES

2.1. INTRODUCTION

For the sake of the organization of this publication, the relevant aspects related to environmental remediation are divided into two major groups. The first one — to be covered in the present section — deals with non-technical aspects, i.e. the components that do not involve the deployment of any sort of fieldwork or technology. Topics to be covered here will include elements of policy, project management and institutional control or long term stewardship (LTS).

2.2. NATIONAL POLICY AND STRATEGIES

Before entering into any sort of discussion on specific elements of remediation projects and what has been learned from their implementation, it is important to recognize that a key element to be addressed deals with the existence of policy and strategies at the national level. Ultimately, these principles will provide an appropriate framework within which decisions will be made and projects developed.

Remediation of legacy sites, in a broader context, raises two fundamental questions. Firstly, how are contaminated properties to be cleaned up (which ones should be targeted and how clean should they be on completion)? Secondly, who is responsible for the costs of the cleanup? The answers to these questions clearly require policy and strategy definitions. In practical terms, when a number of sites need to be remediated, the challenge is to define which one of them will be addressed first and to what extent they will be cleaned. International recommendations which apply to this situation (for existing situations, see Ref. [22]) define that remediation should be justified (i.e. should do more good than harm) and be optimized, for example, by means of cost–benefit analysis or similar decision making strategies. In addition to safety considerations, which are the fundamental aspects considered, economical thinking is inherent to these principles. From the strict economical point of view, those sites where the net benefit is greatest will ideally be prioritized. However, when the full range of elements is taken into account, including the need to weigh political and social issues, the situation is far from simple. The actual measurement of cost and benefits is, per se, a very difficult endeavour.

The assignment of liability is another issue of policy, as it will define the responsibility for the cost of remediation. In some countries (e.g. established market economies), the ‘polluter pays’ principle is commonly adopted. If the polluter is a private firm, it finances remediation. Decisions must be made, however, on how to proceed in such cases where there is no private party that can be identified as responsible for pre-existing pollution. Moreover, financing will be available only if the organization responsible for the pollution continues to function as a legal entity and has the ability to pay for the remediation. If the organization is unable to pay, or where the polluter is a state owned company (non-market economies), the decision becomes whether the state itself accepts the responsibility and finances remediation out of public funds, or whether responsibility is to be transferred to new owners e.g. via a privatization process (applicable to economies in transition). However, although this concept seems to be reasonable from the legal point of view, its practical implementation may not be that easy. One has to consider that several countries faced with the challenge to remediate sites contaminated by past practices have a gross domestic product that is less than a fraction of some of the wealthy western economies. Therefore, economic weakness will (albeit not solely) contribute to slow down the pace of remediation project implementation. Therefore, in such situations, the greatest challenge for environmental remediation policy will be the direction of scarce resources to the site where expenditure will produce the highest benefit. A lesson learned here is that the ad hoc distribution of resources may not be warranted from both fiscal and environmental points of view.

Policies to deal with contaminated sites will vary from country to country, but will involve some of the issues below, which are divided into two broader categories, as suggested by Ref. [23]:

— Elements of protection, including:
  • Safeguarding human health;
  • Safeguarding the environment;
  • Safeguarding water resources.
— Elements that consider land as a resource, including:
  • Preserving soil as a resource for future generations;
  • Reusing land that is in scarce supply;
  • Setting soil quality standards, either through specific standards or by use of individual site assessments.

It is clear that the method a country will choose to deal with the remediation of its contaminated land (sites) will depend on the specific social and economic conditions of that particular country.

Still under the scope of remediation policy, a significant challenge to be faced by policy makers is to establish how clean is clean? Basing remediation decisions on risk estimates seems to be a wise approach, but this can be a problem as residual contaminant levels, or standards at which the cut-off point is set, vary. It is not possible to establish a generic background level for a number of contaminants, as what is normal in one area may not be normal in another.

2.3. FUNDING

Funding is a fundamental prerequisite for remediation. Before any planning can be started, the order of magnitude of the costs should be known, as well as the order of magnitude of the available funds.

In the pursuit of acquiring funding for a remediation project, the following criteria have to be considered for the financial security of the project:

— Clear responsibilities;
— Public information;
— Enforceability;
— Permanence.

Solutions to obtain funding for remediation works are reported in Ref. [23]. A typical example is the taxation of generated wastes, which, however, is applicable only to sites still in operation. On the other hand, subsidies can be given to help meet remediation costs. Another mechanism is to allow land in public ownership to be either sold at low cost and allow developers to remediate it, or have remediation carried out at public expense and allow profits made in selling to accrue to a fund for further remediation work. Large remediation projects, e.g. uranium mining legacy sites, are most often state funded, simply because the uranium industry in most countries was (and in fact still is) a strategic industry under government control, and there are no private operators or licence holders to be held liable for the remediation. However, private finance is important, as remediation activities may also lead to an increase of the value of private property, and consequently private contributions are attracted to a remediation project, complementing public funds. Industry funds may also be an option.

In terms of ongoing operations, the private perspective on remediation projects indicates that the kind of commitments of a company/operator with sound environmental practices is very important. These commitments lead to corporate social responsibility approaches that are defined as the “internalization by the company of the social and environmental effects of its operations through pro-active pollution prevention and social impact assessment so that harm is anticipated and avoided and benefits are optimized” [23].

Environmental financial guarantees also act as a strong incentive for mining companies to start early with remediation (possibly during operation, which is called progressive rehabilitation) and have the guarantee released when remediation is complete. The concept is about companies seizing opportunities and targeting capabilities that they have built up for competitive advantage to contribute to sustainable development goals in ways that go beyond traditional responsibilities to shareholders, employees and the law. The drivers for these changes that will (and maybe should) ultimately be the influencing factors in remediation policy development include:

— Globalization, liberalization and increased foreign direct investment worldwide;
— Societal pressures, which are increasingly expressed as demands to address quality of life impacts, consultation, accountability and disclosure, and are sometimes pushed by special interest groups (e.g. non-governmental organizations);
— Regulation, which is increasingly becoming more integrated across human health and the three environmental media of land, water and air, and which covers impact assessment and planning for closure;
— Financial drivers, which are environmental and social conditions applied to the granting of credit, equity investment or political and environmental risk insurance;
— Supply chain pressure, which includes the purchaser's growing requirements for audited and verified environmental and, more recently, social proficiency;
— Peer pressure from other companies and reputational management;
— Internal pressures from employees and shareholders;
— The natural dynamic of environmental change itself, such as climate change and rising sea levels.

2.4. SOCIAL ASPECTS

Social aspects can be a very delicate issue when a comprehensive remediation programme is implemented in a country and decisions about priorities are to be made. Attention is paid to the need for fair decisions on remediation programmes that involve large scale endeavours. Whether or not decisions are to be based on few or several end points, care is to be taken that decisions are transparent and that they have adequate involvement of the affected communities. Two national scale studies in the USA found that sites in the CERCLIS (comprehensive environmental response, compensation and liability information system) database in predominantly non-white communities took longer than sites in predominantly white areas to reach the national priority list [24]. It was also found that the US Environmental Protection Agency (EPA) had chosen less permanent on-site 'containment' methods (such as capping with clay) more often at sites with larger minority populations, while it had selected more permanent 'treatment' remediation schemes (e.g. relocation of wastes) more often in sites with larger white populations. Evidence like this casts distrust in the decision making process on remediation projects, and will lead the affected communities to demand more conservative cleanup criteria, that is to say, beyond what would be advisable from risk assessments in remediation projects they might be involved in.

On the other hand, sites that manage to attract sufficient public attention and political support may receive funding that is sometimes disproportionate with respect to the actual environmental and health risks, and may therefore divert funds from more relevant issues that receive less attention. This is particularly true in the context of radioactively contaminated sites, which are often associated with strong emotional perceptions of risk, as, for example, sites that have to be remediated after a nuclear or radiological accident, e.g. the remediation of the sites affected by the accident at the Fukushima Daiichi nuclear power plant in Japan.

2.5. THE INVOLVEMENT OF INTERESTED PARTIES

The success of a remediation project relies on the inclusion of all parties from the beginning of the site assessment or remediation activities or both. The sooner the project team, the remediation professionals and the regulators are involved, the more successful the project will be.

Interested parties often have valuable information about site characteristics, history and future intended use that can significantly improve the quality of remediation process decisions. These parties generally show a great interest in the contamination problem, in the remediation process and in the effects that these have on human health and on the environment. Given the financial, technical and regulatory complexities inherent in the remediation process, it is highly recommended that affected interested parties be involved in all phases of the decision making.

If the interested parties have the opportunity for meaningful and substantial participation in the decision making process, they are more likely to support difficult policy, budgetary and technical decisions. It is important to note that affected interested parties are not necessarily limited to those immediately adjacent to the site. For instance, those who live downstream of a site may be affected, even if they are not in the immediate vicinity of the site. In the identification of affected tribes, it is necessary to consider that tribes may have treaties or other pacts with the federal government that grant them fishing, hunting or access rights in places that are not necessarily near their present day reservations. Furthermore, in the USA, individual states and the Native American community may recognize tribes that are not necessarily recognized by the federal government.

Since some remediation decisions are often made at the contracting stage, potential problems could arise if communication with the interested parties is not established by this stage. Exclusion of the interested parties at critical decision making points can engender public opposition, which, in turn, can lead to substantial delays and increased costs.

All interested parties must have access to critical information, the opportunity to provide input to decisions at strategic points in the remediation process, and, where appropriate, representation on the expert team. It is particularly important to involve interested parties in collaborative decision making at the site level. The effective participation of interested parties can promote a more accurate understanding of the relative risks of various technologies and remediation options. Participants gain a greater understanding of the regulatory requirements and processes, as well as a greater understanding of the novel technologies and techniques that might lead to less costly remediation solutions. The likelihood of public support for remediation decisions is significantly increased through the effective involvement of and communication with interested parties.

The level of participation by interested parties and the appropriate process for their inclusion must be tailored to each site and situation. However, from the formulation of the problem through the exit strategy, the issues, requirements and concerns of interested parties must be taken into account. An effective communication mechanism between the expert team and the interested parties must be in place throughout the remediation process.

In the implementation of the remediation project, interested parties can assist in the understanding of site history, the definition of the environmental issues, the formulation of the problem statement, the risk assessment process, the definition of intended future use of the site, and the development of remediation objectives.

2.6. PROJECT MANAGEMENT

2.6.1. Planning

Remediation projects are not a collection of different tasks that will ultimately lead to the cleanup of a contaminated site with its eventual release for reuse. Lessons learned in the implementation of different remediation projects clearly indicate that comprehensive, upfront planning is essential to effectively complete any environmental remediation project. Proper planning will ensure, among other things, that any data collected will lead to defensible decisions. Different approaches dealing with the planning and management of remediation of contaminated sites are available.

One of these approaches, which resulted from the pooling of efforts of the public and private sector in the USA, is the EPA supported Triad approach.

The Triad approach is a scientific methodology to foster modernization of technical practices for characterizing and remediating contaminated sites. The main objective of the Triad approach is to manage decision uncertainty, i.e. to increase confidence that project decisions are being made correctly and in a cost effective way [25]. The basis for site related decisions is the conceptual site model (CSM). A CSM makes use of relevant and available historical data to estimate:

— Where contamination is (or might be) located;
— How much is (or might be) there;
— How variable concentrations may be and how much spatial patterning may be present;
— What is happening to contaminants in terms of fate and migration;
— Who might be exposed to contaminants;
— What might be done to manage risk by mitigation exposure.

The Triad approach is composed of three elements: systematic project planning, dynamic work strategies and real time measurement technologies.

2.6.1.1. Systematic project planning

This component supports the ultimate Triad goal of confident decision making. It is an integrated and overarching approach to developing management plans that both uses scientific methods and considers non-scientific issues that influence site remediation, such as uncertainty about budgets and contracts, the concerns and fears of interested parties, legal concerns and regulatory interpretation. In principle, systematic project planning must address all uncertainties that affect how the project's end goals are framed, shaping the decisions that must be made to bring the site to closure and reuse (if possible). Lessons learned in previous projects are incorporated in this component, which encourages the development of:

- Social capital (i.e. an atmosphere of trust, transparent and open communication and cooperation between parties working towards a protective, yet cost effective resolution of the problem);
- Consensus on the desired outcome (i.e. the end goal) for the site or project;
- A preliminary CSM from existing information;
- A list of the various regulatory, scientific and engineering decisions that must be made in order to achieve the desired outcome;
- A list of the unknowns that stand in the way of making those decisions (i.e. decision uncertainties);
- Strategies to eliminate, reduce or 'manage around' those unknowns;
- Proactive control over the greatest sources of uncertainty in the environmental data (i.e. sampling related variables such as sample volume and orientation, particle size, sampling density, subsampling, etc.).

2.6.1.2. Dynamic work strategies

This element allows projects to be completed faster and cheaper than ever possible under traditional, static work strategies. Work planning documents written in a dynamic or flexible mode guide the course of the project to adapt in real time (i.e. while the work crew is still in the field) as new information becomes available. This allows preliminary CSMs to be tested and evolved to maturity (i.e. sufficiently complete to support the desired level of decision confidence) in real time, saving significant time and money while supporting a better resolution of uncertainties. A valuable aspect of dynamic work strategies, focused quality control (QC) that adapts in real time (a form of process QC), makes analytical QC procedures more relevant and powerful than those possible with traditional static work strategies with the analytical operator far removed from field involvement.

2.6.1.3. Real time measurement technologies

This element makes dynamic work strategies possible by gathering, interpreting and sharing data fast enough to support real time decisions. The range of technologies supporting real time measurements includes field analytical instrumentation, in situ sensing systems, geophysics, rapid turnaround from traditional laboratories, and computer systems that assist project planning and store, display, map, manipulate and share data. Although field analytical methods are usually less expensive to operate than fixed laboratory analyses, under the Triad approach, analytical budgets will generally be the same or even higher than conventional ones. Sample densities are increased to manage the various factors contributing to sampling uncertainty. This allows highly accurate and detailed CSMs to be built as the foundation of confident decision making. In the big picture, per sample costs are much less important to the financial bottom line than are the real time, confident decisions that so dramatically lower the life cycle costs of Triad projects. An ideal Triad project would strongly rely on each element. There are a few basic features that define a Triad project:

- Consensus on clearly worded project goals and intended decisions (with expressions of which decision errors are tolerable and which are not) for fieldwork before it begins;
- A CSM that anticipates site specific heterogeneities and contaminant distributions;
- Strategies to refine the CSM over the course of the project in relation to the intended decisions, and discussions about the mechanisms to manage sampling and analytical uncertainties in data collection.

The advantages offered by dynamic work strategies, high sampling densities and real time refinement of the CSM to lower costs and increase decision confidence make them highly desirable, and Triad projects will naturally include them to the extent feasible. However, the degree to which they are employed is not distinct, since it will vary depending on many technical and logistical factors, not least of which include regulatory, budgetary, contracting and legal constraints and the expertise of the project team.

The US Army Corps of Engineers (ACE) developed the technical project planning (TPP) process to improve planning activities associated with hazardous, toxic and radioactive waste (HTRW) site cleanup [26]. The TPP process is an example of a systematic planning process (as discussed above) that involves four different phases of planning activities. The TPP process is intended to be initiated at the start of activities associated with a HTRW site, and continue through the life cycle of cleanup. The expectation is that the application of the TPP process will ensure that the requisite type, quality and quantity of information are obtained to satisfy project objectives.

The four phases of the ACE TPP process are as follows:

— Phase I: identify current project. In this phase, a team information package is prepared, a site approach identified and the current project defined. The team information package includes information on the multidisciplinary TPP project team members, the customer's concept of site closeout, the customer's schedule and budget requirements and all existing site information (including correspondences, data and reports). The site approach captures the overall strategy for taking the site from its current state to closeout. An initial CSM is part of the site approach. The current project provides a more detailed description of what initial project actions need to be taken as part of the overall site approach. Included with this is an acquisition strategy that will allow the balance of the TPP activities to be performed.

— Phase II: determine data needs. The purpose of phase II is to ensure that all of the data required to meet the project objectives are identified. This includes data that one would obtain from laboratory analyses and also contextual information (drawings, meteorological data, utility locations, etc.) that is important for project success. Part of the data-needs-definition process is determining, for individual decisions, whether data will be used in a 'weight of evidence' mode, or whether data need to be collected and analysed in a fashion that supports statistical analyses. Depending on the answer to this question, the data-needs analysis also addresses the questions of quantity and type of information that will be required. The results of this analysis are captured in data-needs documentation.

— Phase III: develop data collection options. In the third phase of the TPP process, the sampling and analysis approach is identified, and data collection options are developed and documented. The TPP specifically encourages project teams to consider the use of dynamic work strategies and real time measurement technologies as an option for meeting the data needs identified in phase II of the process. When developing data collection options, the TPP process suggests that team members classify options as basic, optimum or excessive. Basic data collection refers to bare bones data that will meet immediate project objectives. Optimum refers to data collection that will not only satisfy immediate needs, but also better position the project to address future requirements. The excessive category includes options that go beyond the known immediate data requirements of the project, as well as any that could be reasonably expected in the future. The results of this analysis are captured in data collection options documentation.

— Phase IV: finalize data collection programme. The last step of the TPP process finalizes the required data collection programme. This includes producing data quality objective statements based on the first three phases of the TPP process, communicating the results of the process with the customers and other interested parties as appropriate, and preparing a scope of work.

2.7. PERFORMANCE BASED ENVIRONMENT MANAGEMENT

Performance based environment management (PBEM) is a common sense approach for reducing the uncertainties in site remediation and enhancing the decision making process to achieve effective cleanups. It is essentially a compilation of several components that can make the remediation of contaminated sites reach the cleanup goals and thereby reduce the impact that contamination may have on water and land resources.

PBEM uses a series of eight key components to manage site remediation. Key components can be applied at different points throughout the remediation, and a few are used throughout the process, such as CSM, but they are not a project management methodology on their own. These key components can also be thought of as best management practices. Systematic planning is visualized as the thread that connects all these related topics and can be an important aspect of the entire PBEM process.

The eight key components of PBEM are:

(1) Problem statement and objectives. Here, the project objectives must be clearly identified at the beginning of the project so that the performance goal of PBEM can be established. The problem statement associated with the objectives then drives the approach to solve the problem to achieve the objectives and derive appropriate performance measurements during implementation to minimize the risk in achieving the objectives. Based on the understanding from the project team, a concise problem statement should be prepared to capture the environmental issues. The problem statement may include the following:
   (i) The current and past conditions at the site causing the concerns;
   (ii) The reasons for undertaking the actions to resolve the concerns, such as levels of protection of human health and the environment or compliance with regulations;
   (iii) The remaining problems not resolved previously;
   (iv) The regulatory, political and non-technical issues affecting how to resolve the concerns, such as applicable or relevant and appropriate requirements (ARARs) or considerations for environmental interested parties;
   (v) The timeline to complete the remedial action to meet the ultimate site use objectives;
   (vi) The uncertainties and associated CSM assumptions made by the team, and their impact on the effectiveness of decisions if they are determined to be incorrect;
   (vii) Approaches for uncertainty management.
(2) Land use risk strategy. Land use is how a contaminated property will be used after the completion of remedial activities, e.g. commercial, industrial, residential, agricultural or recreational. ‘Land use risk strategy’ refers to the management of risks through control of current and future use of real estate. It is important for a remediation project to identify and take into consideration future land use. The land use risk strategy provides the bridge between land planning activities and environmental cleanup activities.
(3) CSM. The CSM synthesizes and crystallizes what is already known about a site that is pertinent to decision making requirements. It is a mental picture of how the contaminants released at a site interface with the environment and potential human and ecological receptors. It is built on all currently available information about site conditions that could influence future remedy selection, design or performance. Thus, as with the Triad approach, the CSM forms the basis for defining and implementing an overall strategy for the site under PBEM.
(4) Decision logic. To provide a flexible and expedited framework by which decisions can be made; decision logic can be prepared to document key milestone events when performance metrics can be compared to expectations and goals. The framework will encourage remediation decision makers to develop performance metrics to objectively assess progress. Furthermore, documented decision logic offers a method to expedite decision making by pre-establishing a consensus on appropriate actions, given a set of assumed conditions. For example, if regulator buy in to replanned decision logic is obtained, it may be possible to proceed at certain decision points with little more than documentation that the conditions of such a decision point are met. Documenting the decision process will minimize disruption when personnel turnover occurs on the project team, among the owners, on the regulatory staff or with any other interested parties. With a documented decision process, the ‘re-education’ process of new parties to the cleanup will be reduced. Since one of the keys to PBEM is flexibility, this flexibility must also be documented.
(5) Remediation process optimization (RPO). RPO is a key element of PBEM and, as such, is a dynamic and flexible process that can be applied at any stage of cleanup. RPO allows for systematic evaluation and refinement of remediation processes to ensure that human health and the environment are being protected over the long term at minimum risk and cost.
(6) ARAR analysis. As part of the dynamic decision analysis process and development of the overall site exit strategy, the regulatory framework for the site must be assessed, and pertinent statutes and regulations reviewed. The applicability and relevance or appropriateness to the project of various state and federal statutes, promulgated regulations and policies, given the site conditions (including contaminants, current and future land use, receptors and physical features), must be evaluated. The evaluation should take place initially

during response action outcome development and remedy selection and periodically thereafter following remedy implementation. As the understanding of the available remedial or corrective action technologies and risks posed by site contaminants evolves, the regulatory framework may change, and the ARARs for the site may change. PBEM involves the thorough assessment of ARARs to verify that the site goals that may be dependent on them are realistic (achievable), yet protective. This assessment requires an understanding of the intent of the regulations and statutes, the application of these requirements at similar sites, and the true current or potential exposures, as well as realistic performance goals considering engineering performance and technical limitations of the remediation technology. The analysis of ARARs should involve team members that are familiar with current legal and regulatory developments.

(7) Exit strategy. This is a detailed plan for accomplishing site specific objectives to reach site closure within a defined period. Its purpose is to document clearly the pathway leading to closure/response complete status, including consideration of contingency measures to be implemented should the progress vary from the plan. Preparation of a written exit strategy is an important component of performance based management practices.

(8) Performance based contracting (PBC). PBC has been applied by project owners for a diverse range of project types, but it has only recently become more common for environmental services such as site assessment and remediation. Through lessons learned from less than successful applications, project owners are increasingly looking at PBC as a means to optimize resources. When properly applied, PBC can be superior to traditional fixed price, time and materials, or cost plus fixed fee contracting approaches. For many programmes, PBC can result in better managed, faster executed and more cost effective site cleanups. However, PBC is not a one size fits all approach. PBC works well in some, but not all, places and under certain, but not all, conditions. Having a good understanding of site specific conditions is essential in determining whether PBC is the best contracting choice. In some cases, properly managed and periodically optimized remediation systems may offer similar benefits in terms of reduced time to completion but at a reduced cost relative to PBC. Different types of contracts will be discussed in the following section.

2.7.1. Contracting

Contracting is a key element in environmental remediation programmes. Typical contracting methods include the following.

2.7.1.1. Fixed price contracts

This type of contract is appropriate for services that can be objectively defined in the solicitation, and for which risk of underperformance is manageable. For such acquisitions, performance based statements of work, measurable performance standards and surveillance plans are ideally suited. The contractor is fully responsible for performance costs and enjoys (or suffers) resulting profits (or losses). The contractor is motivated to find improved methods of performance to increase its profits.

A key objective when using fixed price contracts is the reduction of costs of cleanup. However, it has been demonstrated that some organizations developed cost comparisons in trying to implement this type of approach which showed that the total savings would amount to a certain value that was never fully realized because several of the saving projections were based upon unsupported estimates or invalid cost comparisons. Cost increases can also diminish the prospect of realizing certain projected savings that can be preliminarily anticipated. A main risk of overestimating the savings occurs when it is chosen to award fixed price contracts where uncertainties associated with the work impact the risk of cost increases. Therefore, it is vitally important that estimates be as realistic as possible and that they fully consider the risk that uncertainties impose on the realization of estimated savings.

2.7.1.2. Cost reimbursement

Cost reimbursement contracts are appropriate for services that can be defined in only general terms or for which the risk of performance is not reasonably manageable. One example is the cost plus fixed fee contract, in which allowable and allocable costs are reimbursed and the negotiated fee (profit) is fixed. Consequently, the contractor has minimal responsibility for or incentive to control performance costs. Where possible, they should include specific incentive provisions in addition to the award fee to ensure that contractors are rewarded for good performance, as well as quality assurance (QA) deduction schedules to ensure satisfactory performance. Several variations are possible:

- Fixed price incentive contracts: Final contract price and profit are calculated based on a formula that relates final negotiated cost to target cost (either a firm target or successive targets);
- Fixed price contracts with award fees: Used to 'motivate' a contractor when contractor performance cannot be measured objectively, making other incentives inappropriate;
- Cost reimbursement incentive contracts: Used when fixed price contracts are inappropriate due to uncertainty about probable costs (may be either cost plus incentive fee or cost plus award fee).

2.7.1.3. Time and material or labour hour contracts

Time and material or labour hour contracts are preferred when their use is appropriate; they are employed when site conditions are not well defined, and all risk is carried by the agency in charge of the implementation of the work.

2.7.1.4. Performance based contracts

PBC emphasizes that all aspects of purchasing environmental services be structured around the purpose of the work to be performed, as opposed to the manner in which the work is to be performed. Under PBC, a contractor has the freedom to determine how to meet the client's performance objectives and achieve the appropriate performance quality and quantity levels. PBC is highly efficient because the contracts are structured to encourage contractors to perform only those activities that serve to meet the client's objectives. PBC is not limited to use by private sector companies or regulatory federal agencies. PBC can be used for individual sites, as well as for bundles of sites. PBC can be applied as early as initial investigations all the way up to and including post-closure monitoring, as appropriate, provided there are clearly defined goals and financial flexibility. It is important to note that PBC is not universally applicable; its applicability must be evaluated case by case. PBC focuses on the purpose of the work and has contract requirements set forth in clear, specific and objective terms with measurable outcomes. In contrast, traditional contracting approaches focus less on the requirement to meet project owner objectives and more on the requirement to perform work in a specified manner. Well structured PBC is beneficial to both parties and promotes cost effective services and encourages innovations that enable the procurement system to achieve its goals. Good PBC fosters a customer–contractor relationship that emphasizes clear expectations and roles and responsibilities, which, in turn, enhances performance and timely problem resolution. The mutual benefits of PBC are perhaps best understood within the context of the general contracting preferences of each party, as outlined below.

The owner or customer generally prefers the following:

- Performance that follows the specifications and schedule, with all work performed in accordance with applicable laws, regulations and accepted industry practices;
- Contract terms that define and limit costs and reduce exposure to cost overruns (note that the shift of risk to a contractor does tend to increase the cost of the work);
- Flexibility to allow for optimization to improve remedy effectiveness and/or reduce costs, based on changing site conditions, newly available technologies or equipment, or other developments.

The contractor generally prefers the following:

- A clear scope of work that accurately defines the services associated with the cost proposal;
- A project schedule that reflects the scope of work and is flexible to accommodate unforeseen items;
- Contract terms that fairly address financial risk associated with the given scope of work;
- Fair and timely payment for services rendered.

Typical PBC involves the following:

- Definition of the scope of the work to be done under PBC;
- A well defined CSM and exit strategy;
- Clearly defined performance goals and metrics;
- For remedy or corrective action implementation, a good understanding of the problem;
- Selection criteria for the contractor: qualifications (company and individuals), capabilities, financial ability, etc.;
- The implementation schedule must anticipate regulatory approval and acceptance by interested parties.

In summary, PBC does not fit all cases. Completion of characterization and an understanding of the problems in advance are essential. PBC can be applied at various stages, from initial scoping all the way to post-remediation monitoring. Different agencies or programmes have different requirements and limitations, and can apply PBC at various stages.

2.7.2. Cost estimation and procurement

Uncertainty in site specific project scope and schedule has always been a significant factor for site cleanup programmes. The complete list of contaminants of concern may be unknown, the volumes of affected media imprecise, the efficacy of a proposed remedial action unproven, and the duration of cleanup activities vague. These facts complicate project planning for cleanup projects, including cost estimation and the procurement of characterization and remediation services.

Historically for site cleanup, project uncertainty has been handled by keeping the details of individual project activities fixed and well defined, but leaving open the number of activities that would ultimately be required to bring about site closure. In this paradigm, short term costs and schedules are well understood, but life cycle costs and timelines are unknown.

Cost estimation should be used to produce best estimates of expected costs. Cost estimation should also provide upper bounds on what the potential costs might be for proposed activities based on a contingency analysis of the uncertainties present.

Upper bound calculations cap project cost uncertainties for specific activities. Upper bound cost calculations are important for selecting the appropriate contractual vehicle for service procurement and for determining whether the level of cost uncertainty is acceptable. Relatively small project cost and scope uncertainties lend themselves to fixed price contracts. Relatively large project cost and scope uncertainties may make fixed price contracts undesirable. Project cost and scope uncertainties that are too large to be programmatically comfortable may indicate the requirement for additional data collection activities to reduce scope and cost uncertainty to acceptable levels prior to finalizing project plans.

Sites with restriction of use are often good examples of unacceptable cost uncertainty. For many of these sites, it is the uncertainty associated with environmental liabilities that prevents their redevelopment, not the known extent of contamination problems. In such cases, data collection programmes can be designed to cost effectively reduce liability (and consequently cost) uncertainty to levels that allow authorities or private developers to confidently make economically and financially viable reuse decisions.

Contingency planning is tightly linked to cost estimation. Contingency planning identifies alternative project outcomes based on an analysis of the uncertainty associated with the CSM, evaluates the implications of those outcomes, and develops plans for addressing those outcomes if they should occur. A contingency may be as simple as requiring additional sampling or different analytical methods for particular samples based on data collection results. It may be as complicated as switching remediation strategies based on site conditions that are encountered while work is under way. Cost estimation for individual contingencies contributes to the calculation of upper bound cost estimates for a project as a whole.

The uncertainty presented by upper bound cost estimates may be unacceptable from a programme management perspective. In these cases, additional data collection may be warranted to control cost uncertainty before project work proceeds. An example for soil or sediment contamination is remediation cost uncertainty produced by poorly defined contaminated volume estimates. Properly designed data collection programmes can be particularly effective at filling this kind of data gap since contaminants of concern and action levels are usually well defined by this stage of the process, and decision making is yes/no (i.e. either a location contains contaminants above the criteria or it does not). In this case, data collection can be designed with a volume uncertainty goal in mind, and proceed until that goal is achieved.

Demonstrations of method applicability can also play a role in sharpening cost estimates for remediation projects. The primary goals of demonstrations of method applicability are to document measurement technology performance and fine tune standard operating procedures to match site specific conditions. A related product, however, is much better information about the site specific costs that would be expected from full scale deployment of a particular technology at a site. These demonstrations can also be important for determining technology specific deployment details that would feed a later request for proposals.

Cost estimation is best performed through unitized project costing. Unitized cost estimation identifies costs for logical units of effort (e.g. the per m^2 cost of direct push sample collection, or the per hectare cost of non-intrusive geophysical surveys). Elemental unit cost estimates (e.g. per sample collection or analytical costs) can be aggregated into more complex units (e.g. the cost of closure sampling for each final status survey unit at a site). Costs may be unitized by time (costs for a mobile laboratory per day), by function (costs per sample) or by activity (costs per m^3 of soil that is excavated, shipped and disposed). Costs that are unitized by time often also include a minimum production rate expectation (e.g. costs of a gamma walkover survey per day, assuming a scan rate of at least 8094 m^2 per day).

The way unitized costs are organized into more complex aggregates will be site and activity specific. Aggregation should reflect the way activities at the site are expected to be organized. They will be tightly linked to the CSM for the site, and, as with cost estimation itself, are a product of the systematic planning process. Because the CSM is constantly evolving for a site as more is learned about site conditions, unitized costs and associated cost estimates will also need to be monitored and periodically updated.

For contingency purposes, unitized rates may be required for several different options for any particular activity. For example, the preferred option for obtaining subsurface soil samples may be a direct push technology, but there may also be concerns about direct push refusal or sample loss under site specific conditions. Those concerns would warrant having alternative options available if necessary, such as a hollow stem auger or sonic drilling capabilities. However, the unitized rates for those systems would be different and would need to be accounted for.

Related to contingency planning, unitized rates should take into account costs for extra capacity, if required. The unitized rate for a fixed, well defined piece of work may well be significantly less than a unitized rate that includes standby options which need to be available, because of scope uncertainties, but not necessarily utilized. Developing unitized rates that internalize contingency costs for competing alternatives can be an effective method for providing a cost basis for comparing alternatives when uncertainty exists about component performance or ultimate work scope.

In addition to the effects of contingency planning, there are other important factors to consider for cost estimation, particularly when estimating the costs associated with real time measurement systems. Field deployable real time measurement systems typically are cheaper on a per measurement or analysis basis than their standard, fixed laboratory analytical counterparts. However, care must be taken in the cost estimation process to obtain accurate and complete unitized cost estimates. Factors to consider include:

— QA/QC requirements. Field deployable method costs are usually estimated on a time basis, with per sample costs dependent on throughput. The level of QA/QC required affects per sample costs in two ways. Higher levels of QA/QC reduce sample throughput, which will increase per sample costs. Higher levels of QA/QC also come with their own associated costs, which are passed along on a per sample basis, further elevating per sample costs. For most standard fixed laboratory methods, QA/QC is standardized, and costs already captured in quoted sample analysis costs. QA/QC requirements for field deployable methods are not standardized. For this reason, it is important for cost estimation that the level of required analytical QA/QC be identified and factored into the cost estimation process.
— Vendor/service provider participation. A level of vendor/service provider participation while vetting technologies as part of the systematic planning process can be extremely useful for cost estimation purposes. For some innovative field deployable methods, existing uses may not be sufficiently widespread so that generic cost numbers are available. Potential vendors or service providers may be the only source of this information. Even for those methods that are more commonly available, site specific method modification

requirements may result in site specific unitized cost estimates. Vendors or service providers may be the best resource for generating these numbers. Vendors may also identify field activity sequencing issues that have logistical and cost implications.

— Demonstrations of method applicability. For some field deployable methods, there may be the requirement for investments in gaining regulatory acceptance for the technology. An example would be the requirement for a demonstration of a method applicability study at a site. If required, these costs should be included in the cost estimation process when considering alternative real time measurement techniques.
— Application of managerial practices (to include cost estimates) to hazardous waste site characterization and remediation is expected to result in significantly lower life cycle project costs, compressed schedules and improved decision making. At times, this may be at the expense of higher initial costs associated with the systematic planning process and technology acceptance needs.

2.7.3. Long term stewardship

Remediation is complete when the site has been cleaned up according to federal or state standards, which can include controlling groundwater contamination and sealing off toxic materials and landfills. Even after sites have undergone extensive cleanup, they may require long term management because the engineering controls used to prevent human exposure to contaminants degrade over time. Therefore, long term stewardship (LTS) can be defined as the physical controls, institutions, information and other mechanisms required to ensure protection of people and the environment at sites where completed or plans to complete 'cleanup' (e.g. landfill closures, remedial actions, removal actions and facility stabilization) have been implemented". The concept of LTS includes land use controls, monitoring, maintenance and information management, and may begin immediately after remediation.

In fact, LTS emerged from the requirement to address the reality that cleanup of contaminated sites, in many cases, would not, indeed could not, achieve conditions deemed acceptable for unrestricted use, and would therefore require some form of management far into the future. The concept of LTS is known by several different names, for example, 'long term stewardship', 'long term surveillance and maintenance' or 'legacy management', 'long term monitoring and surveillance'. Depending on the prevailing regulatory framework under which cleanup is accomplished, either state, regional, tribal or federal organizations will bear the responsibilities and/or be overseeing authorities for LTS.

The principal drivers for requiring LTS at a site are a combination of the following:

— Priorities: Federal priorities do not support funding for cleanup to free release levels;
— Long lived contaminants: Radionuclides, chemicals and metals are not easily or quickly broken down to safe constituents;
— Lack of technology: No further environmental benefit from remediation is attainable with current technology or asymptotic levels have been reached (e.g. groundwater and vadose zone);
— Risk: Short term human health or environmental risks of conducting remedial activities outweigh the benefits of remediation.

Probably the best way to carry out LTS functions is to compartmentalize the execution of tasks; that is, different actors should be responsible for carrying out the different functions of LTS.

3. LESSONS LEARNED CONCERNING TECHNICAL ASPECTS OF REMEDIATION PROGRAMMES

3.1. INTRODUCTION

An analysis of 367 remediated sites (not necessarily contaminated by radioactive materials) supplemented by another 1189 contaminated (not necessarily remediated) sites in England and Wales reveals that the factors found to be of significance in remediation technique selection are effectiveness in reducing risk, applicability to contamination, cost and local availability (at the level of the country) [27]. Differences in remediation projects carried out by the local authority and the owner/developer were also reported.

The main civil engineering technique reported was excavation and off-site disposal. That, of course, is valid for situations in which soils have been contaminated by means of accidents or spills (leakage of effluents). In the case of remediation of uranium mining legacy sites, excavation and removal will not be that common, i.e. when one is dealing with tailings and/or waste rock piles. However, four important examples can be provided, in which removal and relocation of tailings and/or waste rock piles have taken place. They are: (1) the US Department of Energy Moab site (Colorado, USA), (2) Ronneburg (Thuringia, Germany), (3) the AMCO site (Kitwe, Zambia), and (4) some of the waste rock piles and tailings at Mailuu Suu (Kyrgyzstan). Despite these examples, the most often used remediation technique at mining and milling sites is encapsulating the wastes with a mineral cover.

3.2. TECHNICAL CONSIDERATIONS IN TECHNOLOGY SELECTION

The selection of appropriate remediation techniques will depend on the characteristics of the contaminated site and the potential exposure pathways. Therefore, the choice will be, in most cases, site specific. Some general approximations can be suggested:

— Remediation that will lead to the generation of high volumes of waste will favour in situ technologies.
— Inaccessible contaminated zones will also call for in situ techniques.
— The presence of large population groups near the site will favour the removal of contaminated material to a more secure or remote location.
— Sites where radon and dust emissions are high will be best treated by either removal of material from the site or the installation of surface barriers above the contaminated material.
— Sites where leaching and off-site migration of radionuclides is significant will be best treated by technologies that reduce groundwater infiltration through the contaminated materials.
— Sites with high external irradiation levels will be best treated by surface barriers or removal of the radioactive material.

Most remediation techniques will, to some extent, reduce on-site and off-site inhalation of radon and contaminated dust, external exposure and consumption of contaminated food. However, in situ solidification technologies will only have a minor impact on the external dose. In addition, the introduction of subsurface barrier technologies will have no effect on on-site exposure pathways, as they will not present a barrier to the occupants of the site.

Because radionuclides are not destroyed, 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.

Regarding the wastes generated in remediation projects, deep geological disposal is not a feasible option on cost grounds, and sea dumping is not feasible on political grounds, leaving surface or shallow land disposal as the only viable option. While it may be the case that the doses from the ‘normal’ evolution of a properly designed and constructed repository could be lower than those arising from leaving the wastes in situ, doses from intrusion scenarios will probably be the same in both cases. Therefore, there may be only marginal benefits to be gained from removing the waste and disposing of it versus adopting in situ options such as capping. This may be an important point on the types of remedial actions that are viable.

In addition to what has been said above, implementation of remediation technologies should consider the potential for radiological exposure to workers (internal and external). The degree of hazard is based on the radionuclide(s) present and the type and energy of radiation emitted (i.e. alpha particles, beta particles, gamma radiation and neutron radiation). The design should take into account exposure considerations and the principle of keeping exposures as low as reasonably achievable (ALARA).

In addition to the above, some of the lessons learned that are relevant to this discussion include the conclusion that:

— Remediation technique selections will focus on the most directly applicable (to contaminants and risk management objectives), cheapest and most readily available options. Cost will remain a determinant factor in remediation techniques.
— Remediation techniques that are unproven on actual sites similar to those that authorities, landowner or developers need to remediate are unlikely to be selected without financial support and regulatory agreement.
— There is a need for demonstration projects on actual sites, the data from which should be made widely available if specific techniques are to be encouraged. Tried and tested methods are very likely to remain predominant in the short term.
— Risk based approaches to contaminated land management can encourage pragmatic remediation solutions. However, there is a need for competent and knowledgeable land remediation professionals and regulatory officials.
— Post-remediation monitoring is essential to prove the effectiveness of remedial action. However, monitoring has to be in relation to clearly defined remediation objectives.
— Monitoring alone is of little use if no provisions are made regarding corrective measures in case the monitoring results show that the performance of the remedial action is not as intended.

As there is no off the shelf solution that can be applied to all sites, the conceptual methodology and general selection procedure to arrive at the preferred remedial solution for a given site is of paramount importance. There is a general lack of systematic approaches in this area. The next subsection will try to provide some useful insights into remediation techniques and technologies.

3.3. REMEDIATION TECHNIQUES AND TECHNOLOGIES

This subsection deals with the lessons learned while applying some of the techniques used in remediation programmes. It should be noted that the costs presented in the text are indicative, and should not be taken as absolute values for all sites. Local and national factors will play a role in the cost formation that will eventually lead to different figures. This publication stresses that each remediation project is unique, and, as much as a general consideration may be proposed, it must be borne in mind that no single solution will fit all cases.

3.3.1. Cover systems

Cover systems can be simple or complex, ranging from a single layer of earthen material to several layers of different material types, including native soils, non-reactive waste materials, geosynthetic materials and oxygen consuming organic materials [28]. Multilayer cover systems may utilize the capillary break concept to keep one (or more) of its layers near saturation under all climatic conditions. This creates a ‘blanket’ of water over the reactive waste material, which reduces the influx of atmospheric oxygen and subsequent oxidation of underlying wastes, the egress of radon, or both.

It is challenging to construct a cover system containing a layer that remains highly saturated (reducing the influx of atmospheric oxygen or the egress of radon) in an arid or semiarid climate, as well as at sites that experience hot, dry summers. The cover system will be subjected to extended dry periods, and therefore the effect of evapotranspiration will be significant. However, subjecting the cover system to evaporative demands can be beneficial and result in a reduction of infiltration to the underlying waste material. An upper cover surface layer possessing sufficient storage capacity can be used to retain water during a rainfall event. Subsequent to the increase in moisture storage in the upper layer, it would release a significant portion of pore water to the atmosphere by evapotranspiration during extended dry periods, thereby reducing net infiltration across the cover system. The objective is to control leachate from the facility in question to an acceptable level as a result of controlling the transport mechanism (i.e. water) into the underlying waste material. A cover system with the above objectives is often referred to as a moisture store and release type cover system. Desiccation and frost induced cracking of mineral infiltrations barriers are processes that typically lead to the ultimate failure of engineered cover systems. Precautions must be taken to avoid or at least minimize these processes, but, realistically, deterioration of the long term performance of engineered mineral multilayer cover systems cannot be entirely precluded.

As a general rule, cover system designs should attempt to be as simple as possible for two key reasons:

- Reducing cost: A cover system that meets design criteria and can be constructed from run-of-mine waste placed progressively during mining will cost substantially less than a complex multilayer cover using manufactured materials (e.g. screened gravels, geosynthetics, etc.).
- Design life: Complex highly engineered cover systems containing a barrier layer designed to resist the natural processes of the surrounding environment will inevitably fail, often over a relatively short timeframe, when compared to designs that address and recognize natural processes which destroy the function of the designed covers.

Cover system design philosophies should integrate the waste material within its environmental context. This is in contrast to isolating the waste from the environment in order to minimize, to the extent technically possible, the production of contaminated seepage. Revegetation is generally a key aspect of long term cover performance; as such, the growth medium layer needs to have adequate available water holding capacity to ensure development of a sustainable vegetation system. The vegetation will assist in minimizing dust and wind erosion, while also providing sustainable functionality of the cover system though removal of moisture via transpiration. Therefore, a waste storage facility cover system must be designed as an unsaturated system exposed to the atmosphere, the performance of which will be significantly influenced by the seasonal, annual and long term site climate conditions.

An approach that attempts to completely 'isolate' the material within the mine from the environment is based on the somewhat flawed viewpoint of considering an engineered cover system as an 'upside down liner'. This latter philosophy would greatly increase the potential for long term performance problems.

The design for a cover system should be developed with respect to the key factors that will control long term performance. These key factors include:

- The climate regime at the site;
- The geochemical processes within the wastes;
- The texture of the waste material, as well as the geotechnical, hydrological and durability properties of economically available cover materials;
- The hydrogeological setting of the waste storage facility;
- The presence of basal groundwater flow that will not be controlled by the cover system;
- Long term erosion, weathering and evolution of the cover system.

The evaluation of cover systems must be consistent with the decommissioning or remediation objectives for the site. Closure or remediation criteria can then be developed to achieve these objectives. In addition, there is a tendency to develop performance criteria for a cover system that is tied directly to a specific design objective, such as a maximum net percolation rate or minimum density for the vegetation planted or maximum radon egress rates. However, the preferred method is to develop cover system performance criteria based on impacts to groundwater, surface water and air quality, prevention of inadvertent access and minimization of radionuclide uptake by plants that may end up in the human food chain.

The longevity of the cover system design should be evaluated in relation to the site specific physical, biological and chemical processes that will alter the as-built performance and determine long term performance.

Examples include, but are certainly not limited to, freeze–thaw and wet–dry cycling, root penetration, bioturbation and settlement or consolidation (particularly differential settlement).

In general, the majority of cover system designs deal with vertical or one dimensional flow of heat, oxygen and moisture in horizontal layers, using numerical models as well as laboratory or field scale physical models. The problem is that a large percentage of waste disposal sites have sloping surfaces. The performance of a cover system placed on these slopes will differ from the performance of a horizontal cover system. The ability of the cover system to mitigate the net percolation of water to the underlying waste material will be influenced by sloping, two dimensional effects. Therefore, a rigorous soil–atmosphere model capable of simulating a cover system placed on the slopes should be used to evaluate the performance of various final cover design alternatives.

An important, albeit often underestimated, ingredient of cover design is meteorological data with high temporal resolution. Annual or even monthly averages are insufficient to predict and optimize cover performance. For example, it is often the short, intense rainfall events that determine the infiltration rate of a store and release cover which relies on equilibrium of precipitation and evaporation. The process of obtaining these data should start well in advance, before the design of the cover and other remedial actions start. Not having data of sufficient quality available will almost certainly lead to insufficient performance of the remedial measures.

For evaluation of the best suited design for the final cover of tailings ponds and waste rock dumps and to test the model predictions, test plots are recommended that expose the wastes and various cover variants to real, site specific climatic and meteorological conditions.

For example, lysimeters[1] were installed at Wismut sites in eastern Germany on each of the test fields for measuring continuous surface runoff, interflow in the storage layer and, if existing, in the drainage layer or in the capillary barrier, respectively.

Infiltration through the sealing layer and infiltration through the underlying interim cover is also measured. Volumetric water content is measured using time domain reflectometry probes installed within the layers. In addition, soil suction is measured using tensiometers and equitensiometers. Temperature is also measured at specific depths to determine frost depth. Percolation through the interim cover is collected using a drainage layer underlain by a foil liner forming a trough. Lateral interflow and runoff are collected downstream in a drainage system and measured continuously by tipping bucket counters. In addition, small (500 cm^2) plate lysimeters are installed in four of the ten test fields. A weather station continuously measures the following meteorological data: air temperature, air humidity, wind direction, wind speed, global radiation, and precipitation at 1 m above the surface and at surface level (the difference accounting for interception by plants).

Regarding the lessons learned, it can be said that:

— The test plots have demonstrated that both the multilayer and single layer cover systems are suitable for reducing infiltration.
— Multilayer cover systems, including infiltration barriers, have the advantage of coping well with extremely wet meteorological situations, but at a considerable engineering effort and, hence, cost. They are also sensitive to quality flaws during cover placement.
— Infiltration barriers on a mineral (clay) base also show deterioration effects due to freeze–thaw and wet–dry cycles, causing their permeability to increase over only a few of these cycles. These effects, which may occur over a few years, are not observed in geosynthetic liner systems.

For modelling the performance of cover systems, high resolution meteorological data (rainfall in particular) are required. Apart from averaged values, such as mean annual precipitation or temperature, information on short time, peak precipitation events is necessary to properly predict the water balance in cover systems.

Another important issue with the closure of tailings impoundments, following construction of a cover system, is the length of time it takes for the phreatic surface in the tailings impoundment to equilibrate with local hydrogeological conditions. This ‘drain down’ period may take several tens of years depending on the characteristics and depth of the tailings. In time, the system will reach ‘steady state’ conditions in which the amount of net percolation through the cover system equals the amount of tailings seepage. A 2-D seepage analysis of the

[1] According to the European definition, a lysimeter is a vessel containing local soil placed with its top flush with the ground surface for the study of several phases of the hydrological cycle, e.g. infiltration, runoff, evapotranspiration, soluble constituents removed in drainage, etc. Therefore, the term lysimeter does not include suction cups.

decommissioned facility is required to reasonably determine the length of the drain down period. Long drain down periods have implications not only for groundwater and surface water quality, but also for the final contouring plan in terms of managing precipitation runoff from the cover surface over the long term. In many cases, a numerical analysis of the consolidation and associated release of pore water from the tailings is required as part of the cover system design.

Another issue that should be considered during the design of a cover system is the potential migration of salts and metals from the waste material into the cover system, and subsequently into the vegetation and food chain. This issue is generally more applicable to the decommissioning of tailings impoundments as opposed to waste rock piles for three reasons: (1) residual process constituents in the tailings pore water, (2) higher moisture retention and potential for capillary rise of pore waters due to the fine textured nature of tailings, and (3) the base of the cover system is typically in close proximity to the phreatic surface in the tailings (particularly in the short term). The upward migration of salts into the cover profile can hinder the development of the desired vegetation community, while the potential uptake of metals by various vegetation species may lead to detrimental impacts on fauna that subsist on the vegetation. This issue is generally addressed by either increasing the thickness of the cover system or incorporating a capillary break layer near the base of the cover system.

The revegetation of covers must be as close as possible to the species and plant communities growing naturally in the area. The plant communities that will evolve after some years or decades are determined by the soil, climate and use scenarios. It is an illusion to believe that unwanted species (e.g. deep rooting plants penetrating a mineral infiltration barrier) can be eradicated in the long term. This would require the perpetual existence of institutional control mechanisms, which is an unrealistic assumption. Instead, the regional vegetation should be part of the cover design, and cover performance should be robust with respect to regionally typical vegetation patterns.

3.3.2. Soil remediation

This subsection discusses four in situ technologies. The key factors that are considered in this analysis are status, range of contaminants treated, major limiting factors and site specific considerations. Status refers to the stage of development of the technology. Range of contaminants treated specifies whether the technology can address a broad range of metals and radionuclides or focuses on a limited range of these contaminants. Major limiting factors are to process considerations that may limit broad use of the technology. Site specific considerations refer to those site characteristics that can influence the effectiveness of the technology.

Table 2 [29] provides an overview of the key factors for each of the four technologies. As Table 2 indicates, electrokinetics, soil flushing and solidification/stabilization (S/S) are at more advanced stages of development than phytoremediation. Soil flushing is currently applicable to a limited range of metals. Soil flushing requires consideration of the potential risk of aquifer contamination by the residual flushing solution at the site. The permeability of the soil and the characteristics of the groundwater flow are the main site specific considerations affecting the applicability of soil flushing. The electrokinetics approach is most applicable to sites at which the soil is homogeneous and the moisture level is relatively high. Phytoremediation requires longer treatment times than other treatment technologies, and may potentially be applied at sites at which the contamination is shallow and the concentration of the contaminants relatively low. S/S is limited by the lack of data concerning the long term integrity of the treated material. The technology is most effective at sites at which little or no debris is present.

3.3.2.1. Electrokinetics

Electrokinetic remediation, also referred to as electrokinetic soil processing, electromigration, electrochemical decontamination or electroreclamation, can be used to extract radionuclides, metals and some types of organic wastes from saturated or unsaturated soils, slurries and sediments. It is a potentially important technique for fine grained soils. It is based on the application of an electrical potential difference or a low intensity direct current between two electrodes inserted in the soil. If the contaminant species are charged, they move by ionic migration towards one of the electrodes, depending on the sign of their electric charge, where they can be recovered. As far as mobilization and removal of heavy metal ions from clayey soil is considered, the interaction between the pollutants and the soil surface mainly depends on the characteristics of the active sites at the soil surface. Different active sites lead to different retention mechanisms, thus an accurate representation of the soil surface is relevant to an assessment of the likely performance of an electrokinetic process.

TABLE 2. SUMMARY OF EVALUATION CRITERIA OF FOUR DIFFERENT TYPES OF SOIL REMEDIATION TECHNIQUES

Evaluation factor	Technology			
	Electrokinetics	Phytoremediation	Soil flushing	Solidification/stabilization
Status	Full scale, applications in Europe Licensed in USA	Pilot scale Used in Chernobyl, Ukraine and Fernald, Ohio, USA	Commercial Selected at four Superfund sites	Commercial
Range of metals treated	Broad	Broad	Limited	Broad
Major limiting factors	State of the art	State of the art Longer time required for treatment Crop yields and growth patterns	Potential contamination of the aquifer from residual flushing solution	Concern with long term integrity
Site specific considerations	Homogeneity of soil moisture level in soil	Depth and concentration of contamination	Permeability of soil Groundwater flow and depth	Debris, depth of contamination

Electrokinetic technologies may be employed both in situ or ex situ. Electrokinetics can be efficient in extracting contaminants from fine grained, high permeability soils. A number of factors determine the direction and extent of the migration of the contaminant. Such factors include the type and concentration of the contaminant, the type and structure of the soil, and the interfacial chemistry of the system. Water or some other suitable salt solution may be added to the system to enhance the mobility of the contaminant and increase the effectiveness of the technology. (For example, buffer solutions may change or stabilize pore fluid pH.) Contaminants arriving at the electrodes may be removed by any of several methods, including electroplating at the electrode, precipitation or co-precipitation at the electrode, pumping of water near the electrode or complexing with ion exchange resins. Electrochemistry associated with this process involves an acid front that is generated at the anode by the oxidation of water, if it is the primary pore fluid present.

The variation of pH at the electrodes results from the electrolysis of the water. The solution becomes acidic at the anode because hydrogen ions are produced and oxygen gas is released, and the solution becomes basic at the cathode, where hydroxyl ions are generated and hydrogen gas is released.

At the anode, the pH could drop below 2, and it could increase at the cathode above 12, depending on the total current applied. The acid front eventually migrates from the anode to the cathode. Movement of the acid front by migration and advection results in the desorption of contaminants from the soil. The process leads to temporary acidification of the treated soil. The alkali front may cause precipitation of heavy metals as hydroxides, decreasing the effectiveness of the process. Moreover, a low electrical conductivity region can originate where the migrating hydrogen and hydroxyl ions meet. In order to prevent these problems, several enhanced processes have been developed, which are based on the control of pH near the cathode by addition of acidic solutions or on the use of ion exchange membranes to prevent penetration of OH in the soil [30].

Metallic electrodes may dissolve as a result of electrolysis and introduce corrosion products into the soil mass. However, if inert electrodes, such as carbon, graphite or platinum, are used, no residue will be introduced into the treated soil mass as a result of the process. The electrodes can be placed horizontally or vertically, depending on the location and shape of the plume of contamination. Combinations of electrokinetics with other techniques can also be implemented. For example, the results of preliminary investigations into the potential application of a remediation system that couples the electrokinetic remediation with the permeable reactive barrier (PRB) concept are presented in Ref. [31].

Atomizing slag was adopted as a PRB reactive material for groundwater contaminated with either inorganic or organic substances. Laboratory experiments were performed with variable conditions including: (a) type of pollutant, (b) processing time, and (c) the application of the PRB system during electrokinetic processing. The results of the preliminary investigations suggest that the coupled technology could effectively remediate contaminated groundwater in situ without extracting pollutants from the subsurface through the effectiveness of the reactions between the reactive materials and contaminants.

Before electrokinetic remediation is undertaken at a site, a number of different field and laboratory screening tests must be conducted to determine whether the particular site is amenable to the treatment technique:

— Field conductivity surveys. The natural geological spatial variability should be delineated because buried metallic or insulating material can induce variability in the electrical conductivity of the soil, and therefore affect the voltage gradient. In addition, it is important to assess whether there are deposits that exhibit very high electrical conductivity, where the technique may be inefficient.
— Chemical analysis of water. The pretreated water should be analysed for dissolved major anions and cations, as well as for predicted concentration of the contaminant(s). In addition, electrical conductivity and pH of the pore water should be measured.
— pH effects. The pH values of the pore water and the soil should be determined because they have a great effect on the valence, solubility and sorption of contaminant ions.
— Chemical analysis of soil. The buffering capacity and geochemistry of the soil should be determined at each site.
— Bench scale tests. The dominant mechanism of transport, removal rates and amounts of contamination left behind can be examined for different removal scenarios by conducting bench scale tests. Because many of these physical and chemical reactions are interrelated, it may be necessary to conduct bench scale tests to predict the performance of electrokinetic remediation at the field scale.

3.3.2.2. Performance and cost

The processing cost of a system consists of energy costs, conditioning costs and fixed costs associated with installation of the system. Power consumption is related directly to the conductivity of the soil across the electrodes. Electrical conductivity of soils can span orders of magnitude. The voltage gradient is often held to approximately 1 V/cm in an attempt to prevent adverse effects of temperature increases and for other practical reasons. It may be cost prohibitive to attempt to remediate high plasticity soils that have high electrical conductivities. The processing time will depend upon several factors, including the spacing of the electrodes, and the type of conditioning scheme that will be used. If, for example, an electrode spacing of 4 m is selected, it may be necessary to process the site over several months.

Energy expenditures in extraction of metals from soils may be 500 kWh/m^3 or more at an electrode spacing of 1.0–1.5 m.

Radionuclides already tested include uranium, thorium and radium. Metals include cadmium, chromium, mercury, zinc, iron and magnesium.

3.3.2.3. Phytoremediation

This technique consists of the use of plants to remove, contain or render harmless environmental contaminants. This definition applies to all biological, chemical and processes that are influenced by plants and the cleanup of contaminated substances. Plants can be used in site remediation, both to mineralize and immobilize toxic organic compounds at the root zone and to accumulate and concentrate metals and other radionuclides from soil into above ground shoots.

Phytoremediation technologies can be developed for different applications in environmental cleanup, and are classified into three types:

— Phytoextraction;
— Phytostabilization;
— Rhizofiltration.

Table 3 presents a summary and comparison of phytoremediation technologies.

(a) Phytoextraction

Phytoextraction uses hyper accumulating plants to transport metals from the soil and concentrate them into the roots and above ground shoots that can be harvested. It is suggested that hyper accumulation is an important ecophysiological adaptation to metal stress and one manifestation of resistance to metals.

Dried or composted plant residues or plant ashes that are highly enriched with metals can be isolated as hazardous waste or recycled as metal ore. The goal is to recycle as ‘bio-ores’ metals reclaimed from plant ash in the feed stream of smelting processes. Even if the plant ashes do not have enough concentrations of metal to be useful in smelting processes, phytoextraction remains beneficial because it reduces the amount of hazardous waste by as much as 95%.

The use of trees can result in extraction of significant amounts of metal because of their high biomass production. However, the use of trees in phytoremedition requires long term treatment, and may create additional environmental concerns about falling leaves. When leaves containing metals fall or blow away, recirculation of metals to the contaminated site and migration off-site by wind transport or through leaching can occur. Some grasses accumulate surprisingly high levels of metals in their shoots without exhibiting toxic effects.

(b) Phytostabilization

Phytostabilization uses plants to limit the mobility and bioavailability of metals in soils. Ideally, phytostabilizing plants should be able to tolerate high levels of metals and to immobilize them in the soil by sorption, precipitation, complexation or the reduction of metal valences. Phytostabilizing plants should also exhibit low levels of accumulation of metals in shoots to eliminate the possibility that residues in harvested shoots

TABLE 3. OVERVIEW AND COMPARISONS OF PHYTOREMEDIATION TECHNOLOGIES

General characteristics		
Best used at sites with low to moderate disperse metal and radionuclide content and with a soil media that will support plant growth Application limited to depth of the root zone Longer times required for remediation compared with other technologies Different species have been identified to treat different metals and radionuclides		
	Phytoextraction (harvest)	Phytostabilization (root fixing)
Description	Uptake of contaminants from soil into above ground plant tissue, which is periodically harvested and treated	Production of chemical compounds by the plant to immobilize contaminants at the interface of roots and soil Additional stabilization can occur by raising the pH level in the soil
Status	Applied in Chernobyl in the vicinity of the damaged reactor	Research is ongoing
Applicability	Potentially applicable for many metals and radionuclides	Potentially applicable for many metals and radionuclides
Comments	Cost affected by volume of biomass produced that may require treatment before disposal Cost affected by concentration and depth of contamination and number of harvests required	Long term maintenance is required

might become hazardous wastes. In addition to stabilizing the metals present in the soil, phytostabilization plants can also stabilize the soil matrix to minimize erosion and migration of sediments. Some researchers consider phytostabilization an interim measure to be applied until phytoextraction becomes fully developed. However, there are others who consider the technology suitable for metal remediation, especially for a site at which removal of metals does not seem to be economically feasible.

(c) Rhizofiltration

Rhizofiltration uses plant roots to absorb, concentrate and precipitate metals from wastewater, which may include leachate from soil. Rhizofiltration uses terrestrial plants instead of aquatic plants because the terrestrial plants develop much longer fibrous root systems covered with root hairs that have extremely large surface areas. This variation of phytoremediation uses plants that remove metals by sorption, which does not involve biological processes. Use of plants to translocate metals to the shoots is a slower process than phytoextraction.

Another type of rhizofiltration, which is more fully developed, involves construction of wetlands or reed beds for the treatment of contaminated wastewater or leachate. The technology is cost effective for the treatment of low contaminant loads (flow rate times concentration) in the wastewater. Practical experience has shown that the window of application for biological remediation methods is rather narrow; if the contaminant load is too small, there is often no need for treatment at all, while at high loads, passive systems are easily overloaded, and conventional treatment methods are preferred. Note that the performance in terms of reliability and predictability of biological systems is often insufficient when clearly quantifiable remediation objectives must be met (e.g. discharge limits of a water treatment installation).

Management of the wastes resulting from a biological treatment system (sludge retained by the rhizosphere, plant tissue, etc.) is a widely underestimated issue that becomes the decisive factor in the large scale application of phytoremediation systems. The residues are typically organic, which is problematic under conventional waste management schemes. Removing sludge from a rhizofiltration system, or replacing biomass to keep performance up, is, in effect, a disturbance of an (albeit artificial) ecosystem. Re-establishing a normal operation mode after such perturbations is a complex process that takes time, during which the performance may be much lower than intended.

Apart from biogeochemical aspects, the most pronounced problems of practical application lie in the field of hydraulics. Typical failure scenarios of rhizofiltration systems and constructed wetlands are linked to clogging of flow paths by sedimentation products, hydraulic overload of the installations and alteration of the hydraulic properties of substrates. Careful design, extensive piloting and, often, readjustment of the systems after commissioning are required before a biological treatment system can be said to work reliably.

A decisive factor is the availability of off the shelf biological solutions. As pointed out in Section 3.2, an important determinant to apply a technology is whether successful demonstration cases exist. The number of sites where phytoremediation has been applied successfully over an extended period of time and beyond a mere pilot phase is surprisingly small, if compared with the enthusiasm with which this promising technology was received in the early to mid-1990s. Table 4 [32] summarizes the advantages and disadvantages of each of the types of phytoremediation.

3.3.2.4. Performance and cost

Amount of biomass is one of the factors that determines the practicality of phytoremediation. Under the best climatic conditions, with irrigation, fertilization and other factors, total biomass productivity can approach 100 $t \cdot ha^{-1} \cdot a^{-1}$. One unresolved issue is the tradeoff between accumulation of toxic elements and productivity. In practice, a maximum harvest biomass yield of 10–20 $t \cdot ha^{-1} \cdot a^{-1}$ is likely, particularly for plants that accumulate metals.

These values for the productivity of biomass and the metal content of the soil would limit annual capacity for removal of metals to approximately 10–400 $kg \cdot ha^{-1} \cdot a^{-1}$, depending on the pollutant, species of plant, climate and other factors. For a target soil depth of 30 cm (4000 t/ha), this capacity amounts to an annual reduction of 2.5–100 mg/kg of soil contaminants. This rate of removal of contamination is often acceptable, allowing total remediation of a site over a period of a few years to several decades.

TABLE 4. TYPES OF PHYTOREMEDIATION TECHNOLOGY: ADVANTAGES AND DISADVANTAGES

Type of phytoremediation	Advantages	Disadvantages
Phytoextraction by trees	High biomass production	Potential for off-site migration and leaf transportation of metals to surface Metals are concentrated in plant biomass and must be disposed of eventually
Phytoextraction by grasses	High accumulation	Low biomass production and slow growth rate Metals are concentrated in plant biomass and must be disposed of eventually
Phytoextraction by crops	High biomass and increased growth rate	Potential threat to the food chain through ingestion by herbivores Metals are concentrated in plant biomass and must be disposed of eventually
Phytostabilization	No disposal of contaminated biomass required	Remaining liability issues, including maintenance for indefinite periods of time (containment rather than removal)
Rhizofiltration	Readily absorbs metals	Applicable for treatment of water only Metals are concentrated in plant biomass and must be disposed of eventually

Costs involved in phytoremediation projections should include those related to:

— Design costs: site characterization, work plan and report preparation, treatability and pilot testing.
— Installation costs:
  • Site preparation: facility removal, debris removal and utility line removal or relocation;
  • Soil preparation: physical modification (tilling), chelating agents, pH control and drainage.
— Infrastructure: irrigation system.
— Fencing.
— Planting: seeds, plants, labour and protection.
— Operating costs:
  • Maintenance: irrigation water, fertilizer, pH control, chelating agents, drainage water disposal, pesticides, fencing/pest control, replanting;
  • Monitoring: soil nutrients, soil pH, soil water, plant nutrient status, roots, shoots, stems, leaves, tree sap flow monitoring, air monitoring, weather monitoring.

The following cost breakup is summarized in Ref. [32] (all figures correct as of 1998):

Phytoextraction costs:
— The estimated 30 year costs for remediating a 40 000 m^2 lead site were $12 000 000 for excavation and disposal, $6 300 000 for soil washing, $600 000 for a soil cap and $200 000 for phytoextraction;
— Cost estimates made for remediation of a hypothetical case of a 0.5 m thick layer of sediments contaminated with Cd, Zn and 137Cs from a 4000 m^2 chemical waste disposal pond indicated that phytoextraction would cost approximately one third of the amount of soil washing;
— Costs were estimated to be $60 000–100 000 using phytoextraction for the remediation of 3300 m^2 of 0.5 m thick sandy loam compared to a minimum of $400 000 for just excavation and storage of this soil.

Rhizofiltration costs:
— The cost of removing radionuclides from water with sunflowers has been estimated to be $0.5–1.6 per m^3 of water.

Phytostabilization costs:
— Cropping system costs have been estimated at $200–10 000 per ha, equivalent to $0.02–1.00 per m^3 of soil, assuming a 1 m root depth;
— Hydraulic control costs;
— Estimated costs for the remediation of an unspecified contaminant in a 6 m deep aquifer at a 4047 m^2 site were $660 000 for conventional pump and treat (P&T) methods, and $250 000 for phytoremediation using trees;
— Vegetative cover costs;
— Cost estimates indicate savings for an evapotranspiration cover compared to a traditional cover design to be 20–50%, depending on the availability of suitable soil.

3.3.2.5. Soil flushing

Soil flushing techniques promote the mobility and migration of metals by solubilizing the contaminants so that they can be extracted. Soil flushing is an in situ process that is accomplished by applying the flushing fluid to the surface of the site or injecting it into the contaminated zone. The resulting leachate is then typically recovered from the underlying groundwater by P&T methods.

Soil flushing can dissolve contaminants using either water as the flushing fluid or chemical additives to enhance the solubility of the contaminant. Water alone can be used to remove certain water soluble contaminants. The use of soil flushing chemicals may involve adjusting the soil pH, chelating metal contaminants or displacing cations by other less hazardous ones. The in situ flushing process requires that the flushing fluids be percolated through the soil matrix. The fluids can be introduced by surface flooding, surface sprinklers, leach fields, vertical or horizontal injection wells, basin infiltration systems or trench infiltration systems.

The finer sized fractions (clays, silts, iron and manganese oxides, and organic matter in soil) can bind metals electrostatically as well as chemically. Factors regulating the sorption of metals would include pH, soil type, cation exchange capacity (CEC), particle size, permeability, specific types and concentrations of metals, and types and concentration of organic and inorganic compounds in solutions.

Generally, as the soil pH decreases, solubility and mobility of cationic metals increase. In most cases, the mobility and sorption of a metal are likely to be controlled by clay content in the subsoil and by organic fraction in the top soil. Clays can adsorb metals present in the soils. It has been reported that the high inorganic matter of surface soil retained significantly more metal than subsurface soils, which contained less organic matter. Organic matter in soil is of significant importance because of its effect on CEC. CEC, which measures the extent to which cations in the soil can be exchanged, is often used as an indication of the soil's capacity to immobilize metals.

Once the infiltrated or percolated solution has flushed the contaminants to a certain location, the contaminated fluids must be extracted. Extraction techniques include vacuum extraction methods in the vadose zone and P&T systems in the saturated zone.

Recovered groundwater and flushing fluids containing desorbed contaminants may require treatment to meet appropriate discharge standards before such fluids are recycled or released to public owned wastewater treatment works or receiving streams. If regulations so allow, recovered fluids should be reused in the flushing process to reduce disposal costs.

Table 5 summarizes the main aspects of soil flushing technology.

3.3.2.6. Performance and cost

There is evidence that metal extraction technologies have a removal efficiency of 90%. A concentration of uranium in groundwater of 5–20 mg/L was reduced to 1–2 mg/L after soil flushing. Groundwater contaminated with 250–500 mg/L of ammonium contained 10–50 mg/L after treatment.

It should be noted that, if the soil contains relatively high levels of calcium, substantial amounts of HCl flushing solution would be consumed in neutralization reactions.

The factors that most affect costs are the initial and target concentrations of contaminants, permeability of the soil and depth of the aquifer. Capital costs for chemically enhanced solubilization (CES) are similar to those for traditional P&T systems, except for the initial expense of equipment required to handle the flushing solution. Operating costs are also similar, except for the cost of handling and replacement of flushing solutions and additives. Overall, for the life of the treatment process, CES should be significantly less expensive than P&T systems because of the much shorter timeframes for treatment and smaller volumes of water to be extracted and treated [33].

3.3.2.7. Solidification/stabilization technologies

Solidification treatment processes change the physical characteristics of the waste to improve its handling and to reduce the mobility of the contaminants by creating a physical barrier to leaching. Solidification can be achieved through the use of conventional pozzolans such as Portland cement. Stabilization (or immobilization) treatment processes convert contaminants to less mobile forms through chemical or thermal interactions. Vitrification of soil is an example of an S/S process that employs thermal energy. S/S treatment processes can be performed in situ or ex situ. Table 6 depicts some general characteristics of S/S technologies.

Solidification and stabilization technologies are used to change the physical characteristics and leaching potential of waste. The term S/S refers to processes that utilize treatment reagents or thermal energy to accomplish one or more of the following objectives:

- Reduce the mobility or solubility of the contaminants to levels required by regulatory or other risk based standards;
- Limit the contact between site fluids (such as groundwater) and the contaminants by reducing the permeability of the waste, generally to less than 1×10^{-6} cm/s;
- Increase the strength or bearing capacity of the waste, as indicated by unconfined compressive strength.

TABLE 5. OVERVIEW OF SOIL FLUSHING TECHNOLOGY

General characteristics		
Best used in soils with high permeability Different delivery systems available to introduce flushing solutions Cost is primarily influenced by potential requirements for interim containment, the depth of contamination and the time required for operation Associated risk of contamination of underlying aquifers with unrecovered flushing solutions that contain solubilized contaminants; best used at sites with aquifers that have low specific yields		
	Water flushing	Reagent flushing
Description	Use of water to solubilize the contaminant prior to extraction	Use of a chemical reagent to solubilize the contaminants for extraction
Status	Commercial	Limited research
Applicability	Water soluble metals and radionuclides	Bench scale, lead and uranium
Comments	Applicable only for water soluble metals and radionuclides, focus is often on organics In situ flushing has been selected at four US Superfund sites at which soils are contaminated with metals (most of the sites are also contaminated with organics)	Some small scale testing has been conducted with chelators as the primary reagent for the removal of metals from soils; the results of those tests have led to further testing on a larger scale pH adjusters and chemical binders are also being studied for potential applicability to metals Surfactants are primarily targeted for removal of organic contaminants

TABLE 6. OVERVIEW OF SOLIDIFICATION/STABILIZATION TECHNOLOGIES

General characteristics		
Commercially available Cost is affected by the depth of the contamination, the degree of homogeneity of soil and the presence of debris and excess moisture		
	Reagent based in situ stabilization	Vitrification
Description	Addition of pozzolanic reagents with or without additives to physically and chemically convert contaminants to less mobile forms	Use of energy to melt soils and physically and chemically encapsulate contaminants into less mobile and more stable forms
Status	Commercial	Commercial
Applicability	Broad general applicability to most metals	Broad general applicability to most metals including radioactive metals
Comments	Performance is highly dependent on mixing efficiency Soils with high clay content or significant debris may be difficult to mix Various auger sizes and mixing configurations can be used, and various reagents are available In situ applications are less common than ex situ applications because it is difficult to verify whether mixing is sufficient	High moisture content will increase costs substantially Debris or high concentrations of organic contaminants may decrease performance

3.3.2.8. Reagent based solidification/stabilization processes

In situ reagent based S/S technologies consist of a reagent formulation and a delivery system. With the exception of near surface applications (i.e. to depths of about 5 m), a reagent based S/S delivery system usually consists of a slurry batch plant, delivery hoses and one or more augers. Most reagent formulations for in situ S/S applications consist of ordinary pozzolanic reagents, although a proprietary reagent is often used in conjunction with or instead of pozzolanic reagents. Pozzolanic mixtures are based on siliceous volcanic ashes similar to substances used to produce hydraulic cement. Depending on the characteristics of the waste to be treated and the desired properties of the treated wastes, additives such as bentonite or silicates may be added to the cement or fly ash mixture or both. For example, the addition of bentonite increases the ease of pumping of the wet reagent slurry and decreases the permeability of the treated waste. Silicates form chemical complexes with metals, often providing greater insolubility than hydroxide, carbonate or sulphate precipitates.

At Wismut's former in situ leaching site in Königstein, Germany, and at some sites in Canada, an S/S technique based on supersaturated salt solutions has been successfully applied [34]. The technique is based on the idea that supersaturated barium sulphate or calcium sulphate solutions can be prevented from precipitating for a period of time from several minutes to several days using proprietary phosphate based additives. If injected into the contaminated soil, the viscosity of the brine equals that of water and therefore moves along a certain distance with the groundwater flow. After a defined period, the dissolved constituents ($BaSO_4$, $CaSO_4$) finally precipitate from solution. This delay time can be adjusted to reach the source of the contamination. Two effects lead to the immobilization of the plume:

— The pores of the contaminated soil are hydraulically blocked, reducing the hydraulic permeability of the soil, so that the hydraulic flow in the aquifer is diverted around the contamination source.
— The individual grains that may act as a contamination source are encapsulated by the precipitates, which prevents further release of contamination.

Advantages of this technology include:

— The low viscosity of the supersaturated solution is in the same range as that of water, thus allowing the solution to migrate long distances with the groundwater flow to the location where precipitation eventually occurs.
— The reagents used are naturally occurring, which minimizes unwanted side effects.

3.3.2.9. Vitrification

Vitrification uses electrical power to heat and melt soils and metal bearing wastes. The molten material cools to form a hard monolithic, chemically inert, stable product of glass and crystalline material that incorporates and immobilizes the inorganic compounds and metals. The resultant vitrified product is a glassy material, with very low leaching characteristics. Organic wastes are initially vaporized or pyrolysed by the process. These contaminants migrate to the surface, where they are treated in an off-gas treatment system.

3.3.2.10. Performance and cost

It is reported that in most cases involving in situ S/S, the site cleanup manager contracts a testing laboratory to develop and optimize a suitable reagent formulation that will meet the desired performance objectives for the site of concern. Occasionally, the vendor of the in situ technology will develop the formulation on a bench scale to achieve the desired immobilization of contaminants and post-treatment permeability and unconfined compressive strength. Therefore, testing on the bench scale consists of optimizing the reagent formulation. Testing at the pilot or full scale consists of the QC of grout and confirmation sampling to determine whether the treated material meets required performance specifications.

In terms of vitrification, experience recommends that it should not be applied at sites at which organic content in the soils exceeds 10% by weight. In addition, it is not recommended at sites at which metals in the soil exceed 25% by weight or where inorganic contaminants exceed 20% of the soil by volume. The cost of vitrification is influenced principally by the requirement for electric power, which increases substantially with increasing moisture in the soil.

3.3.3. Water treatment

One of the problems regarding environmental remediation of some industrial sites, for example, a mining site, is water treatment. Waters draining from abandoned metal mines and coal mines are a major cause of river pollution in many regions of the world. Such drainage is often enriched in heavy metals and radionuclides, which may lead to undue exposures of members of the public and other ecological problems.

Generally associated with the end of operations is the cessation of dewatering, which leads to a gradual flooding of the mined voids and adjoining strata, which is reflected in a gradual rise in the water table across an area of abandoned workings until surface discharges commence, balancing the rate of rainfall recharge to the mined strata [35]. This process of water table rise after cessation of dewatering is generally called water table or groundwater rebound.

Contaminated water can also originate, in mining sites, from waste rock dumps and tailings dams or tailings piles. Acidification of these waters as a result of the process of sulphide oxidation by oxygen and water, generally intermediated by bacteria, can lead to the long term requirement for water treatment or the implementation of passive strategies for water cleanup.

A few questions about the long term aspects of water treatment have been discussed in the literature [35]. Answering these questions will be very important in designing appropriate remediation schemes:

- How long will contaminant loads and pH be of concern?
- If a treatment plant is installed at the present time, how long will it have to remain in operation?
- If a passive treatment system is designed (e.g. wetland) on the basis of current pollutant loadings (with a considerable capital investment in land acquisition and plant construction), is there a chance that it will be over designed for the long term?

In order to answer these questions, it is necessary to have a good understanding of the geochemical and hydrogeological processes involved, which need to be mathematically modelled so that predictions that are as accurate as possible can be made.

It is proposed that a distinction between two types of acid waters be made, i.e. vestigial acidity, arising from pyrite oxidation products that are flushed into solution during regional water table rebound, leading to a highly polluted ‘first flush’, and juvenile acidity, arising primarily from pyrite oxidation during seasonal water table fluctuation [35].

Lessons learned indicate that:

- The poorest water quality from any uncontrolled mine water discharge can be expected to occur within the first 40 years.
- Where rainfall is high and/or the extent of interconnected workings is reasonably modest, the worst of the pollution may pass in only 10 or 20 years.
- Asymptotic levels of pollution (relating to juvenile acidity production rates) are generally around 10–30 mg/L of iron.
- Higher levels (≤300 mg/L) can be expected where:
  - Water table fluctuation is very vigorous in near surface areas;
  - The pyrite content of the strata is very high.

It should be noted that, apart from the well known acid rock drainage/acid mine drainage (AMD) problems associated with some mining and milling sites, other sites are characterized by carbonate rich waters. Treatment strategies of carbonate rich waters must take into account that uranium occurs in uranyl–carbonate complexes which must be hydrolysed before uranium can be effectively precipitated from aqueous solution.

Remediation strategies to deal with contamination of water (especially by acid generation due to sulphidic material oxidation) can be divided into solutions to be applied to water itself — water treatment techniques (active versus passive treatments) — and solutions to be applied to the source.

3.3.3.1. Treatment strategies for solutions applied to water

Generally speaking, treatments can be grouped into two categories: active and passive. In some situations, active treatment of these waters using oxidation and chemical neutralization can be the most effective. Another categorization concerns acid and non-acid water types, which need different treatment approaches. A review paper on the topic, which covers different aspects of the problem, can be seen in [36].

It is generally agreed that the choice of which option to use to remediate AMD is dictated by a number of economic and environmental factors. Traditionally, large discharge volume mine waters have been treated by active chemical processing, particularly when the waters are acidic. It should be noted that the necessary land surface area and topographic problems may rule out passive biological systems in some situations. However, mining industries are becoming increasingly attracted to such systems, as they avoid the high recurrent costs of lime addition and sludge disposal. The land areas required for passive systems can, in theory, be made dramatically smaller by focusing on optimizing biological processes; for example, packed bed bioreactors for removing iron from acidic mine waters are far more effective than aerobic wetlands.

It does need to be recognized, however, that virtually no remediation system is maintenance free. Passive systems also require a certain amount of management, and will eventually fill with accumulated ochre (aerobic wetlands) and sulphides (compost bioreactors). The long term stabilities of these materials are uncertain, but as they may contain toxic elements (arsenic, cadmium, uranium, etc.), their storage or disposal requires careful consideration.

As discussed above, the sustainability of any remediation system is a factor that is becoming increasingly critical in decision making. Products of AMD remediation have not been perceived as a resource, but this view may be changing. To support this view, iron oxide sludge recovered from drainage in an abandoned coal mine may be used to manufacture burnt sienna pigment, and base metals recovered by the active biological treatment of AMD from metal mines provide some financial return on the investment and running costs of sulphidogenic bioreactors. In the same way, a possible strategy which could be applied to mitigate the impacts of acid drainage generated by pyrite oxidation in one of the waste rock dumps of the Pocos de Caldas (Brazil) is the economic recovery of uranium present in the drainage [37]. However, this is not a widely tested approach, and lessons still need to be learned in the future, once these systems are up and running. Presently, these drainages, along with the drainage from other waste rock piles, are being neutralized with lime. Approximately 30 t of uranium per year are disposed of as waste. The challenge here is to establish an efficient method to extract uranium from these waters. With a uranium price of about $40 per kg, it was calculated that about $1.2 million per year would be gained by the recovery of uranium from acid drainage. These figures were contrasted with values reported by the operator, which show that about $145 000 per year are expended on lime for water treatment.

Ultimately, legislation is likely to become the dominant factor in determining which remediation system can be used in any situation. For example, it might become increasingly untenable to dispose of base metals in sludges and sediments (with all of the inherent storage problems) when there are technologies available for their recovery and recycling. Limits on the concentration of sulphate that can be discharged from processing plants may restrict the choice of a system to one that effectively removes sulphates, as well as metals and acidity, from mine waters. One certainty is that the problem of what to do about the pollution threat posed by AMD will be with us for very many years to come.

A general rule is that the rigid regulatory framework usually applied to conventional treatment systems is hardly applicable to biological systems. Experience shows that their performance cannot be guaranteed over the entire year, but is subject to fluctuations that necessitate a conventional plant as backup. This is typically the case in densely populated areas such as western and central Europe, where downstream water users (and hence regulatory authorities) are more sensitive with respect to water pollution, even short term pollution, than in sparsely populated areas.

3.3.3.2. Treatment strategies for solutions applied to the contamination source (in situ treatment)

Treatment processes for AMD, such as those described above including precipitation through neutralization (and possibly peroxide addition), have major disadvantages, including large doses of lime and peroxide and costly sludge disposal fees.

Fly ash can be used to prevent the generation of AMD. A column experiment filled with a pyrite rich sludge with artificial irrigation leached acid drainages (approximately pH2) containing high concentrations of sulphates, iron and other metals. However, non-saturated column experiments filled with pyrite rich sludge and fly ash drained leachates characterized by an alkaline pH (pH up to 10), low sulphate concentration, and lack of iron and other metals in solution. The pyrite oxidative dissolution at high pH, as a consequence of the leaching of fly ash (releasing CaO and subsequently $Ca(OH)_2$ into solution), favours the metal precipitation inside the column (mainly iron), the coating of pyrite grains and the attenuation of the oxidation process, resulting in a great improvement in the quality of the leachates.

The use of red mud bauxite (RMB) that is very alkaline to neutralize acidic tailings has been investigated [38]. Experiments showed that RMB has a good neutralization capacity for a short time, but the long term neutralization potential is uncertain. Brine was then added to RMB to verify whether it could improve the long term alkalinity retention of RMB. Results showed that neutral pH conditions were maintained over the entire test for RMB and a mixture of RMB with brine. Addition of brine to RMB slightly lowered the pH compared to RMB alone. RMB alone lost a lot of dissolved alkalinity at the beginning of the test. Most of the alkalinity was lost in water after a few flushes for RMB samples. The addition of brine helped to keep neutralization potential over more cycles of leaching.

The applicability and limitations of granular zerovalent iron for the treatment of water impacted by mine wastes has been examined [39]. Rates of acid neutralization and metal uptake were determined in batch systems using simulated mine drainage (initial pH2.3–4.5; total dissolved solids 14 000–16 000 mg/L). Metal removal from solution and acid neutralization occurred simultaneously, and were most rapid during the initial 24 h of reaction. Reaction half-lives ranged from 1.50 ± 0.09 h for Al to 8.15 ± 0.36 h for Zn. Geochemical model results indicate that metal removal is most effective in solutions that are highly undersaturated with respect to pure metal hydroxides, suggesting that adsorption is the initial and most rapid metal uptake mechanism. Continued adsorption onto or co-precipitation with iron corrosion products are secondary metal uptake processes. Sulphate green rust was identified as the primary iron corrosion product, which is shown to be the result of elevated $[SO_2^{-4}]/[HCO_3^{-}]$ ratios in solution. Reversibility studies indicate that zerovalent iron will retain metals after shifts in redox states are imposed, but that remobilization of metals may occur after the acid neutralization capacity of the material is exhausted. A small scale laboratory experiment to define the longevity of limestone drains has been implemented [40]. Synthetic AMD (100 mg/L Fe, pH4–4.8) was pumped through a column containing limestone particles for 1110 h, when the effluent pH had dropped from a maximum of 6.45 to 4.9. The decline in neutralization during the experiment was due to the formation of Fe hydroxide coatings on the limestone grains. It was reported that the coatings were composed of lepidocrocite/goethite in three distinct layers: an initial thick porous orange layer, overlain by a dense dark brown crust, succeeded by a layer of loosely bound, porous orange globules. After 744 h, a marked increase in the rate of pH decline occurred, and the system was regarded as having effectively failed. At this time, the Fe hydroxide crust effectively encapsulated the limestone grains, forming a diffusion barrier that slowed down limestone dissolution. Between the coating and the limestone substrate was a 60 µm wide space, so that agitation of the limestone sample would readily remove the coating from the limestone surface. It was concluded that passive limestone systems can be used in AMD treatment when the influent Fe concentration is considerably greater than 1 mg/L, the currently recommended limit, particularly given that the Fe precipitates armouring the limestone grains may be loosely bound and relatively easily dislodged. Therefore, limestone drains are more widely applicable than presently realized.

A three step process for the removal of uranium from dilute wastewaters is described in Ref. [41]. According to their scheme, step 1 involves the sequestration of uranium on, in and around aquatic plants such as algae. Cell wall ligands efficiently remove U(VI) from wastewater. Growing algae continuously renew the cellular surface area. Step 2 is the removal of uranium algal particulates from the water column to the sediments. Step 3 involves reducing U(VI) to U(IV) and transforming the ions into stable precipitates in the sediments. The algal cells provide organic carbon and other nutrients to heterotrophic microbial consortia to maintain the low E_h, within which the uranium is transformed. Among the microorganisms, algae are of predominant interest for the ecological engineer because of their ability to sequester uranium, and because some algae can live under many extreme environments, often in abundance. Algae grow in a wide spectrum of water qualities, from alkaline environments (Chara, Nitella) to acidic mine drainage wastewaters (Mougeotia, Ulothrix). It was speculated that if these plants could be induced to grow in wastewaters, they would provide a simple, long term means to remove uranium and other radionuclides from uranium mining effluents.

3.3.4. Groundwater treatment

3.3.4.1. Pump and treat

P&T technology involves extracting groundwater from the subsurface through one or more wells and treating the extracted groundwater above ground (ex situ). Above ground treatment systems typically include one or more biological, physical or chemical technologies for treating the extracted groundwater and one or more technologies for treating any off-gases.

The permeability, porosity, moisture content and heterogeneity of the soil and the depth and stratigraphy of the contamination in the subsurface affect the number and placement of the extraction wells, the radius of influence of the extraction wells, and the ease with which contamination can be removed from the subsurface. Properties of the aquifer that define contaminant transport and groundwater extraction system design needs include hydraulic connection of aquifers, which allows contamination of more than one aquifer, aquifer flow parameters, influences of adjacent surface water bodies on the aquifer system, and influences of adjacent groundwater production wells on the aquifer system.

The geochemical properties and concentration of contaminants, along with the physical extent of the contamination (plume size), affect the size of the extraction system (number and depth of wells and pump size), the type and complexity of the above ground treatment system, and the need for off-gas treatment. In general, groundwater contamination concentrated in an isolated area and at a shallow depth is typically easier and less costly to remediate than the same mass of contaminant when it is extended deeper and spread out over a larger area. Given below are correlations for capital and operating costs for groundwater treatment:

— Unit capital cost versus volume of groundwater treated.[2] There is a correlation between unit capital costs and volume of groundwater treated. Economies of scale are observed where unit costs decrease as larger quantities are treated. For example, unit capital costs decreased from \$16–200 per m^3 treated per year for projects treating up to 100 000 m^3 of groundwater per year to less than \$5 per m3 treated per year for projects treating relatively larger quantities of groundwater per year [42].

— Unit average annual operating cost versus volume of groundwater treated.[3] A similar correlation for unit average annual operating costs per volume of groundwater treated per year is found, with economies of scale observed where unit costs decreased as larger quantities are treated. For example, unit average annual operating costs decreased from \$2.5–30 per m^3 treated per year for projects treating less than 75 000 m^3 of groundwater per year to less than \$0.26–1.5 per m^3 of groundwater treated per year for projects treating relatively larger quantities of groundwater per year. Table 7 summarizes these costs.

TABLE 7. SUMMARY OF REMEDIAL COSTS AND UNIT COST DATA FOR 32 PUMP AND TREAT SITES

Cost category	25th percentile	Median	75th percentile	Average
Total capital cost (\$)	1 700 000	2 000 000	6 000 000	4 900 000
Average operating cost per year (\$)	180 000	260 000	730 000	770 000
Unit capital cost (capital cost per m^3 of groundwater treated per year, \$)	6.0	20	93	74
Unit average annual operating cost (average annual operating cost per m^3 of groundwater treated per year, \$)	1.3	4.2	11	8.5

[2] Capital cost per m^3 of groundwater treated per year. This value is calculated by dividing the total capital cost by the average quantity of groundwater treated each year. This value represents the relative costs of installing P&T systems of various sizes and complexities.

[3] Average annual operating cost per m^3 of groundwater treated per year. This value was calculated by dividing the average operating cost per year of operation by the average quantity of groundwater treated per year. This value represents the relative costs of operating P&T systems of various sizes and complexities.

3.3.4.2. Other factors

Potential correlations between unit cost and other factors, such as type of contaminant and type of ex situ groundwater treatment used, may exist, but no correlations have been evident so far. While quantitative correlations for these factors are not evident, the following qualitative information about potential factors affecting the design and operation of P&T systems is provided. The specific effects of these and other factors on the cost of a P&T system are highly site specific.

3.3.4.3. Soil type and hydrogeological setting

The permeability, porosity, moisture content and heterogeneity of the soil and the depth and stratigraphy of the contamination in the subsurface affect the number and placement of extraction wells, the radius of influence of the extraction wells, and the ease with which contamination can be removed from the subsurface. Properties of the aquifer that define contaminant transport and groundwater extraction system design needs include hydraulic connection of aquifers that allows contamination of more than one aquifer, aquifer flow parameters, influences of adjacent surface water bodies on the aquifer system, and influences of adjacent groundwater production wells on the aquifer system.

3.3.4.4. Properties of the contaminant and extent of contamination

The properties and concentration of contaminants, along with the areal extent of the contamination (plume size), affect the size of the extraction system (number and depth of wells and pump size), the type and complexity of the above ground treatment system, and the requirement for off-gas treatment. For example, both capital and average annual operating costs tended to be higher for projects where combinations of contaminants (solvents, BTEX (benzene, toluene, ethylbenzene, xylenes), metals, PCBs (polychlorinated biphenyls) or PAHs (polycyclic aromatic hydrocarbons) were present because more complex systems are generally required to treat complex combinations of contaminants. In general, groundwater contamination concentrated in an isolated area and at a shallow depth is typically easier and less costly to remediate than the same mass of contaminant when it extends deeper and is spread out over a larger area.

3.3.5. Permeable barriers

PRBs are developing into an entirely new class of technology for groundwater remediation. A permeable barrier is a porous barrier that is placed in the path of a groundwater plume, in various configurations. The barrier, or at least the permeable portion of the barrier, contains a reactive or adsorptive medium that helps remove the contaminants from the plume, as the groundwater flows through the barrier. The primary advantage of permeable barriers is their passive 'capture and treat' mode of operation and the resulting potential for long term cost savings.

The technology emerged in the mid-1990s with the use of granular zerovalent iron as a reactive medium for the treatment of groundwater contaminated with chlorinated volatile organic compounds, such as trichloroethylene and perchloroethylene. More recently, there has been interest in developing other treatment media and methods of construction to address a broader variety of contaminants and sites.

As with P&T systems, different hydraulic capture configurations and different permeable barrier media are making it possible to address a number of contaminants of concern under a number of different site characteristics.

When assessing these systems for longevity, it is important to focus on sites with a history of at least a few years of operation.

Many of the PRBs evaluated so far are of the trench type (excavate and fill type). The more innovative PRB installations, where the reactive medium is injected into the ground using special methods, such as jetting or hydraulic fracturing, have not been extensively evaluated. The performance of injected PRBs is more difficult to evaluate in the field. Conclusions regarding the performance of these systems are expected to be applicable to several different types of PRBs.

In the short term, the key performance issue is the ability of the PRB to prevent the target contamination from progressing beyond the plume cut-off location, thus reducing the risk to down gradient receptors. In the long term, the key performance issue is one of longevity; in other words, the question of how long a PRB may be expected to retain its reactive and hydraulic performance.

Short and long term issues are best addressed in the pre-installation design stage at any prospective PRB site. A PRB is a more or less permanent installation, much more so than a P&T system. Once a PRB is installed, modifications can be relatively expensive; therefore, it is more important to ensure that the PRB is designed and installed correctly.

Pre-installation monitoring (site characterization) is an important tool in achieving a good design. Post-installation monitoring is required to verify compliance and to identify long term performance trends. Lessons learned in terms of the monitoring tools available and their effectiveness provide important pointers for future sites.

Some general conclusions concerning the long term performance of PRBs are:

— Adequate site characterization, especially to improve understanding of the hydraulic flow regime at a prospective PRB location, is imperative to maximize the potential for success of a PRB meeting cleanup goals.
— Low flow or passive sampling approaches are required for collecting representative data from PRBs.
— Over long periods of groundwater exposure, the reactivity of the granular zerovalent iron declines due to precipitation of native groundwater constituents.
— The ability of easily measurable water quality indicator parameters, such as pH and ORP, to provide early warning of reduced PRB performance in the long term is unclear and requires further study.
— In geological settings where low flow (fine textured formations) conditions exist, extra care should be taken to ensure a good hydraulic connection between the native aquifer material and the permeable reactive zone during system installation.
— Increased microbial activity and biomass in the immediate vicinity of a barrier wall may contribute to loss of reactivity and/or permeability over time.
— Additional studies are required to monitor PRB longevity and improve lifetime predictions based on site specific hydrological, geochemical and microbiological conditions.

4. REMEDIATION OF URANIUM MINING AND MILLING SITES

4.1. URANIUM MINING AND MILLING WASTE

Mining and milling of uranium ores give rise to a variety of wastes and residual materials, such as top soils (enriched by particulate airborne transported material), overburden material and non-mineralized rock (removed to reach the ore body). In addition, waste rock that contains subeconomic levels of mineralization, and is thus not milled for extraction of uranium, may contain environmentally significant levels of radionuclides and other minerals. Mill tailings (consisting of the ground ore from which the uranium has been extracted) and sludge (containing metals and radionuclides from water treatment plants) are also relevant types of waste. In addition, there are also different types of processing waste.

Many uranium mine sites throughout the world have become orphaned sites, and are waiting for remediation. However, little progress has been made in the management of some, particularly in the understanding of the associated environmental and health risks. Table 8 outlines some of the changes that have taken place since the onset of mine waste management practices, which also apply to other mining wastes beyond uranium mining.

4.1.1. Acid mine drainage

Uranium tailings and waste rock can generate acid drainage when the ore mined is sulphidic, a major environmental issue for some base metal, precious and coal mining wastes as the acid drainage will mobilize contaminants in the above mentioned systems. In this case, the contaminant generation process, the weathering or oxidation of the waste rock and tailings particles, is driven by oxygen and water, and catalysed by microbial growth. Thus, many remediation measures focus on reduction of access to the drivers of the oxidation. However, engineering works such as covers, barriers and diversion ditches, which can remain stable and effective in the long term, are extremely difficult to build, and still remain a challenge.

One could argue that with no passage of water through the waste material, the oxidation products would remain in the wastes, and therefore contaminants would not be released, and thus no effluents would be released. However, such a scenario is virtually impossible to achieve due to the physical dimensions and the geomorphological location of mining wastes, often located in former valleys with springs, creeks or rivers, where ultimately former drainages will make their passages through or below the waste depositories, with inevitable deterioration of covers over the long term.

TABLE 8. COMPARISON OF MINING WASTE MANAGEMENT STRATEGIES FOR SITE SELECTION AND DESIGN FOR WASTE ROCK AND TAILINGS PRE- AND POST-1970

Post-1970	Pre-1970
Site selection for waste rock and tailings with hydrological and economic considerations	Economic considerations only (e.g. proximity to mine)
Ore stockpile placement and exposure	Not considered
Runoff drainage systems isolated from contaminated flows	Sometimes considered
Progressive remediation of site during operations	Not considered
General mine closure plan considered	Not considered
Strict design criteria for storage facilities for chemicals	Sometimes considered
Segregation and stockpiling of rock types according to acid generating potential	Unsegregated waste rock piles
Improved dam design including liners and leak detection systems	Dams constructed from coarse tailings, overburden or waste rock
Thickened tailings, underwater tailings management facilities	Above ground tailings management facilities, no thickening
Tailings cleaning — sulphide separation	Not available
Tailings — high density paste backfill	Not available
Highly acid generating material used as backfill	Conventional backfilling, using only coarse fractions of tailings

Phosphate addition as a fertilizer has been the focus of many studies in the laboratory, with a limited number carried out in the field. A reduction of acid generation is expected due to the formation of ferric phosphate precipitates on the mineral surface. The approaches are referred to as coating or encapsulation of the mineral surfaces on the mining wastes. In addition to phosphates, bactericides and other reagents have been studied with good results in the laboratory. The limitation of surface coatings lies in the practical translation to waste rock piles and tailings. Difficulties are encountered when the reactant has to reach the point of oxidation on the mineral surfaces. Even if the reactants reach the oxidation point, the inhibition effect is often short lived.

Progressive rehabilitation is another concept that has gained widespread attention over the past decade. It is common sense to start closing and remediating parts of a mining, milling or production site as early on as possible, even though production in other parts of the operation is still in full sway, because this minimizes environmental risks and liabilities. Financial guarantees for closure and rehabilitation can serve as strong incentives to start remediation works as early as possible because the guarantees are released only after these works have been completed.

4.2. OPEN PITS

Open pit mining involves the excavation of overburden and rock to expose a shallow ore body and the extraction of that ore. The result is a cavity in the surface of the Earth. The cavity can take many forms; it commonly has a more or less symmetrical shape, such as an inverted truncated cone, but, particularly in mountainous countries, it may be asymmetric with a wall on one side much higher than the other. Water enters most pits as atmospheric precipitation and regional runoff, and, where an aquifer is intercepted, as groundwater. Pumps may be used to keep the pit dry during active mining. Once mining ceases, water is allowed to accumulate in the pit. Open pits of uranium mines do not differ from those of other mines, and thus the environmental issues of remediation are quite similar.

When sulphidic material is present and pit walls are exposed to oxidation, driven, for example, by oxygen in the air, sulphidic compounds within the surrounding rocks may dissolve and be flushed into the pit. This can lead to water quality that may be of concern, depending on the mineralization, the hydrogeology and the climatic region in which the pit lake is forming. This process can be slow or relatively rapid. Forced flooding of the open pit could otherwise represent the most effective method to create the pit lake, as the water would reduce the rate of formation of oxidation products and consequently the rate of contaminant generation.

Forced flooding is not often an achievable measure as insufficient water may be available to fill the pit, but would represent a desirable option. Prior to flooding, backfilling of the pit lake is often considered, but the removal of special wastes from the dumping areas may be necessary. The bottom of the pit might be capped with a low permeability material. Backfilling of the entire pit with waste rock can sometimes be considered, but frequently it is not found to be economic, and the environmental consequences are difficult to predict.

Hydrogeological considerations and the final geomorphology in which the pit lake with the rebounded water table will be situated are of utmost importance. These factors determine whether the pit lake will be flow through, i.e. if excess water will be leaving the lake, or if it will be a stagnant water body. In most cases, the lake will be formed through natural rebound of the groundwater. In climates where evaporation is greater than precipitation, the lake water level can form a depression in the water table, and weathering products can concentrate in the water. Generally, U and ^{226}Ra are not the main contaminants, and can even be of secondary importance compared with other contaminants of greater ecotoxicological significance.

Water treatment methods are specific to the contaminants to be removed. Chemical and physical methods are generally considered uneconomic, and may lead to the formation of secondary waste products that will demand further disposal. If in situ treatment is to be applied, it may lead to accumulations in the bottom of the pit. Limnological conditions (stratification, seasonal turnover) can lead to redissolution of the contaminants. Recently, bioremediation (also referred to as eutrophication) achieved through fertilization of the pit lake water has been tested. The fertilization promotes phytoplankton growth, leading to sedimentation of the biomass to the bottom of the pit adsorbing the contaminants.

Sulphate reducing bacteria can be introduced into acid pit lakes, but this technique is restricted to lakes that possess a stable stratification and thus allow the microbiological processes to develop without seasonal perturbations (e.g. inversion of the stratification due to temperature gradients) [43].

So-called liming (adding lime slurry to the pit water) with the objective of introducing excess alkalinity has been shown to work over a certain period of time (some years), but is not considered a sustainable option because, sooner or later, the alkalinity will have been used up. The lake will eventually acidify unless lime continues to be added.

4.3. UNDERGROUND WORKINGS

Underground mining is employed where ore bodies are too deep for practical or economic open pit mining. Vertical shafts, declines or horizontal adits provide access to the underground ore. Pumps are used during active operation to keep the mine dry. Flooding of the mine usually occurs naturally once the mine has been decommissioned. The water quality in the inactive workings is of little concern, except where water emerges on the surface or is considered to pose a threat of contamination to an aquifer system. Force flooding is generally not considered, and backfilling the underground opening is carried out during mining, utilizing tailings, waste rock generated underground, or both. Subsidence of the surface is often considered a significant issue. The void space from the mining creates underground instability, which can lead to rock busts and seismic events at the surface above the underground mine workings. Again, these issues are not specific to uranium mines, but apply to all underground mines. At shutdown, all openings are sealed with concrete to prevent physical injury to wildlife and humans. Depending on the groundwater level depth, many underground mine workings are of no environmental significance, which is quite often the case for older mines. Remediation of effluents from the surface workings is, again, specific to the contaminant. In situ treatment approaches are not often used, but trials with injecting various types of organic matter and zerovalent iron (occasionally as very fine powder) have been reported with some success.

Another issue that is of radiological relevance of active and closed underground mines is the exhalation of radon. Underground mines may pose elevated health risks to humans entering the mine workings with insufficient ventilation. Radon concentrations in underground mines and around unplugged mine adits may be some orders of magnitude higher than the regional background. Homes and public buildings are at risk of radon ingress through cracks and fissures in the ground through which radon can penetrate from underground mines. A combination of active and passive ventilation, sealing the fissures, and other mitigation measures can reduce the radon concentrations to acceptable levels.

4.4. PLANNING, MANAGEMENT AND IMPLEMENTATION OF REMEDIATION PROGRAMMES IN URANIUM MINING

In the context of a mining site, the practical outcomes of a remediation programme are to delay or minimize contaminant release rates (including oxidation rates, especially of acid generating materials) and erosion of waste storage structures to a level where the resulting contaminants are released or produced at rates that the receiving environment can absorb and assimilate them without adverse impacts, or when impacts occur, they are low enough and can be termed as ‘acceptable to the community’.

A comprehensive mine (or mill site) remediation plan will ensure that the above objectives are met. There are a number of aspects, both technical and sociological, to be considered when developing a mine remediation plan. Demonstrating the successful remediation of mining and processing operations is of critical importance to the mining industry if it is to continue to be allowed to access and exploit natural resources (recently, the term ‘social license to operate’ has been used in this context).

The mining industry and the broader community now recognize that mining is an interim or short term land use, and that permanent alienation of land from beneficial postmining land uses is unacceptable and must be avoided whenever possible. It is only through the demonstration of successful remediation which is sustainable over the long term that the mining industry will continue to be permitted to access and exploit natural resources.

Many of the impacts of inappropriate waste management or radioactive material handling are neither transient nor short term, and unless managed correctly, they have the potential to adversely impact on the environment for decades, if not centuries, to follow. Waste rock and tailings management decisions, at least to an advanced conceptual stage, must be made before a mine commences production. Before informed decisions can be made on various potential management strategies, both the short and long term physical, radiological and geochemical properties of all material streams generated during the mining and processing phases need to be understood, as well as a complete understanding of the environmental setting of the operation.

It is absolutely critical that remediation planning is undertaken in a holistic manner, i.e. when planning for remediation of an individual aspect of an operation, its interrelationship to other aspects of the operation is to be taken into account.

Remediation solutions are site specific, and rarely can methodologies/designs from one site be transferred to another without modification; usually, they will require site specific investigations as physical and geochemical material properties of the mine wastes, geological conditions, hydrogeology, climate and setting are unique to each site.

During the development of a mining project, starting from exploration moving through all the stages to the closure of the economically depleted resource, it is essential that a mine closure plan is developed, and that it is then amended in parallel with any changes to the scope of a mine’s operations, such that it continues to reflect the changing state of the project. Development of a mine remediation plan is an integral part of all phases of a mining project, and must not be considered something to be left until late in the resource exploitation phase. Maintaining a dynamic mine remediation plan will maximize the remediation options that can be considered while minimizing the overall costs of the mine life cycle. Correctly informed planning decisions can only be made after considering their impacts on the mine remediation plan and on the mine life cycle costs.

Life cycle mine costs are significantly different to operational costs, and decisions on operational costs made without full consideration of their long term impacts often increases mine life cycle costs for short term gain. Mine life cycle encompasses all activities from initial exploration through to the long term post-closure stewardship phase, i.e. it includes:

— Exploration;
— Project feasibility;
— Development and construction;
— Mining;
— Decommissioning and remediation;
— Post-closure monitoring;
— Post-closure stewardship.

It must be recognized that the mining phase will only represent a portion of the total life of a mine. Commencing remediation planning at the earliest stage of an operation allows for consideration of the maximum number of remediation strategies or options, and will also allow them to be implemented for the lowest possible cost. The remediation plan may take several forms over the mine life cycle that relate to different phases in a project's development, for example:

— Conceptual closure plan: exploration, feasibility and design phases;
— Closure plan: construction and operational phases;
— Decommissioning plan: immediately preceeding closure to site closure and final remediation;
— Post-closure plan: post-closure stewardship.

End stage objectives are the fundamental building foundation for the development of a mine remediation plan. Historically, a common failure has been to undertake remediation works without clearly defined objectives. The most frequently encountered examples of this are where waste rock dumps or tailings storage facilities have been 'capped', and the fundamental questions with respect to cover design have not been addressed adequately. This has led, in the worst case, to the complete loss of all value from the works undertaken and required complete repetition of the works at a later date once the failure had become apparent.

Without defined criteria, it is impossible to calculate realistic remediation costs for the main cost centres (typically, these are: waste rock dumps, tailings storage facilities, land contamination, buildings, equipment and scrap). Frequently, considerable effort and expense are applied to the calculation of remediation and closure costs for these areas. However, if closure criteria setting out the required outcomes of the remediation works on these areas have not been defined, much, if not all, of these efforts and resources are potentially wasted. It is only once the remediation criteria have been defined that a remediation strategy can be selected, and only once this has been carried out can the process of costing begin. Attempting to develop remediation strategies beyond the basic conceptual stage is likely to be a misdirection of resources.

Closure planning starts with a clear monitoring concept in order to assess the current situation and derive the need for remedial action, closure design and planning of post-closure measures based on realistic remediation targets and post-closure conditions that are to be achieved. The development of a closure strategy for radioactively contaminated sites may require additional data and information that is not part of the regular monitoring programme during the operation phase. For example:

— Specific tests may have to be made in order to forecast the long term geochemical behaviour of the tailings under various cover options;
— Test plots may have to be installed to test and compare different cover systems.

At each site, sufficient time and resources should be allowed to obtain sufficient data and information to quantitatively predict or estimate the quality and quantity of mine water and seepage from mining and milling wastes, if this information is not yet available. Pre-closure monitoring may take some time and financial resources, but pays off through better, more sustainable closure and remediation concepts. In particular, the following aspects should be taken into consideration:

— Geochemical stability of the wastes;
— Water balance;
— In the case of tailings, consolidation and dewatering behaviour;
— Long term mobilization of radionuclides, mainly via the water path;
— Sources of uncertainty in long term predictions;
— Long term behaviour of the cover material (to be investigated on test plots).

Quantitative forecasting models of an appropriate level should be developed based on the data and other information obtained from pre-closure monitoring. Predictive models are required in order to provide quantitative forecasts of the dispersion of radionuclides and other contaminants in the environment and finally to human receptors. Models are also required to predict the time period over which technical controls such as water treatment plants are needed, and institutional control is essential to ensure operation and maintenance of these installations.

Typically, the most important field of modelling concerns the water path. As inputs, these models require:

— Existing knowledge about the site and its surroundings (hydrogeology, environmental features such as rivers, groundwater aquifers, current and future use scenarios);
— Mobilization mechanisms of radionuclides from the wastes (source term) under different geochemical conditions;
— Results of the operational and post-closure monitoring programme.

The level of detail of the data and models must be adapted to the specifics of each individual site. For example, a simple stirred tank (dilution box) model may be fully sufficient to gain a first understanding of mine water quality evolution in some cases, while other sites may require more sophisticated models that include geochemical reaction terms and complex coupling of a tailings pond and groundwater flow.

The main value of predictive models derives less from their ability to provide ‘accurate’ results (which is rarely the case anyway), but from the fact that:

— They can serve as highly useful tools to understand the important processes and thus to focus remedial action on the critical parameters;
— They highlight those parameters and assumptions that have the most pronounced impact on the radiological impact, which, in turn, allows the derivation of conclusions for the improvement of monitoring systems;
— They provide valuable information about the order of magnitude of the impacts and the relevant time period, which is an important basis for optimization procedures.

There is a vast body of literature, theoretical approaches and practical experience in the field of modelling water and airborne contaminant transport. There are also numerous computer aided numerical models that may be used. However, the set-up, calibration and operation of predictive models require specialized and highly skilled staff and an adequate hydrogeological database. Moreover, the source term (mobilization of contaminants from the wastes or contaminated soil) must be quantitatively described, which requires a substantial geochemical investigation programme of the wastes or contaminated soil.

Only models that can be calibrated so as to reproduce the situation today should be used for making predictions about the future. However, there are still numerous sources of uncertainty that must be handled appropriately. Uncertainties of contaminant transport models can be reduced by:

— A dense network of sampling points for both hydraulic and hydrogeochemical parameters;
— A sufficiently large model space, both in terms of area and depth (number of aquifers covered by the model, vertical extension of the model);
— A long observation period of the relevant parameters.

This requires a close cooperation between radiological and modelling experts. This necessitates the formation of an interdisciplinary team of radiological assessment experts, the significance of which should not be underestimated.

Models may have been developed as part of a wide variety of documents such as environmental impact assessments or in other areas of environmental or water legislation. These models, if properly constructed, are calibrated with respect to geohydraulics and transport of non-radioactive contaminants such as arsenic and heavy metals. They should also be used as a basis for modelling the transport of radionuclides. This helps to ensure consistency of assessment of radiological and non-radiological impacts.

One of the challenges to successful mine remediation planning is the issue of 'shifting goalposts' (evolving standards). Shifting goalposts are a significant challenge, both for operators and regulators, particularly so for mines with longer lives. It may be a considerable number of years after the project feasibility study is completed before the site is offered to the regulators and interested parties for 'sign off'. It is important to understand that any remediation strategy, once developed and accepted, which does not allow for changes in legislative and regulatory requirements, as well as often evolving community expectations, carries a high risk of failure.

Using the example of a mine with a 20 year life, there is a great risk, as its remediation criteria were developed based on the minimum acceptable standards at the time of project inception. Based on the evolution of regulatory and community standards over the past 25 years, there is a strong likelihood that regulatory requirements and community standards will continue to evolve over the intervening 20 years of the mine's life. What had been acceptable 20 years ago will (or may) no longer be acceptable. Mining operations should try to anticipate likely movements in standards and build them into development of remediation objectives. Regularly reviewing site environment targets, goals and remediation objectives to ensure that they continue to reflect current regulatory regimes, along with the expectations of the community will minimize impacts from changing requirements to the overall remediation project.

5. CONCLUSION

This publication has consolidated the accumulated experiences of the implementation of environmental remediation projects. The following summary points are offered:

— The need to develop a national or regional prioritization of remediation measures, in order to spend limited resources with the highest effect. Even within a site with many waste facilities, plants, tailings ponds, etc., a prioritization may be very useful. It can be proposed that the criteria to be used in the prioritization and decision making process should be part of the national policy and strategies to guide the implementation of remediation works. The prioritization should be based on facts and measureable/quantifiable risk rather than emotion, and should also take into account alternative options to spend scarce financial and human resources within a country.
— Definition of remediation objectives before even starting to design any technical solution. Without clear definition of quantitative, measurable remediation objectives, design and implementation of remedial action remain vague, and remediation success cannot be measured.
— The use of multiattribute decision tools has clearly pointed to the difficulty of assigning relative weights to the decision criteria (costs, social factors, radiological and non-radiological health effects, other environmental impacts). This is understandable because decision making in the field of environmental remediation involves very diverse interested parties, and must reconcile short and long term objectives that are not easily traded off against each other. On the other hand, this should encourage close communication between the interested parties starting early in the decision making process, and the use of quantitative decision criteria wherever possible.
— It is a myth that remediation activities are justified mainly by radiological or other health risks. In fact, in many cases, remediation measures are justified by geotechnical stability, general safety and socioeconomic considerations. Once the decision to carry out remediation works is taken, radiation protection and general environmental factors must be taken into consideration as part of the optimization procedure.

- The importance of well trained, knowledgeable regulators that take plausible decisions within a reasonable timeframe and based on a sound understanding of international good practice cannot be overestimated.
- At the local level, the engagement of interested parties and individual 'movers and shakers' (e.g. mayors, community councils, entrepreneurs) in expediting successful post-closure redevelopment and exploiting opportunities that arise from the remediation activities at a site are decisive factors.
- Before any technical solution is designed and implemented, a clear conceptual understanding of a site, its main processes, contamination inventory, pathways and timescales of contaminant release, etc., is required.
- In addition to routine monitoring during operations, pre-closure monitoring data should be obtained in order to properly design remediation solutions. It should be noted that a remediation design that involves long term predictions of contaminant release and transport, as well as geotechnical stability, may require more detailed information than is usually available from operation monitoring.
- Plausible (but not necessarily precise) estimates of typical timescales of remediation solutions are essential in order to gain a clear understanding of the remediation strategy, costs and the requirement for institutional control (such as the time period over which water treatment is needed or the time tailings will need for consolidation).
- The value and limitations of predictive models (groundwater, geochemical), etc., should be realistically assessed. The main value of predictive models derives less from their ability to provide 'accurate' results (which is rarely the case anyway), but from the fact that they help to understand important processes, provide an understanding of the order of magnitude of environmental and health impacts and assist in focusing remedial action on critical parameters.
- Detailed meteorological data sets (hourly rainfall, not just monthly averages) are necessary in order to properly design cover systems.
- Monitoring always serves, among other purposes, to trigger corrective action. This holds for the post-closure phase. Long term monitoring plans must always be linked to an action plan that contains the corrective action to be taken if a remedial solution does not function as intended.
- Clear and quantifiable design criteria are needed for all components of a technical remediation solution, including water treatment plants.
- The issue of safe and long term stable disposal of water treatment residues should be integrated into the overall closure concept.
- The limited lifetime of engineered cover systems on wastes should be integrated into the remediation concept. The achievement of remediation objectives, particularly in the long term, should not critically depend on the performance of a single design component. Rather, the design should be sufficiently robust so that remediation objectives are met, even if single components fail.
- There seems to be an inevitable tradeoff between engineered, complex multilayer cover systems with (initially) excellent performance and simpler, robust covers, but with less ambitious performance targets.
- Passive or semipassive water treatment systems (often based on biological treatment processes) can certainly reduce the contaminant load in effluent streams, but the window of applicability is rather narrow. Under strict regulatory constraints, their reliability may not be sufficient, or they may require maintenance to a substantial extent, or both, contrary to their original concept of maintenance free, self-sustained systems. The management of wastes (precipitates, biomass) from passive or biological systems is still largely unresolved.

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