Radioactive Waste Management
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Strategic Considerations for the Sustainable Remediation of Nuclear Installations

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NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 31 countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, Russia, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission also takes part in the work of the Agency.

The mission of the NEA is:

– to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes;

– to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information.

The NEA Data Bank provides nuclear data and computer program services for participating countries. In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

Cover photos: The Brennilis Nuclear Power Plant, a decommissioned site located in Monts d'Arrée, France (EDF).

Foreword

The OECD Nuclear Energy Agency (NEA) seeks to assist its member countries in developing safe, sustainable and societally acceptable strategies for the management of all types of radioactive materials, with particular emphasis on the management of long-lived waste and spent fuel and on the decommissioning of disused nuclear facilities. The programme of work covering these areas is carried out for the most part by the NEA Radioactive Waste Management Committee (RWMC), assisted by three of its working parties and their subgroups. The Working Party on Decommissioning and Dismantling (WPDD), for example, provides a focus for the analysis of decommissioning policy, strategy and regulation, including the related issues of management of materials, release of buildings and sites from regulatory control and associated cost estimation and funding. Beyond policy and strategy considerations, the WPDD also reviews practical considerations for implementation, such as techniques for the characterisation of materials, for decontamination and for dismantling.

The WPDD brings together senior experts in decommissioning from 21 NEA and observer countries: Belgium, Canada, the Czech Republic, Finland, France, Germany, Greece, Hungary, Italy, Japan, Korea, the Netherlands, Norway, Poland, Russia, the Slovak Republic, Spain, Sweden, Switzerland, the United Kingdom and the United States, with the involvement of other international organisations such as the European Commission and the International Atomic Energy Agency (IAEA). Its membership includes policy specialists, regulators, implementers, researchers and waste management experts. The WPDD tracks decommissioning developments worldwide and produces reports and position papers on emerging issues. Its overarching aim is to contribute to the development of best practices through the dissemination of its reports and through dialogue among policymakers, practitioners, regulators, researchers and representatives of international organisations.

The WPDD formed the Task Group on Nuclear Site Restoration, involving nuclear operators, experts and regulators, to review the strategic aspects of nuclear site remediation. This report summarises work carried out between March 2014 and December 2015, providing observations and recommendations relating to the development of strategies and plans for sustainable site remediation at nuclear sites. Sustainable remediation requires the application of a holistic approach, and a balance between the environmental, social, and economic impacts of remedial actions so as to provide an overall net benefit.

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List of abbreviations and acronyms

ALARA	As low as reasonably achievable
ARAR	Applicable or relevant and appropriate requirements
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CNL	Canadian Nuclear Laboratories
CPD	Co-operative Programme on Decommissioning (NEA)
CSM	Conceptual site model
D&D	Decommissioning and decontamination
DOE	Department of Energy (United States)
DQO	Data quality objectives
EPA	Environmental Protection Agency (United States)
HI	Hazard index
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ITRC	Infrastructure Transitions Research Consortium
NCP	National Contingency Plan
NDA	Nuclear Decommissioning Authority (United Kingdom)
NEA	Nuclear Energy Agency
NPL	National Priority List
NRC	Nuclear Regulatory Commission (United States)
OECD	Organisation for Economic Co-operation and Development
RWMC	Radioactive Waste Management Committee (NEA)
WPDD	Working Party on Decommissioning and Dismantling

Executive summary

Nuclear sites around the world are being decommissioned, and remedial actions are being undertaken to enable sites, or parts of sites, to be reused. The term "remediation" is used here to refer to actions taken to reduce the impact from contamination in land areas and in the associated groundwater, in order to protect the environment and leave the site in a state that is suitable for its next use. Experience has shown that remediation of contaminated land and groundwater is relatively straightforward for most sites and, using best practice for characterisation, sites can be returned to society for any use. However, removing all contamination in order to make a site suitable for any use has associated environmental, social and economic drawbacks and benefits. In some cases, the drawbacks from the disposal of the waste (and associated activities) that are generated during the clean-up operations will outweigh the associated benefits. In addition, clean-up of a site allowing it to be suitable for any use may not be appropriate in a remote area or in an area where local stakeholders have a strong preference for remediation to a natural environment such as heathland. Such cases have given rise to the concept of sustainable remediation.

"Sustainable remediation" represents remediation actions and goals that are informed by an understanding of the safety and environmental benefits, the impacts of remediation activities, and the social and economic benefits and impacts, including the impacts on natural resources and climate change, both in the short term and the long term.

In comparison to the wider problems of industrial soil contamination, the footprint of nuclear activities is relatively small. Nevertheless, it is important that contamination from radioactivity is identified promptly and remediated according to a risk assessment that demonstrates appropriate protection of humans and the environment, and that a sustainability assessment shows remediation will have a net benefit.

There are good examples of sustainable nuclear site remediation across many countries. However, substantial challenges remain for remediation of nuclear sites, in particular for large and complex sites where many different facilities have existed and various processing activities have taken place. Some countries have relatively straightforward remediation challenges, but the increasing pressures on disposal facilities and expanding stakeholder interest has meant that careful strategic planning is required. This report draws on the experience in nuclear site remediation of NEA member countries to identify strategic considerations for the sustainable remediation of subsurface contamination – predominantly contaminated soil and groundwater – on nuclear sites during their operation and decommissioning. It also provides observations on good practice and priorities for further work.

Traditional site remediation approaches typically focus on the reduction of contaminant concentrations to meet goals or risk-based levels, with an emphasis on the remediation programme cost and time frame. In the case of radioactive contaminants, this has typically meant the disposal of affected soils or water treatment media at licensed waste repositories. In contrast to a traditional remediation approach, sustainable remediation is a holistic approach to remediation that considers wider environmental, social and economic impacts, and aims for a balance in the net effects. The objective of the approach is to achieve risk-informed remedial goals through more efficient, sustainable strategies that conserve resources and protect air, water and soil quality through reduced emissions and other waste burdens. Sustainable remediation also simultaneously encourages the reuse of remediated land and enhanced long-term financial returns on investment; it does not necessarily take the site back to past or pre-operational conditions. Though the potential benefits are enormous, many environmental professionals and project stakeholders do not use sustainable strategies or technologies because they are unaware of methods for selection and implementation. This report describes the decision framework and assessment tools, underlining at the same time that further work is required to develop sustainability performance indicators for remediation of nuclear sites. It also suggests that much can be learnt from the *in situ* clean-up approaches applied mainly to non-nuclear site clean-up.

Decommissioning, remediation and waste management plans should be integrated and a remedial approach developed, taking into consideration both the radioactive and non-radioactive contaminants. Stakeholder involvement must occur throughout the remediation process: "the optimal end state is the end state the stakeholders decide is optimal".

The long timescales involved in remediation are best addressed using a phased (adaptive) approach. An adaptive approach allows for the end state to change as time progresses, as a result of changes in stakeholder preferences, regulatory or policy requirements, or as further information on the contamination of a site is made available. Interim states can be defined to mark progress towards the end state. Complex sites and/or sites where remediation (and decommissioning) will take several decades to complete may benefit from the use of interim states and the division of sites into zones to manage characterisation and remedial activity.

This report describes the concept of sustainable remediation of contaminated land and groundwater in the context of the decommissioning of nuclear sites. The main steps in the determination of end states are described and the importance of an adaptive approach is highlighted. The report was prepared by the Task Group on Nuclear Site Restoration. Members of the group were nominated by members of the Working Party on Decommissioning and Dismantling (WPDD), and many had participated in a preceding task group established under the NEA Co-operative Programme on Decommissioning (CPD) that examined worldwide practice for nuclear site remediation, which was the subject of a report published by the NEA in 2014.[1]

Following a sustainable remediation approach will mean that it is not always optimum to remove all contamination, or to clean up sites to be fit for any use. The optimal remedial approach may be to include administrative controls (long-term stewardship) to break the pollutant linkage. Management arrangements need to be made to ensure that these controls are reviewed periodically. Examples of sustainable approaches to the remediation of contaminated land resulting from industries other than the nuclear industry could provide useful lessons learnt. The task group provided participating countries with a valuable opportunity to discuss the remediation (clean-up) of land and groundwater that is contaminated by radioactive materials on nuclear sites, and to identify strategic considerations and good practice.

The report makes the following recommendations for useful actions:

- Integration of remediation of contaminated land and groundwater into the decommissioning plan at an early stage. A collation of case studies describing instances when site authorities first became aware of groundwater problems, and the actions that were taken, would also be useful.

1. NEA (2014), *Nuclear Site Remediation and Restoration during Decommissioning of Nuclear Installations: A Report by the NEA Co-operative Programme on Decommissioning*, OECD, Paris, www.oecd-nea.org/rwm/pubs/2014/7192-cpd-report.pdf.

- A review by regulators of the various approaches to achieving safety and environmental protection goals, including those applied in non-nuclear industries. A case study approach and sharing of experience could be facilitated using the International Atomic Energy Agency (IAEA) web portal CONNECT.[2]
- The development of performance indicators for the assessment of the sustainable option through an exchange of experience in sustainable remediation among countries, building on good examples of sustainable remediation existing across countries.
- The development of a long-term strategic approach to the lifecycle design and operation of nuclear facilities, which takes into account waste management, decommissioning and site remediation, as well as the reuse of sites.
- The introduction of remediation of contaminated land and groundwater at nuclear sites as a specific topic in conferences and seminars on nuclear decommissioning to ensure that strategic and practical considerations are addressed.
- The organisation of a conference on the risk assessment of mixtures of radioactive and chemotoxic contaminants, as a first step in the development of an internationally agreed approach. The NEA or the World Health Organization (WHO) could be suitable host organisations.
- The continuation of the Task Group on Nuclear Site Restoration, initially established by the NEA Co-operative Programme on Decommissioning (CPD) to provide a forum for exchange of information on the remediation of land and groundwater, to develop guidance and good practice, and to further consider topics identified in this report that are in need of further study.

2. http://nucleus.iaea.org/sites/CONNECT.

1. Introduction

During the planning, design, operation and decommissioning of a nuclear site, it is important to prevent contamination of the soil and groundwater at the site. However, this may not always have been achieved in the past, and hence contamination from radioactivity and other hazardous substances has occurred. Remediation or partial remediation of these sites therefore needs to be actively considered, irrespective of the stage of the lifecycle of the site, in order to manage the associated risks.

The term "remediation" is used here to refer to actions taken to reduce the impact from contamination in land areas and in the associated groundwater in order to leave the site in a state that is suitable for its next intended use. This is a more generic use of the term than that adopted recently by the International Atomic Energy Agency (IAEA) in their Safety Standard on the decommissioning of facilities (IAEA, 2014). In that document, the IAEA reserve the term remediation for areas contaminated from past activities that were either never subject to regulatory control or were subject to regulatory control in a manner not in accordance with IAEA Safety Standards. The IAEA uses the term "clean-up" for actions taken to reduce the impact from contamination in sites that are undergoing decommissioning. Here, the generic term remediation is used to describe clean-up in the context of decommissioning. In line with the IAEA definition of remediation (IAEA, 2007), it does not necessarily imply complete removal of the contamination or returning the site to its background conditions, something that may be neither practicable nor necessary. Other terms that are sometimes used include site clean-up, decommissioning and restoration. Long-term stewardship may also be considered as a remediation action.

Experience has shown that remediation of contaminated land and groundwater is relatively straightforward for most sites and, using best practice for characterisation, sites can be returned to society for any use. However, removing all contamination in order to make a site suitable for any use has associated environmental, social and economic drawbacks and benefits. In some cases, the drawbacks from the disposal of the waste (and associated activities) that are generated during the clean-up operations will outweigh the associated benefits. In addition, clean-up to be suitable for any use may not be appropriate in a remote area or in an area where local stakeholders have a strong preference for remediation to a natural environment. These cases give rise to the concept of "sustainable remediation".

Sustainable remediation represents remediation actions and goals that are informed by an understanding of the overall impact of remediation activities. Sustainable remediation is therefore informed by safety and environmental benefits and impacts, the social and economic benefits and drawbacks, and the impacts on natural resources and climate change, both in the short term and in the long term (see Chapter 2 for a more detailed definition of sustainable). Hence, sustainable remediation requires not only identification of a technical solution, but an element of social science in the form of an informed debate, discussion, negotiation and transparent decision making. Radiological protection principles and environmental principles provide the framework for this discussion, and the optimum solution will be site specific.

In most decommissioning cases, the site remediation challenges are relatively small and the expected "end state" is unrestricted use (i.e. clean-up to be "suitable for any use"). An end state is a remediation objective (goal) that meets regulations and is protective of human health and the environment: it describes the site conditions to be achieved by the remedial actions. Any end state will have associated requirements for the long-term management of the site, for example to continue the existing level of regulatory control, or to reduce the level of regulatory control of the site – recognising that release from regulatory control for radiological protection purposes corresponds to a reduction in regulatory control, not a total release from any regulatory control. Remediation to be "suitable for any use" does not necessarily imply that useful infrastructure, such as a road, has to be removed.

There are good examples of sustainable nuclear site remediation across many countries (see, for example, Annexes D-H). However, substantial challenges remain for the remediation of nuclear sites, in particular for large and complex sites where many different facilities have existed and various processing activities have taken place. Many of the large, complex sites are a result of practices during the Cold War that are completely unacceptable on civilian sites.

Remediation action must be considered at all stages of the lifecycle. In particular, remediation will need to be integrated with decommissioning planning, as many redundant facilities have residual contamination issues. There is a strong interface between site remediation, decommissioning and waste management that is, unfortunately, often overlooked. An overarching strategy that accommodates these interfaces is thus very helpful.

For many sites, although it might be possible to start remediation early, it might not be possible to complete remediation for many decades, for example because of the timescales for decommissioning. Hence, sequences of time-concentrated remediation steps followed by periods of less activity may be appropriate. A structured, systems-based approach should be developed for planning, optimising and determining the interim and final end states (the goals of the remediation). The approach will be adaptive and iterative to accommodate the gathering of new information and the need for greater detail as achievement of the end state approaches. In these cases, determining "interim states" will allow for progress with decommissioning. This will facilitate decision making and implementation at complex sites where remediation may require long timescales, or need to account for changing conditions and improved understanding. This technical approach should also be aligned with wider sustainability considerations, such as wider economic and social justice factors.

It is obvious that the sustainable remediation of subsurface contamination (soil and groundwater) requires consideration of many factors, at a strategic level. These strategic considerations are the focus of this report.

1.1. Objective

The objective of the report is to provide insights to decision makers, regulators, implementers and stakeholders involved in nuclear site decommissioning so that they can achieve sustainable remediation of nuclear sites, now and in the future. The report sets out the current situation, suggests a strategic approach and its implication for remediation planning; and finally, it provides observations and recommendations for the future.

1.2. Scope of the report

This report draws on the experience of NEA member countries in nuclear site remediation during decommissioning to identify the strategic considerations and to make recommendations for good practice and further research and development. The report covers all types of nuclear sites throughout their lifecycles. It excludes consideration of uranium mining sites, abandoned sites and contamination following a major accident. Nevertheless, many of the approaches discussed in the report are equally applicable to these other circumstances.

1.3. Summary of the task group approach

This report was prepared by the Task Group on Nuclear Site Restoration that was formed by nominations from the members participating in the Working Party on Decommissioning and Dismantling (WPDD). In recognition of the significant interaction of regulatory bodies with site remediation programmes, the task group included representatives from both safety and environmental regulators together with site owners and remediation specialists. The NEA also provided secretarial support. The task group also benefited from advice and support from the IAEA. The task group shared information on experiences, approaches and techniques for environmental remediation at selected nuclear sites with the aim of identifying the strategic planning aspects. Many of the task group members participated in a preceding task group that examined worldwide practice for nuclear site remediation. The learning from this earlier work and the outcome reflected in the recently published NEA report (NEA, 2014) was used as an information resource.

1.4. Organisation of the report

The remainder of report is divided into the following chapters:

- Chapter 2 addresses general principles and remediation approaches.
- Chapter 3 describes how to determine the end states and remediation goals, drawing on the task group members' experiences.
- Chapter 4 describes the preparation of the remediation plan and the identification of different technologies.
- Chapter 5 presents discussion, lessons learnt and recommendations.

A glossary is included in Annex A, and detailed examples are given in further Annexes.

1.5. References

IAEA (2014), *Decommissioning of Facilities*, IAEA Safety Standards Series, IAEA, Vienna.

IAEA (2007), *IAEA Safety Glossary: Terminology used in Nuclear Safety and Radiation Protection*, IAEA, Vienna, www-pub.iaea.org/MTCD/publications/PDF/Pub1290_web.pdf.

NEA (2014), *Nuclear Site Remediation and Restoration during Decommissioning of Nuclear Installations: A Report by the NEA Co-operative Programme on Decommissioning*, OECD, Paris, www.oecd-nea.org/rwm/pubs/2014/7192-cpd-report.pdf.

2. General principles and remediation approaches

This chapter describes remediation, the general principles underpinning remediation, sustainable remediation, policy and strategy.

2.1. What is remediation?

Remediation is taking action to reduce the exposure due to existing contamination through actions applied to the contamination itself (the source) or to the exposure pathways to people and the environment, for example. to cut the pathways from source to receptor (people and the environment) or to minimise the dose from that pathway. Remediation does not necessarily imply complete removal of the contamination or returning the site to its background conditions, something that may be neither practicable nor necessary. It is therefore not just "dig it all up and put it somewhere else", which is a common misconception.

Examples of remedial approaches:

- immobilise source *in situ*;
- separate contaminant from source;
- implement long-term stewardship restricting access to source;
- contain source to delay or prevent exposure of receptor;
- monitor natural attenuation of source, and implement action as necessary;
- excavate source and dispose off-site.

In fact remediation is about understanding and taking appropriate action to reduce or mitigate the hazard and risk posed by the contamination by using a combination of physical, economical and administrative actions. The key is to find the right balance of these actions for the site being considered. Hence a number of remediation methods should be considered and the overall optimum approach may comprise a combination of different remediation methods.

The use of a combination of different remediation technologies may be beneficial. Hence, a logical combination of options should be considered and there may be restrictions in practice on the order in which the combination may be applied.

2.2. General principles

It is expected that nuclear sites are operated using best available techniques and good practice so that contamination of soil and groundwater on the site does not occur. However, many sites have become contaminated in the past either as a result of poor practice, accidents or poor design. Operators therefore have responsibilities to understand the extent and potential impact of this contamination and to have plans to ensure it is managed appropriately: we have a moral and ethical duty to take care of these contaminated sites. In addition, since we do not wish to create additional contamination, all current operations, particularly for sites that have been in operation for a long time, should follow today's best practice even though past operations may not have been to modern standards. Good practice includes actions that identify the extent of any contamination early on so that preventative actions can be taken to reduce the spread of the contamination, especially where contaminated groundwater is known or suspected to exist. Again, it is good practice to consider the remediation options for any identified contaminated groundwater as early as possible to avoid subsequent issues.

Remediation of nuclear sites is guided by the principles underlying international environmental law and the principles of radiation protection.

2.2.1. Environmental law

The key concepts underlying international environmental law are: intergenerational equity, transboundary responsibility, public participation and transparency, the "polluter pays" principle, the "precautionary principle", prevention, and sustainability. These principles work together to drive responsible and timely protection of the environment. They are briefly described below.

Intergenerational equity

Intergenerational equity refers to the concept that humans hold the natural and cultural environment of the earth in common with … other generations (Weiss, 1990). It implies an obligation to pass it on to future generations in a reasonable condition.

Transboundary responsibility

Transboundary responsibility refers to the idea that the benefits derived from activities in one geographical area (county, district, country or continent) should not result in unfair detriment to other geographical areas.

Public participation and transparency

This principle refers to the concept that the goals and process of a decision-making process should be publically available and the public should be involved in the decision-making process, particularly for decisions where the goals or approaches are less tangible.

"Polluter pays"

This principle states that the polluter (owner/operator) is responsible for providing the funds that are or will be needed to remediate the site. In addition, the polluter has a clear responsibility to remediate these sites and not to pass the burden of remediation on to society or to future generations. The "polluter pays" principle should also be reflected in the arrangements to ensure protection of the environment so that unnecessary waste creation and remediation is avoided. Remediation to be fit for any use is aligned with the "polluter pays" principle.

Precautionary principle

The basis of the precautionary principle is that, "where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation" (UN, 1992). The "precautionary principle" therefore drives preventative action to minimise the potential size and complexity of what may need to be remediated. The principle implies that there is a social responsibility to protect the public from exposure to harm whenever there is a plausible risk.

Prevention

This principle encourages action to be taken to protect the environment at an early stage, not just repairing damages after they have occurred, but preventing those damages occurring at all. It is similar to the precautionary principle in that it drives a shift from post-damage control of risks to pre-damage control (anticipatory measures).

Sustainability

The principle of "sustainability" (Weiss, 1990) emphasises the importance of taking an intra and intergenerational perspective for environmental protection. Sustainability calls for a decent standard of living for everyone today without compromising the needs of future generations. This principle stresses the need to consider the social, economic and environmental implications of actions across locations and time. The objective is to avoid the transfer of environmental burden.

2.2.2. Radiation protection

Radiation protection protects people and the environment from the effects of ionising radiation. Three types of exposure situation are considered: planned exposure, existing exposure, and emergency exposure situations. The types of nuclear sites considered in this report (sites regulated by specialist nuclear regulators) correspond to the International Commission on Radiological Protection (ICRP, 2007) "planned exposure" situation. Thus, site remediation is guided by three main principles: justification, optimisation and dose limitation.

Justification

Any remediation should be justified, i.e. it should do more good than harm. For planned exposure situations, e.g. the operation of nuclear facilities, no specific justification is needed for decommissioning or for remediation activities on contaminated land and groundwater, since these have been taken into account in the justification process of the operation of the facility.

Optimisation

Remediation measures should be optimised, i.e. the level of protection to be achieved by the remediation should be the best under the prevailing circumstances, maximising the benefit over harm. Optimisation should result in the likelihood of incurring exposures, the number of people exposed, and the magnitude of their individual doses, all to be as low as reasonably achievable (ALARA) taking into account economic and societal factors. Examples of the economic and social factors to consider when determining the optimum option include cost, sustainability, social acceptability, and distribution of doses over space and time, psychosocial effects such as stigma, and environmental impacts (IAEA, 2012).

Individual dose restrictions (or limitation)

There should be restrictions on the doses or risks to individuals affected by the contaminated territory and to individuals carrying out the remediation actions.

Protection of non-human biota

International approaches have been developed to address the radiological impact on non-human biota. Non-human biota is to be protected at the population level; however, endangered species and species at risk may warrant protection at the individual level. Sets of reference non-human biota (e.g. mammals, birds and phytoplankton) have been developed and the impact on these reference groups is determined by comparison with dose rate screening criteria. These screening criteria are applied with understanding of the radiosensitivity of the biota and the population dynamics (e.g. taking into account fecundity). In some countries, if criteria are protective of humans, then it is assumed that the same criteria will also protect biota, e.g. in Germany 10 µSv y^{-1} to humans is sufficiently protective of biota.

2.3. What is sustainable remediation?

Historically, remediation of regulated nuclear sites has meant cleaning up the site so that it is fit for any future use. This will continue to be the right approach for some sites, but experience indicates that planning for unrestricted use may not necessarily be the overall optimum approach if the wider implications of this clean-up on the environment as a whole are taken into account.

In general terms, sustainability is the capacity of systems and processes to endure. Hence, combining the definition of remediation described in Section 2.1 and the environmental principles and principles of radiation protection described in Section 2.2 leads to the concept of sustainable remediation. Sustainable remediation therefore applies the principles of sustainable development to site clean-up (Holland et al., 2011).

The term sustainable development was defined in 1987 by the United Nations (WCED, 1987) as: “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs”.

Sustainable remediation is defined by the United Kingdom’s Sustainable Remediation Forum (SURF) – an initiative set up to progress the UK understanding of sustainable remediation as: “the practice of demonstrating, in terms of environmental, economic and social factors, that the benefit of undertaking remediation is greater than its impact and that the optimum remediation solution is selected through the use of a balanced decision-making process” (CLAIRE, n.d.). This is closely related to the US Environmental Protection Agency (EPA) concept of green remediation, which is defined as “the practice of considering all environmental effects of remedy implementation and incorporating options to maximise the net environmental benefit of clean-up action” (EPA, 2008).

As introduced in Chapter 1, sustainable remediation therefore represents remediation actions that are informed by the short- and long-term impacts on: safety and the environment, society and the economy, natural resources and climate change. Sustainable remediation therefore considers the benefits and impacts of each remediation option, including the impacts of the waste management options, and selects the overall optimum approach. It includes, but is not limited to, a risk informed approach, which considers the risks to future users of the site.

> Sustainable remediation is:
>
> Remediation actions that deliver a net benefit and are informed by the short- and long-term impacts on: safety and the environment, society and the economy, natural resources and climate change.

If the remediation activities cause greater impact to the well-being of people and the environment than the contamination they seek to address then they would not be considered to be sustainable. More information on sustainability and sustainability indicators is given in Annex C.

Our understanding of a site is not just based on the physical condition of the site but the context of the site; for example where it is located, and the environmental, social and economic value of the land. This information helps us decide whether alternative remediation approaches (that control the risk from contamination) would present a sustainable solution which still protects human health and the environment and enables beneficial some reuse of all or part of the site.

2.4. National policies on sustainable remediation

> The formulation of a national policy will encourage the establishment of a legal framework for ensuring coherent and consistent remediation approaches.

It is expected that national governments will have policies that take account of the principles of radiation protection and environmental protection. Policies on nuclear safety will often assume that remediation of contaminated land and groundwater is part of decommissioning, and this is consistent with a common safety philosophy advocated by the International Atomic Energy Agency (IAEA, 2014a). Hence, these policies do not explicitly address remediation. In most cases where contamination of licensed sites has occurred due to long-term operations, an integrated approach to decommissioning and remediation may be cost effective. However, in some cases early remediation prior to decommissioning may be necessary to protect groundwater and to minimise the spread of contamination and thereby reduce environmental detriment and costs. A policy explicitly addressing remediation would therefore be required. The IAEA have published information on policies and strategies for environmental remediation (IAEA, 2015).

In the environmental remediation of a given site, different stakeholders may have diverse and often conflicting interests with regard to remediation goals, the time frames involved, reuse of the site, the efforts necessary and cost allocation. An established remediation policy will set the nationally agreed position and plan, and will give visible evidence of the concerns and intent of the country (IAEA, 2015). Ideally, policies should be as generic as possible and not specific to the needs of individual sites. The internationally agreed requirements for a regulatory framework and a regulatory body, or other relevant authority, regarding remediation are laid down in IAEA Basic Safety Standards (IAEA, 2014b).

The policy for the release of licensed sites from nuclear and radiation protection regulatory control, after remediation (clean-up), should ensure that an adequate legal and regulatory framework, supported where necessary by appropriate guidance, is in place. This framework will ensure that workers, the public and the environment are protected during site remediation and after the release of the site from nuclear and radiation protection regulatory control. It should also specify the responsibilities of the parties involved (IAEA, 2014b).

In the development of policy in environmental remediation it is essential, among other things, that the role of the stakeholders and their means of participation in the decision-making process are defined. This is because the overall decision-making process and the resulting remediation solutions may be of interest to a wide range of stakeholders, including regulators, the general public and especially local communities. Stakeholders constitute a highly heterogeneous group with varying levels of knowledge and experience. Ideally, all relevant stakeholders should be involved in the decision-making process, with due weight given to professional and lay knowledge. The aim is to achieve a shared understanding of the situation and its implications for all parties leading to – as far as possible – a participative decision-making process where the stakeholders can influence the decision-making process or assume shared responsibility for the final decision. The economic, social, environmental and health impacts of leaving sites in their present condition, and of different methods of remediation, should be discussed openly (IAEA, 2015).

2.5. National strategies in sustainable remediation

Some countries rely on a national remediation strategy to guide remediation planning (e.g. the United States as described in Section 3.5.4). Such strategies need to be aligned with the national remediation policy, and integrated with the relevant decommissioning and waste management policies and strategies. The remediation strategy sets out the approach to ensuring that the options for remediation of sites are optimised taking into account relevant factors. The national strategy will expect each site to have a site strategy or plan as described in Chapter 4.

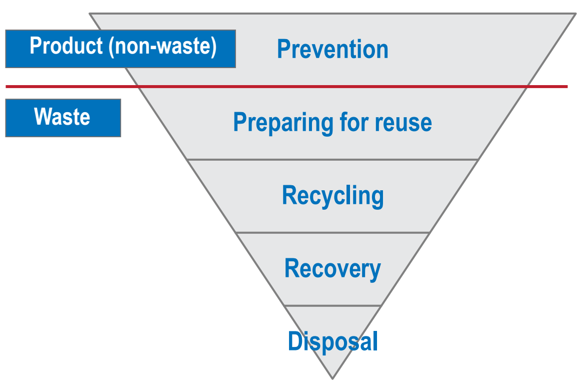
The availability of funds and appropriate waste routes are key issues for the development and implementation of a remediation strategy and can determine whether or not remediation can go ahead and the rate at which it can be implemented. The adopted remediation strategy will also need to take account of hazard and risk reduction priorities and decommissioning activities on the site. Examples of strategies are to focus early spending on ensuring short-term safety of the site, giving priority to tackling those tasks that tackle the greatest and most urgent risks, or implementing a phased remediation programme.

For the purposes of planning and ensuring that funding is available when it is needed, it is necessary to have an estimate of the likely costs of remediation, and when it will be needed. Funding arrangements for remediation are established early in the lifetime of any facility, particularly in the nuclear fuel cycle, to enable remediation to be carried out in a safe, timely and efficient manner. These arrangements should also identify when these funds, or portions of these funds, are required. Further work is required to understand the funding arrangements for early remediation, particularly in the operational or early phases of decommissioning.

2.5.1. Waste management

A national remediation strategy would not be complete without a description of how the wastes arising from remediation will be managed. Integration of the management of operational and decommissioning wastes, and of waste generated during the implementation of remediation activities, is critical to the success of the project. Waste management planning will be informed by the waste management hierarchy, see Figure 2.1.

Figure 2.1 Waste management hierarchy



Source: EU, 2008.

A fuller discussion of the need for an integrated waste management approach is given in Section 4.4. An important aspect is therefore to pursue appropriate ways to minimise the wastes to be generated by the remediation process, taking account of the overall optimisation of the remediation activities and the wider sustainability factors discussed earlier (an example of this is given in Case Study CS3 in Annex 5 of NEA, 2014). Wastes containing radioactive and/or non-radioactive contaminants need to be considered. The concept of clearance, whereby radioactive waste or radioactive material containing very low levels of radioactivity can be removed from any further regulatory control that is applied for radiation protection purposes, is also described in Section 4.4 (regulatory controls for chemotoxic properties still apply). Clearance is an important concept that can be applied to waste and materials from remediation in many countries and internationally agreed clearance levels have been derived (IAEA, 2004).

2.5.2. Regulatory approaches

A national remediation strategy will need to be compliant with the regulatory approach within that country. Approaches to remediation are also influenced by the type of regulatory environment existing in a particular country. Experience shows that a change in the regulatory approach is being observed, i.e. a move away from a prescriptive to a more adaptive performance or risk-based approach. IAEA have summarised the advantages and disadvantages of a prescriptive and a performance-based regulatory system in which sustainable remediation might be undertaken (see Annex C). This document supports the use of an adaptive approach to site remediation, both from the perspective of regulator and operator. From a stakeholder confidence perspective, transparency of the regulatory system and decisions taken is an important factor.

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3. Determining end states and remediation goals

3.1. Introduction

> The end state should protect both people and the environment. The process of identifying and achieving the end state should be approached adaptively through optimisation.

As described in Chapter 1, the end state is a remediation goal (objective) associated with the closure or long-term management of a site that meets regulations and is protective of human health and the environment. The end state can be based on constraints on the level of residual risk to human health or the environment. In some countries however, regulatory requirements may exist for some contaminants in the form of specific criteria (e.g. activity concentrations, the performance of liners, or the presence of capping materials). These requirements may override any risk-derived criteria. In line with a sustainable approach to remediation, societal and economic impacts must be considered as well as safety and environmental impacts when developing end states and setting remediation goals.

To practice sustainable remediation, all environmental effects of remedy implementation should be considered so that the overall environmental footprint of remedial actions can be minimised. The choice of a remediation option will depend on its performance in achieving the planned remedy and the wider environmental, social and economic factors. Once the remedy is chosen, its implementation will be optimised to reduce its wider impacts.

The description of the end state should include details of any remaining contamination, possible end uses for the site, the final destination of the waste that is generated during the remediation work and any associated institutional control that is required for the possible end uses of the site. The end state may be achieved through one straightforward clean-up campaign for a relatively simple site or through one or more intermediate or interim remedial milestones (with associated interim states) for a more complex site.

Section 3.2 addresses strategic considerations and Section 3.3 the constraints that influence the choice of end state. Section 3.4 describes a generic process for determining end states, from initial site characterisation to implementing remedial actions. Country-specific examples are described in Section 3.5 and insights in Section 3.6.

3.2. Strategic considerations

In many cases the end state is a requirement of the regulatory authority. The operator is required to remediate the site to meet the specified future use and risk target. For some more complex sites great flexibility is often required. Development of the possible end states for a site can then be a lengthy process and many aspects need to be considered during the process; examples are: environmental risk levels, stakeholder priorities, scope and type of long-term controls, scale of remediation actions, regulatory regime, available funding and complexity of the site.

3.2.1. Adaptive remediation determination process (includes phased approach, iterative approach)

Although many nuclear sites can be remediated to "unrestricted use" status, remediation of groundwater to a condition allowing for unlimited use/unrestricted exposure remains a significant issue in some cases. Issues that can make nuclear site remediation complex include difficult subsurface access, deep and/or thick zones of contamination, large areal extent, and subsurface heterogeneities that limit the effectiveness of remediation. Complexity also exists because of significant uncertainty with respect to understanding source distribution and contaminant behaviour as well as response to a remedial action. Sites where long-term remedies will be needed to address contamination also are categorised as complex.

For remediation of complex nuclear sites, sequences of remediation steps and an adaptive approach is often appropriate. In this case, the steps in the process can be adaptive to account for changing conditions and improved understanding as additional data about the site are obtained, for example, through remedy implementation and monitoring (e.g. NRC, 2003). There are costs and benefits associated with the timing of clean-up and it is important to understand both when deciding on interim end states.

The sequences of steps may also reflect the different requirements for the contaminated land (and groundwater) over different timescales, for example clean-up to be suitable for a specific use of the land in the near future and for unrestricted use of the land at a later stage. With an adaptive approach, initial decisions do not necessarily need to result in selection of final remedies that fully meet remediation goals.

3.2.2. Graded approach

The level of effort required to determine site end states and remediation goals and criteria should be commensurate with:

- complexity of the project;
- anticipated end state of a site (including the timescale at which it is to be achieved);
- relative importance and magnitude of radiological and non-radiological hazards;
- regulatory requirements;
- need for adaptive approach.

An adaptive, phased approach being used for a more complex site will require a greater level of planning effort than a site with a straightforward set of remedial actions to be completed within a short time frame.

3.2.3. Zoning, operable or management units on physically complex sites

A site may be considered complex for several reasons. These include:

- technically challenging physical environments;
- restrictive or expansive site layouts;
- numerous facilities and/or impacts to soil and groundwater;
- complicated geological, hydrological and hydrogeological setting;
- limited knowledge of past operations;
- large areas exist with intensive industrial activity and/or no industrial activity.

Complex sites may be divided into zones, or other smaller, more manageable areas, based on:

Complex sites may be divided into zones, or other smaller units to facilitate decommissioning and remediation decision making.

- historical use of the area;
- type and extent of ground and groundwater contaminants;
- opportunities for reuse of the area;
- access considerations;
- physical characteristics of the areas;
- anticipation of similar remedial action strategies (economy of scale);
- spatial relationships to other waste units;
- contribution to the same groundwater plumes;
- reasonable number of units to effectively manage.

Each unit on a larger site may have different end use scenarios with different end states and clean-up criteria. Furthermore, the composition of zones may be fluid over time. As remedial actions change the configuration or conditions of the landscape or further information becomes available, changes in zone or unit boundaries may be desirable.

There is a danger that zoning the site can become focused on short-term decommissioning or remediation aims. This can distract from achieving the end state and result in differing end state conditions being reached across the site. For example the groundwater clean-up targets derived in the context of a zone may be more onerous than those that would be required if a site-wide approach was taken. Remediation of zones should therefore always be cognisant of the site end state. For less complex sites, zoning may not be necessary or advisable.

3.2.4. Use of long-term stewardship

Long-term stewardship may be in the form of institutional controls, either physical or administrative or a combination of both.

Remediation may not, in all cases, achieve end state conditions that are suitable for unrestricted use of the site. In addition, interim end state conditions are, by definition, not suitable for unrestricted use of the site. Consequently, some form of management may be required to ensure an acceptable risk level for whatever use is achievable.

Institutional controls are non-engineered instruments such as administrative and legal controls that help minimise the potential for human exposure to contamination and/or protect the integrity of the remedy. In general, they are not intended to reduce the quantity, toxicity, or mobility of hazardous substances in the environment, but to reduce exposure to contamination by limiting land or resource use and guiding human behaviour. They may therefore provide for temporary or permanent restrictions on land use by limiting development and/or restricting public access to a site which has residual contamination.

Administrative types of institutional controls may include property controls such as easements and covenants; governmental controls such as zoning, permits, and restrictions on land and water use, and excavation permit requirements; informational devices like deed notifications and restrictions and title transfers; and legal enforcement tools such as administrative orders and consent decrees. These controls are often implemented or enforced by off-site land-use authorities.

Physical controls can also limit activities and/or access to land, groundwater, surface water, and waste disposal areas to prevent or reduce exposure to hazardous substances using engineered features. These kinds of controls include the use of barriers to provide protection. Institutional controls supplement engineering controls and there are some examples of pump and treat systems being used as part of the institutional controls in the US Department of Energy (DOE) legacy programme.

Long-term stewardship primarily involves the care and maintenance of the site and of any ongoing remediation solutions, such as structures. The US Environmental Protection Agency (EPA) guidance (EPA, 2001) provides recommendations for conducting five-year reviews of the institutional control measures, in a manner similar to the review of the engineering components.

Potential problems of enforcing controls can occur when voluntary remediation occurs outside the development planning regime since owners are under no obligation to provide related information to other parties. Consequently, controls may not be enforced when small-scale redevelopment occurs under the permitted development rules or when controls and relevant information are not passed to subsequent owners following the initial divestment of land.

Long-term monitoring may be required, as a component of the stewardship, to confirm that the controls are effective in allowing the end (or interim) use of the site, and it may last for many years, decades or more. This monitoring may be used to demonstrate that contamination is behaving in a predictable manner consistent with the conceptual site model and that additional risk is not created by changes over time in contaminant location, contaminant chemistry or receptor behaviours. Long-term monitoring may verify that the site continues to perform in line with the conceptual model or to give early information to allow prompt preventative actions. It may also be used to support long-term remedial options such as "monitored natural attenuation" (IAEA, 2006a).

Other issues to consider include:

- What constitutes a reasonable period of time over which any society can expect institutional controls to be maintained: does this need to consider the properties of the contaminant, e.g. differences between asbestos, organic solvents, "short-lived" radioactive substances, etc.?
- Should the safety subsequent to the cessation of such controls be predicated only on passive measures that do not require any intervention, or even knowledge?
- Wider issues such as funding and availability of competent resource within the enforcing organisations.
- What is the appropriate review period to be applied to institutional controls and what management arrangements are needed to ensure this? Best practice is to review every five years.
- Should controls be passive (e.g. the presence of markers or records as a reminder) or depend on active administration (e.g. monitoring, periodic review) by human institutions?

An evaluation should be undertaken to determine whether removing the hazard or installing institutional controls will be more cost effective over the long term, while still achieving the site remediation (clean-up) goals.

In some cases, a permanent solution may have been deferred until a (more) suitable remediation technology has been developed, and hence the site has been put into a suitable state for long-term stewardship. A long-term stewardship programme should be developed during the remediation and/or decommissioning phase(s), and needs to address monitoring and maintenance as well as to include provisions for corrective actions in the case of deviation from the predicted behaviour of the site (IAEA, 2006b).

3.3. Constraints

In many cases, decisions will be constrained by one or more factors. Constraints may be strategic or tactical, and perhaps time dependent. It is important that constraints be identified, explained and documented and that any dependencies that may modify the constraints are identified. How the constraint can impact either defining an option or assessing an option should also be described. This may lead to identifying opportunities to challenge the constraints, perhaps achieving a different outcome. It is important to remember that a constraint acts to limit the options that can be implemented. It does not limit the identification of options.

When remediating a site, an ideal solution is often not possible and it is necessary to balance the ideal with the attainable. Understanding the barriers to these ideal solutions promotes good decisions in two ways. First, this understanding enables options to be reconsidered if these barriers are overcome. Indeed, early consideration of constraints may mean they can be removed by regulators, policy makers or managers. Second, identifying the barriers enables greater transparency when explaining how decisions have been reached. The IAEA Constraints in Decommissioning and Environmental Remediation (CIDER) project is preparing a "baseline report" that analyses the constraints to implementing decommissioning and remediation projects, and provides recommendations on how to overcome such constraints, based on the experience gained from existing and past projects (IAEA, n.d.). Further discussion on constraints is in Annex F (UK approach).

3.3.1. Waste management constraints

Disposal facilities can impact remediation activities in different ways. Examples of topics to consider include the availability of suitable disposal facilities, the time taken to develop additional disposal facilities, the possibility that waste material could be used to fill underground decommissioned facilities (beneficial reuse of materials), and whether older waste disposal facilities on the site also need to be remediated.

The availability of suitable waste management facilities can impact the timing of remedial actions. It will be more protective of the environment if the need for treatment and/or disposal infrastructure is identified early to ensure this infrastructure is in place to allow the most sustainable solution to be implemented. If this is not possible then it may be more cost effective to delay remediation that results in large waste volumes until disposal facilities are available.

In some countries, provision of disposal facilities for radioactive and hazardous waste can be problematic. Despite good waste management planning and minimisation techniques it is possible that pressures on limited available capacity will provide strong drivers to consider local disposal or *in situ* techniques for remediation. Good practice is to use a range of characterisation technologies and three-dimensional statistical techniques to reduce uncertainties when demarcating the more contaminated land or groundwater. In other cases the drivers to commit resources to sophisticated and complex characterisation, waste sorting and segregation will not be justified if disposition paths are well established and there is sufficient capacity to accommodate disposals. Nevertheless, it is good practice to achieve as great a level of segregation of wastes as practicable to reduce the burden on disposal facilities. In some cases, particularly with complex sites, there will be greater emphasis on natural attention and institutional controls to reduce pressures on waste management. In some cases, less waste will be generated if managed *in situ*, due to the bulking factor associated with excavation and repackaging, and the allowance for natural attenuation.

Since disposal costs can often be the most expensive part of project costs, money can be saved if the amount of contamination left in the ground is optimised rather than assuming that it all has to be removed.

The location of a disposal facility can also impact site end state options and remedial approach (or action) decisions. If feasible, it may be better and more cost effective to locate a disposal facility on-site than to transport wastes to another off-site disposal location. An on-site disposal facility may constrain the next use of that part of the site and could be managed by zoning the site.

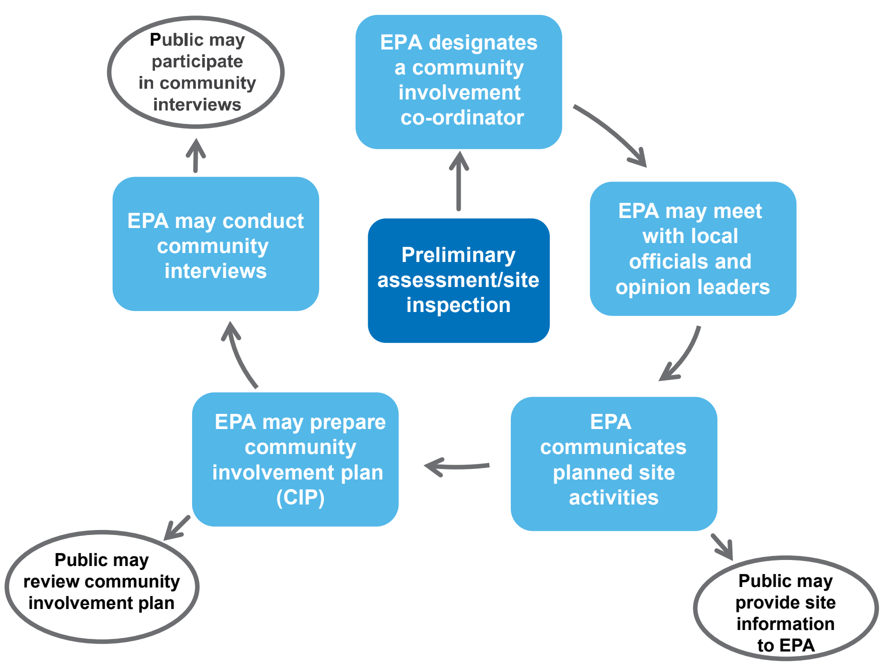
Stakeholder interactions are very important. Stakeholder acceptance is necessary to transport waste through communities on public roads, to locate a disposal facility on-site or to leave wastes *in situ*.

Sometimes remediation of old waste disposal areas may be required. If these areas require significantly different remedial actions and remedial targets than other parts of a site, cost, schedule and risk acceptability may lead to a different remedial approach (or action) than that for the rest of the site. If the decision is made to leave a disposal facility on-site, different long-term controls may be required.

3.3.2. Stakeholder opinions and expectations

Stakeholder opinions and expectations must be considered in the decision-making process. Providing too little information may lead to unfounded perceptions of risk and may drive an excessive demand for a potentially high level of remediation incommensurate with accepted risk norms. Paucity of information, or poorly presented information, may also lead to distrust which can disrupt end state negotiations with stakeholders. Hence, the stakeholder participation process must be co-ordinated and discussed with the stakeholders in advance of considering end states. An example of a co-ordinated stakeholder involvement process, as used by the EPA, is shown in Figure 3.1.

Figure 3.1 Superfund process for stakeholder involvement



Source: EPA.

3.3.3. Decommissioning constraints

The planning of site remedial actions needs to be fully integrated with the decommissioning of the nuclear installation. It is expected that clean-up targets for facilities will influence targets for foundations and associated land and vice versa.

In rare cases, *in situ* storage or entombment can place constraints on interim or final end states and end uses. Buildings left in place may impact on future land uses, as well. Existing buildings or plant may also limit access to ground or groundwater contamination, or the timing of this access. In some cases decisions may be made to reuse buildings and options to remediate land under these buildings can be considered depending on the levels of contamination and the interim end state.

3.3.4. Environmental constraints

It may not be feasible to successfully remediate contamination in some situations; for example, remedial actions may not be feasible if an entire aquifer is contaminated. Similarly, it may not be feasible to clean up river or lake sediments, or attempting to remediate them may require disproportionate levels of effort or generate a disproportionate volume of waste. This may lead to the consideration of partial or targeted remediation. Institutional controls may be required to manage ongoing or residual hazards or risks in these cases.

3.3.5. Funding constraints

For some legacy situations, availability of funding can mean limits on the amount of remediation that can be done and consequently on the ability to achieve certain end states. In these cases, remediation activities will need to be optimised or prioritised to align with the amount and timing of available funding (see Chapter 4).

Indeed, timing of available funding may make some options unviable. For example, if a project requires a large initial investment but funding comes in small instalments, a less sustainable approach may have to be adopted. Furthermore, funding which is only allocated for short-term time frames (e.g. for five years), can make long-term remediation actions and stewardship difficult to plan.

3.4. Generic steps for development of site end states and a remedial approach

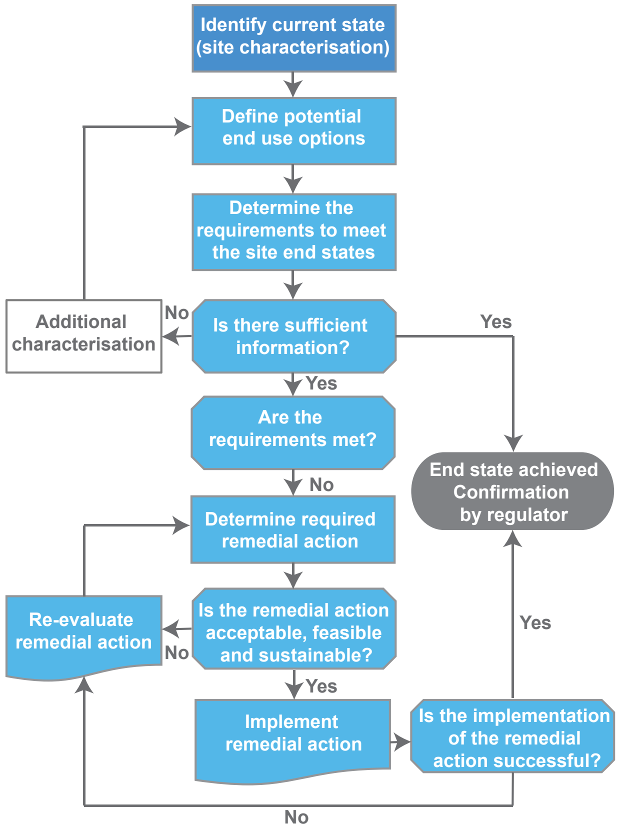
The establishment of an end state may be needed for various reasons, e.g.:

- change of land use is imminent or anticipated;
- operational monitoring indicates that a problem exists;
- upset conditions or an "event" occur.

The second two reasons are operational, not strategic. They may require interim end states to be determined, rather than a final end state, although knowledge of the final end state may help to optimise the path to the final end state.

Figure 3.2 illustrates a generic process which leads to the determination of the preferred site end state. This end state can be associated with one or more end uses of the site. The process starts with determination of the current state and the credible end uses, and then assesses the possible remediation actions in terms of their sustainability in order to determine the preferred end state. This is an iterative process (shown as a loop) for a more complex site, but for a simple site, it may be a "once-through" process.

Figure 3.2 General end state determination process and achievement



Participation of the public and other stakeholders in decision-making will be necessary to ensure that the end state will be accepted, and thereby ensure the success of site remediation. Therefore, involvement of stakeholders should be considered at every stage of the process illustrated in Figure 3.2. The progressive steps are described in greater detail in the following text.

3.4.1. Identify current state

A site investigation should be performed to identify the source, nature and extent of contaminants of concern. All relevant media, pathways and receptors should be included in the investigation. Exposure pathways need to be determined for all receptors and selected land-use scenarios.

Existing information should be sought first, with further site characterisation taking place as required, so that a sufficient amount of information is available to adequately define contamination issues and develop an initial conceptual site model that will feed into a preliminary risk assessment. Data collection may be an iterative process, using a systematic planning approach, e.g. the data quality objectives (DQO) process (EPA, 2006).

Data from the site assessment and conceptual models are used to assess the risks from the contamination with respect to contaminant concentrations and exposure pathways. Guidance on performing site assessments can be found in most countries.

In addition to understanding the physical condition of the site, the wider context of the site should be considered including:

- the site setting (for example, proximity to settlements, proximity to natural and heritage assets, characteristics of the local landscape, adjacent land uses);

- availability and location of disposal facilities (e.g. on-site or off-site, sufficient capacity);
- market considerations (for example, economic value, identified future owner or realistic opportunities for reuse, resources available, funding framework);
- stakeholder preferences (for example, outputs from local stakeholder engagement, local plans, national policies affecting future use of the site);
- policy and regulatory framework (for example, government and regulatory policies and regulations, internationally agreed conventions).

3.4.2. Identify potential end use options

End uses can vary from unrestricted (all uses are possible) to very restrictive (e.g. open space controlled by government in perpetuity). Typical generic use types include: residential, commercial/industrial, public open space/park land and nature conservation.

The first step is to determine the range of end use options that may be feasible, given national polices, regulatory requirements, location of the site, local natural resources, and local infrastructure. The end use is then selected by either the land owner (or next land owner, if known), with the participation of stakeholders and taking into account the constraints and practicalities of the range of end use options i.e. sustainability considerations.

Associated with the use will be a particular set of exposure pathways which will be used to define the remedial targets in terms of activity concentrations in soil or groundwater. If the end use is "for any purpose", as currently is the case in France, Italy, Germany and the United Kingdom, all credible potential exposure pathways need to be assessed.

One or more intermediate remedial targets, often termed "interim end points", may be defined along the way to meeting the final remediation targets and achieving the end state. In some cases, implementing a sequence of progressive remediation end points may be more appropriate, with subsequent adaptation as more data about the site are gained through remedy implementation or longer-term monitoring. Hence, remedial actions that meet interim end points may be preferred if they provide adequate protection of people and the environment, make appropriate progress towards reducing future risk, and provide information to evaluate subsequent remedy actions. In this way, conservatism can be progressively reduced as uncertainties with end use and final end states diminish. Decommissioning project managers often tackle ground contamination at the same time as dismantling because they have mobilised workforce, equipment and waste disposition routes. Interim end states provide confidence that remediation during dismantling projects is right first time. There are costs and benefits associated with early clean-up and it is important to understand both when deciding on interim end states.

End use assumptions can change over time. An end use chosen by today's stakeholders may be dismissed at a later time if stakeholders or other conditions change. Thus, there may be a risk that sites that have been remediated to a particular residual level of contamination require further remediation. Sometimes institutional control for a specified number of years can be invoked if that is the case. This risk can be mitigated by conservatism in the choice of interim states.

Determine end state requirements

End states and end uses are linked since each end use option has associated considerations and constraints that result in the identification of one or more end state options. Conversely, a specific end state can allow for a number of end uses. Clean-up goals for each contaminant for the identified end state scenarios are first identified. Risk assessments are then performed to determine activity concentration levels, in terms of

Bq g^{-1}, for specific radionuclides that are protective of humans and the environment for the relevant exposure pathways. These contaminant concentration levels are therefore case specific and will vary from case to case. On many sites the non-radioactive substances are of greater concern and the same process will be used to evaluate the end state. Specific regulatory requirements are used, if they exist; for example, criteria for the dose/risk to the public may be mandated by the government or regulators. Having mandated clean-up levels takes away some flexibility in the determination of clean-up goals, but provides certainty for long-term planning and cost estimation.

End state assumptions should be revisited as planning and remediation advance to address changes in understanding of risks to humans and the environment, regulatory requirements, stakeholder input or other factors. This is an iterative process that will continue for the life of the site clean-up until an interim state or end state has been achieved.

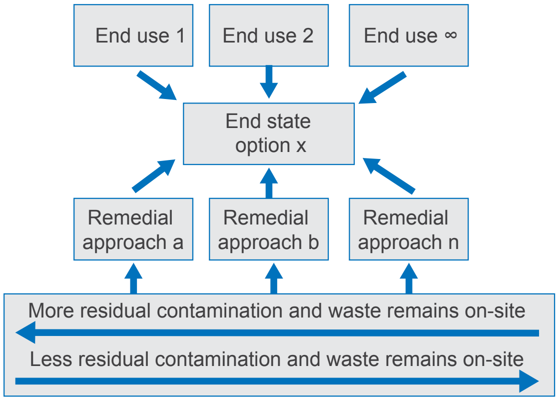
Identify preferred (optimal) end state and remedial approach

The gap between the clean-up objectives and requirements and the existing conditions will guide the selection of sustainable remedial actions. The selection of remedial actions will consider the socio-economic and environmental costs and benefits. An example of the different factors considered in an assessment of the trade-offs in the choice of the best option is given in Section 3.5.4. An important issue is the predicted effectiveness of the remedy.

The most common remedial actions are characterisation and removal of the contamination, and treatment of groundwater using pump and treat, or reactive barrier. Other options are the immobilisation of the source term, *in situ* disposal of source terms, disposal in a facility elsewhere on-site, or monitored natural attenuation: these options also require fencing, caps or other barriers to isolate the source term or contamination, cutting or minimising the pathway to receptors. Long-term monitoring is required to confirm the effectiveness of the chosen remedy.

There may be a number of remedial approaches to achieve the end state (i.e. remove or control the risk) depending on the site, each with different amounts of residual contamination and waste remaining on-site, see Figure 3.3.

Figure 3.3. End states and options for the remediation approach



Each of the end use/end state combinations then undergoes an optioneering assessment to identify the preferred or optimal option. This can be performed using multi-attribute decision-making software, analytical hierarchy software or even a simple pros and cons analysis. If there is only one potential end use (e.g. unrestricted use) then each of the remedial action options should undergo an optioneering assessment to identify the preferred or optimal remedial action. As above, this can be performed using a range of decision aiding techniques to weigh up the costs and benefits associated with the remedial action in the context of social, economic and environmental aspects. Aspects related to the extent and timing of the remedial action include whether the effort and cost is proportionate to the hazard level and to the next (interim or end) use; the level of uncertainty regarding the extent of the contamination; the best use of existing disposal facilities (this can be mitigated to some extent by application of the waste hierarchy and suitable waste acceptance criteria); and whether the remediation approach leads to the optimum timing for beneficial reuse of the site. An example of a multi-criteria decision analysis method that has been developed to provide a transparent assessment of the sustainability of possible remediation alternatives for non-radioactively contaminated sites, relative to a reference alternative, is described in Rosén et al. (2015). It argues that successful application of decision aiding techniques requires *i)* a clear conceptual model of the major components and boundary conditions of the assessment; *ii)* clear definition of sustainability; *iii)* a set of key criteria (indicators) with well-defined performance scales; *iv)* clear and transparent handling of uncertainties; and *v)* a structured stakeholder involvement in the assessment process.

Winning remedial action alternatives must meet certain predetermined requirements, such as:

- achieving clean-up criteria within the specified end point time period;
- complying with existing regulations;
- costing less than or equal to an allowed budget, or its agreed extension;
- being technically feasible and technologically available i.e. a proven technology or a recognised trial or pilot process.

The winning remedial alternative should be identified and be agreed to by decision makers and other stakeholders.

3.4.3. Implementation and verification of remediation

The development of the remediation plan prior to implementation and verification of remediation is addressed in Chapter 4. When the remedial actions have been implemented, the predetermined interim or end state criteria should be met, otherwise an additional effort may be required, at extra time and expense, to achieve the desired end conditions. The operator has responsibility to show compliance, and the regulator has responsibility to verify that compliance has been shown. It is important that verification of compliance is performed by an independent body (i.e. a body other than the operator). Regulatory agreement will also be required if the end state includes releasing the site from nuclear regulatory control.

An important component of the remedy design is establishing metrics to support intermediate transition decisions and final long-term management and closure decisions associated with final remediation goals. If, during verification activities, remedial actions are found not to have achieved the end state, it may be necessary to return to the stakeholders and agree upon appropriate measures such as additional or alternative remediation, or other approaches where this is not practicable. The other approaches could include a different end state resulting in a restricted use, a different physical remedial approach, or stronger institutional controls to facilitate an appropriate level of institutional control.

Knowledge management for future users of the site is an important component of achievement of the end state (Section 4.8).

3.5. Country-specific examples of the application of generic steps

The process (generic steps) used to determine end states and end state clean-up criteria shown in Figure 3.2 is implemented in slightly different ways in different countries. Only some of these explicitly promote a sustainable remediation approach, although many allow sustainable approaches to be implemented. Examples of each country's basic process are shown in Figure 3.4 and summarised below. The examples that allow or explicitly promote a sustainable approach will enable others to see the different ways in which this can be achieved.

3.5.1. Germany

In Germany sites are released from regulatory control (cleared) on the basis of the 10 µSv *de minimis* concept, meaning that the effective dose (above background) caused by the release of the site is in the range of 10 µSv y^{-1} for members of the public. Clearance of buildings and soil areas (site clearance) is an option laid down in §29 of the Radiation Protection Ordinance (StrlSchV)[1]. The nuclide-specific clearance levels listed in the Radiation Protection Ordinance are given as values per unit mass or area (Bq g^{-1} and Bq cm^{-2}, respectively). Case-by-case decisions can also be made in this matter and case-specific clearance levels must be derived on similar principles (10 µSv concept). These decisions are usually presented by the site owner, reviewed by independent experts (on behalf of the regulatory authority) and then approved by the authority. Groundwater contamination always needs a case-by-case decision. It is mandatory that all remediated and released sites must meet unconditional clearance contamination levels as the end state, e.g. without restrictions and all relevant exposure pathways have to be taken into account.

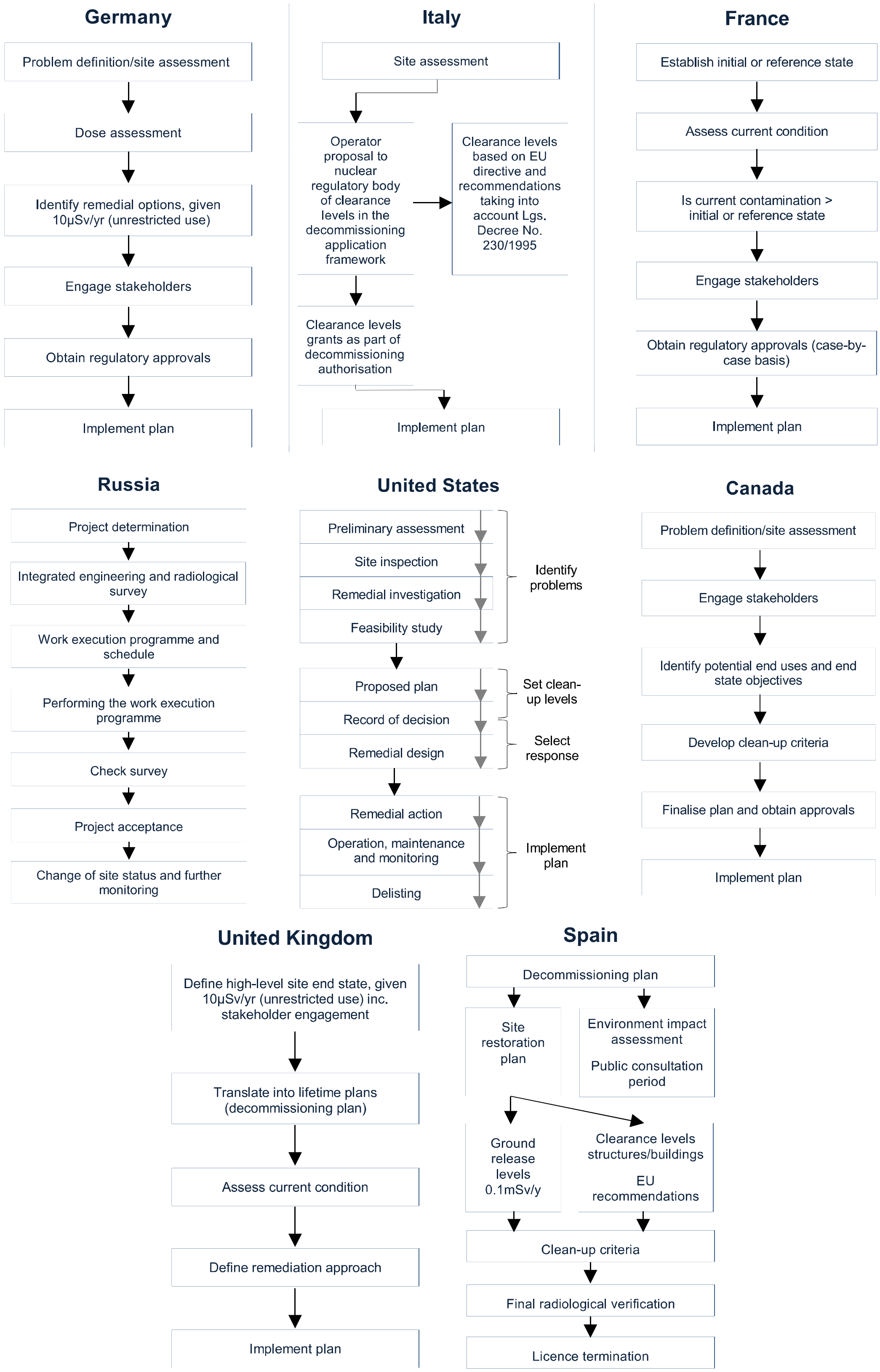
3.5.2. France

In France, the principle of "polluter pays" overrides the consideration of risk. It is expected that all artificial contamination is removed. For nuclear decommissioning facilities, the French nuclear safety authority, ASN, considers that the primary objective is to achieve a clean-up that is as complete as possible (reference approach), aiming for removal of the radioactive pollution so as to allow free use of the cleaned premises and land. Every time a site is cleaned up, one must justify why the reference approach could not be followed. An intermediate end state may also be defined.

In some cases, the characteristics of the site do not enable complete clean-up to be achieved. In this case, the as low as reasonable achievable (ALARA) principle once again applies: clean-up must be as complete as reasonably feasible given the technical, economic, environmental and social constraints. In any case, it is essential to prove that the residual radiological impact remains acceptable for the intended use, as well as for any future use of the site, if necessary with the application of usage restrictions. Exposure scenarios must be developed and, for a given use, must be able to demonstrate that there is no risk for the persons frequenting these premises (examples of exposure scenarios are: residential use, recreational and car park/parking lot).

1. Ordinance on the Protection against Damage and Injuries Caused by Ionizing Radiation (Radiation Protection Ordinance, StrlSchV) of 20th July 2001 (Federal Law Gazette I, p. 1714), last amendment by the Ordinance amending the Ordinances on Protection against Damage and Injuries Caused by Ionizing Radiation of 4th October 2011 (Federal Law Gazette I, p. 2000).

Figure 3.4 County-specific examples of defining end states



When the pollution remains on the site, justification must be provided. It may also be necessary to take action concerning the transfer pathways, in order to reduce the exposure pathways and ensure that the solution adopted leads to acceptable levels of exposure. Steps must also be taken to retain a trace and a record of the site and inform the public.

Validation of the clean-up project and targets by the public authorities concerned is necessary prior to implementation of the chosen solution. It is important to remember that there is no predefined release or clean-up level in France. The management values are those defined by the public authorities to ensure the general protection of the population and the environment. Further details are given in Annexes E and H.

3.5.3. Italy

In Italy clearance levels have been established taking into account European Union Directives and recommendations and these comply with the basic “below regulatory concern” criterion for practices established in the European Directive 96/29/Euratom. In particular, soil clearance levels have been determined taking into account the recommendation in RP122 (EU, 2000a) in conjunction with an upper specific activity limit of 1 Bq g^{-1}. It is mandatory that released sites must meet the clearance levels for unrestricted use. National legislation requires that decommissioning plans define, inter alia, the destination of resulting radioactive materials. Authorisation of a decommissioning plan requires an environmental impact assessment to have been undertaken.

3.5.4. United States

The majority of decommissioning activities in the United States occur in two sectors: facilities licensed by the Nuclear Regulatory Commission (NRC) or agreement states and sites that come under the purview of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), including DOE and the Department of Defence (DOD) sites. EPA has broad authority under CERCLA to address clean-up of radioactive contamination through the National Contingency Plan (NCP), its implementing regulation.

US Environmental Protection Agency

As with all hazardous substances, CERCLA requires clean-up of radionuclides to limit the risk to a specified range, as well as compliance with certain other laws and regulations. Radioactive contamination is generally addressed in the same manner as other hazardous substances at CERCLA sites and normally should follow the same remedy selection process. EPA provides guidance for addressing radiologically contaminated sites that is consistent with its guidance for addressing chemically contaminated sites. The EPA guidance has been developed to facilitate clean-ups that are consistent with the NCP at radiologically contaminated CERCLA sites.

The NCP defines nine criteria for evaluating remedial options which allow the optimum or most sustainable option to be identified. The first two criteria are known as “threshold” criteria. They are the minimum requirements that each option must meet to be considered for selection as a remedy and are a reiteration of the CERCLA mandate that remedies must ensure *i)* overall protection of human health and the environment and *ii)* compliance with applicable or relevant and appropriate requirements (ARARs).

In addition to the two threshold criteria, EPA considers the following five “balancing” criteria that help in the assessment of certain trade-offs so that the best option can be chosen, given site-specific data and conditions:

- long-term effectiveness and permanence;
- reduction of toxicity, mobility or volume;
- short-term effectiveness;

- implementability;
- cost.

The final two criteria are called "modifying" criteria:

- state acceptance;
- community acceptance.

These two criteria may cause comments from the state or the community to modify the preferred remedial action alternative or cause another alternative to be considered. The NCP addresses how the detailed analysis of options should be performed using these nine criteria (see 55 Federal Register at 8719–8723, 8 March 1990).

Clean-up levels for response actions under CERCLA are typically developed based on site-specific risk assessments, ARARs (unless an ARAR is waived), and/or to-be-considered material (TBCs). ARARs are often the determining factor in establishing clean-up levels at CERCLA sites (see EPA, 1988, 1989 and 1997). State standards that are more stringent than federal standards are potential ARARs. However, where ARARs are not available or are not sufficiently protective, EPA generally sets site-specific remediation levels *i)* for carcinogens at a level that represents an excess upper-bound lifetime cancer risk to an individual of between 10^{-4} and 10^{-6} and *ii)* for non-carcinogens such that the cumulative risks from exposure will not result in adverse effects to human populations (including sensitive subpopulations) that may be exposed during a lifetime or part of a lifetime, incorporating an adequate margin of safety (see CFR, 2011). The latter approach is used to determine the non-carcinogenic risks of uranium. The specified clean-up levels are designed to account for exposures from all potential pathways and through all media (e.g. soil, groundwater, surface water, sediment, air, structures and biota).

Alternatives for achieving a site-specific clean-up are evaluated using the nine criteria described above. The 10^{-4} to 10^{-6} cancer risk range described in the NCP can be interpreted to mean that an exposed individual may have a 1 in 10 000 to 1 in 1 million increased lifetime chance of developing cancer because of exposure to a site-related carcinogen under the exposure scenarios. Some states have adopted single risk goals (e.g. 10^{-6}, 10^{-5} or 10^{-4}).

While clean-ups will generally achieve a risk level within 10^{-4} to 10^{-6} for carcinogenic risk, risks of greater than 10^{-4} may be acceptable under appropriate circumstances. CERCLA guidance states that "the upper boundary of the risk range is not a discrete line at 10^{-4}, although EPA generally uses 10^{-4} in making risk management decisions. A specific risk estimate around 10^{-4} may be considered acceptable if justified based on site-specific conditions" (see EPA, 1991: 4 and EPA, 1997: 5). Once a decision has been made to take an action, the Superfund Remedial Program recommends clean-ups achieving the more protective end of the range (e.g. 10^{-6}).

US Department of Energy

The DOE manages a large programme of remediation of land contaminated by radionuclides and other contaminants, and is exploring potential improvements in developing, selecting, and implementing remedies.

The development and iterative refinement of a site conceptual model is performed in conjunction with defining a path for remediation that provides information to evaluate subsequent remedial actions or to support assessment of the ability to reach remediation goals. Successful implementation includes addressing the risks to human health and the environment and re-evaluating the system behaviour over the course of the remedy to ensure the most appropriate actions have been taken.

The process of selecting an appropriate remediation approach and reaching a regulatory decision needs to consider the site setting, potential exposure pathways, the nature and extent of the contaminants, and expected contaminant fate and transport. That is, the full "system" related to the contaminant issue should be considered. This process includes steps of developing and screening alternatives, treatability investigations, and detailed analyses of potential remedies. Key elements to consider are current exposure, exposure pathways, and remediation approaches in conjunction with resource use, institutional controls, or other measures that can be implemented to manage exposure during the remedy period. The ability to manage exposure during the remedy period using institutional controls may be considered in negotiating the remediation time frame and determining an appropriate remediation strategy. Consideration of exposure management during the remedy process is important with respect to selecting adaptive remediation approaches that are iteratively applied. These efforts maintain protection of receptors and provide the time needed for interpretation of monitoring data to guide subsequent steps towards the remediation goals established for the site.

Remediation management includes remedy design, implementation, monitoring, and adaptation leading to final long-term management or closure decisions associated with the remediation goals for the site. Remedy actions need to include appropriate measures to verify performance in terms of maintaining protectiveness, making progress towards reducing future risk, and providing information to evaluate subsequent remedy actions or in support of assessing the ability to reach remediation goals. Thus, important components of the remedy design are *i)* selecting an appropriate design for the remedy implementation that enables adaptation and progression with respect to the identified endpoints; *ii)* defining the means of performance evaluation and remedy optimisation; and *iii)* establishing metrics to support intermediate transition decisions and final long-term management and closure decisions associated with final remediation goals.

The monitoring approach should adapt to the progression of remedy implementation stages and provide suitable information to interpret performance and maintain compliance (Bunn et al., 2012). The monitoring approach also links with the conceptual model to identify appropriate lines of evidence (monitored parameters) that can be used to verify that contaminant behaviour over time is within expected limits and will meet the site remediation goals.

Throughout the approach, the implementation process, remedy performance, environmental risk, and remediation costs need to be jointly considered by the site and regulators, with input from other stakeholders where appropriate. This communication is particularly important for implementing adaptive remediation. Site, regulator, and stakeholder interactions can be facilitated during this process by using a conceptual model as the technical foundation for decisions and by identifying appropriate metrics that support decisions during the remediation process.

3.5.5. *Canada*

In Canada, the Canadian Standards Association has produced a standard (N294-09) that describes the process to define end state objectives for decommissioning activities, recognising that these end states may be either interim or final. Federal, territorial, and provincial jurisdictions in Canada may also have their own process to define end state remediation goals. Licensed nuclear sites that are being decommissioned or remediated under Canadian Nuclear Safety Commission (CNSC) regulations have end states defined as the proposed physical, chemical, and radiological condition of the facility at the end point of the decommissioning (CNSC, 2000).

Future uses of the site, to be discussed with stakeholders including Aboriginal peoples, may include unrestricted use, agricultural, traditional Aboriginal use, commercial, industrial, institutional, recreational or residential use. Risk-based clean-up criteria or deterministic criteria, if available, can be used. End states should consider protection of environmentally sensitive areas, protection of human health, potential impacts on groundwater, and the socio-economic consequences of the decommissioning and environmental clean-up. The proposed end states should be reviewed and revised if necessary as clean-up progresses. A process for determining the end state is shown in Figure 3.5.

Figure 3.5 Canadian process for determining the end state

3.5.6. *United Kingdom*

In the United Kingdom, the Nuclear Installations Act 1965 (NIA65) controls hazards associated with nuclear licensable activities and the site containing the nuclear facilities is defined as a “licensed site”. It continues to be a licensed site under NIA65 until it can be demonstrated “that there has ceased to be any danger from ionising radiations” on the site, or on the portion of the site being considered for delicensing (this is known as the “no danger” criterion). Thus, NIA65 endures beyond the point at which licensable activities cease. The Office for Nuclear Regulation (ONR) has equated the “no danger” requirement to a risk of 10^{-6} y^{-1}, corresponding to clean-up to the IAEA clearance levels specified in R-S-G1.7 (IAEA, 2004) or to a dose to the public of 10 µSv y^{-1} for any foreseeable use (i.e. unrestricted use), plus the reduction of dose to as low as reasonably practicable (ALARP).[3] The ONR guidance states that the approach to demonstrating “that there has ceased to be any danger from ionising radiations” should be based on the following principles:

- Residual radioactivity on the site (or portion of the site to be released) has been reduced below out-of-scope levels defined by relevant UK legislation (currently the EC unconditional clearance criteria specified in RP122 [EU, 2000a]).
- The licensee has taken action to reduce levels of radioactivity on the site below the levels defined in (I), so far as is reasonably practicable.
- The licensee has demonstrated that the requirements of (I) and (II) have been met by showing that the site is radiologically indistinguishable from the parts of the surrounding area that have not been influenced by previous nuclear operations on the site.
- An independent check has confirmed that the requirements of (I) and (II) have been met.

This approach is currently (2013-2016) being reviewed (see www.onr.org.uk/operational/assessment/ns-per-in-005.pdf). UK policy recognises the potential for releasing a site at levels above these unconditional clearance levels but the regulations do not currently have this flexibility.

The Nuclear Decommissioning Authority’s (NDA) mission is to decommission and remediate its sites and release them for other uses. In 2006/07 NDA undertook engagement focused on stakeholders local to its sites. The feedback formed the basis of a high-level site end state description for each site which is published in the NDA strategy (NDA, 2015). This description subsequently became the basis of the lifetime plan (the decommissioning plan) for each of the NDA sites. Although preferred next uses were identified the current regulation requires unrestricted use. Therefore the site end state cannot be optimised to achieve the most sustainable approach. The NDA is working with the nuclear and environmental regulators and UK government to enable proportionate regulatory control of decommissioned sites with contamination of soil and groundwater. This should allow for the optimisation of the site end state and subsequent remedial approach, taking into account sustainability considerations.

3.5.7. *Russia*

The term “remediation” is not used in the regulations of Russia. Remediation is understood to be the same as rehabilitation of land that is degraded as a result of radioactive contamination, either as a result of man-induced actions or decommissioned highly hazardous facilities located on the territory. According to the Law No. 92-FZ of 07/10/2001, a radioactive contaminated area of the territory is an area which is hazardous

3. The term ALARP in UK legislation can be taken to be synonymous with ALARA.

for the population's health and for the environment. The nature and degree of land contamination is evaluated in accordance with the regulations for sanitary (health) and epidemiological welfare of the population, radiation safety and environmental protection. In practice, the following approach is generally accepted: depending on the land purpose (land category) land is remediated using a dose criterion of 0.6 mSv y^{-1} for industrial uses, or 0.3 mSv y^{-1} for residential use. Financial matters are very important. Ecological programmes are preferably financed from the federal budget, although lately landowners have been involved with joint financing (e.g. the Mosrentgen remediation project has been financed in the ratio 2:3, with private financing dominating).

Remediation of territories to background values is costly, and the main criteria for determining the appropriateness and completeness of the decontamination that has to be performed are:

- equivalent dose of gamma radiation;
- the specific activity of man-made and effective specific activity of natural nuclides;
- exposure quotas of the population in the territory after rehabilitation of the site;
- permitted levels of residual specific activity and content of toxicants: in soil, surface and ground water, sediments.

The decision must be based on the economic approach, which defines a mechanism for assessing the costs and the identification of key economic indicators that determine the cost structure.

Further information on strategic considerations on remediation in Russia is in Annex E.

3.5.8. Spain

The release from regulatory control of a decommissioned nuclear facility after the remediation of the site is well established in the Spanish regulations: the future release from regulatory control of the site is considered a part of the decommissioning plan of the nuclear facility. Spain is also currently working on a regulatory framework for the decontamination or rehabilitation of radiologically polluted industrial sites not belonging to a previous nuclear regulated facility. This second regulatory framework is not in force yet but exists in a draft form.

The dismantling process of a nuclear facility ends up with a decommissioning statement (licence termination) freeing the owner of the installation from their responsibilities as an operator, and establishing, if some radiological restriction applies, the future use of the site, and the person or organisation in charge of safeguarding such restrictions and ensuring due compliance.

As far as the installation site is concerned, the Spanish regulations require a site remediation plan to be submitted along with the decommissioning authorisation application. In the case of a nuclear power plant, the decommissioning authorisation is granted after the environmental impact assessment has been performed and the impact assessment statement (Declaración Impacto Ambiental, DIA) has been granted, and after a public consultation period for the full decommissioning plan.

The site remediation plan should specify, when necessary, the planned monitoring schedules for the verification of the radiation and contamination levels at the site to be released. Releasing a site without restrictions implies eliminating all future radiological monitoring.

The Spanish Regulations on Nuclear and Radioactive Installations do not explicitly state the radiological conditions to be met by the site to be released, or to be partially released – with or without restrictions – or the criteria required for a release with restrictions. However, radiological criteria for the release of sites containing nuclear installations are given in the Nuclear Safety Council Instruction IS-13 (NSC, 2007). This instruction considers an effective dose to the representative individual from the critical group, from the residual activity in the site's ground, of less than 0.1 mSv y^{-1}.

On the other hand, any buildings, facings, or structures that are to remain on the site at the time of release shall comply with the clearance criteria recommended by the European Union in RP113 (EU, 2000b).

These radiological criteria shall apply to the entire released site, regardless of any possible future use restrictions for the site.

The new background radiation dose at the released site shall be equal to the addition of the dose arising from residual activity and the existing dose previous to the operation of the installation (in other words the old background dose).

The release of part of a site containing a nuclear installation is also allowed in the IS-13 Safety Instruction (NSC, 2007). As far as radiation protection is concerned, the release of part of the nuclear site prior to the licence termination of the facility shall be considered acceptable only if the decommissioning authorisation has been previously granted. If such a partial release needs to be carried out with restrictions, the radiological criteria shall apply to the entire site to be released. The operator shall keep the records with the radiological classification data of the released part of the site until the last release becomes effective and the decommission statement (licence termination) of the installation is issued.

A total or partial release of a site with future use restrictions shall be considered acceptable:

- Provided that it can be proved that any additional reductions in the residual activity required to release the site without restrictions may result in actual harm to the public or the environment, taking into account all possible radiological damages in the process; or provided that the residual levels associated with the restricted conditions are as low as reasonably achievable (ALARA), taking into account social and economic factors.
- Provided that the operator supplies sufficient means to establish and keep legal and institutional controls to reasonably guarantee that the effective dose from background residual activity received by the representative individual of the critical group does not exceed 0.1 mSv y^{-1}. This value shall apply to the entire ground of the site, regardless of the compliance with the clearance radiological criteria in force for buildings, facings, and structures.
- Provided that it can be ensured that the dose received by the representative individual of the critical group as a consequence of any allowed uses under the restrictions in force does not exceed the maximum established value. Should the institutional control on the restrictions fail and render them ineffective, the dose received by the representative individual of the critical group shall not exceed a value of 1 mSv y^{-1}.

The operator shall put forward and provide evidence of compliance with radiological criteria for a set of release levels in accordance with the radiological criteria and with the site's planned end use.

The operator shall also put forward and provide evidence for the methodology used to perform the final radiological classification for the site, in order to demonstrate that all established radiological criteria are met.

3.6. Insights on the determination of end states

Identifying and achieving the end state for a site undergoing decommissioning is a multi-step process. It should be approached adaptively through optimisation. An adaptive approach with interim end points also allows decisions to be made at an earlier time, enabling progress towards the final end state to be demonstrated.

It is important to recognise the distinction between end states and end uses. There are opportunities to optimise the end state for a given set of end uses since different practical outcomes (e.g. areas of residual contamination) may enable the same end use. Long-term stewardship may be required if the end state or interim end state is restricted use of the site and institutional controls (both administrative and physical) ensure that the risk level is acceptable for the chosen end use. Periodic reviews of these institutional controls are required to ensure their continuing effectiveness and therefore the review period needs to be specified, as well as the management arrangements to ensure this review takes place.

Sustainable remediation is applied in many countries, particularly for non-radioactive contaminants. The end states are determined through an optimisation process involving decision aiding techniques and discussion with stakeholders. The different applications of the generic steps in the different countries illustrate that the starting point for the optimisation is not always the assumption that the site will be cleaned up to background levels. The important point is that the approach taken to the adaptive optimisation process is supported by stakeholders in the country. Each country therefore finds the best way to derive sustainable end states within their socio-political context. Regulators therefore need to consider the overall policy that defines sustainable approaches for their country and then apply the adaptive approach within this context.

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4. Preparing the remediation plan

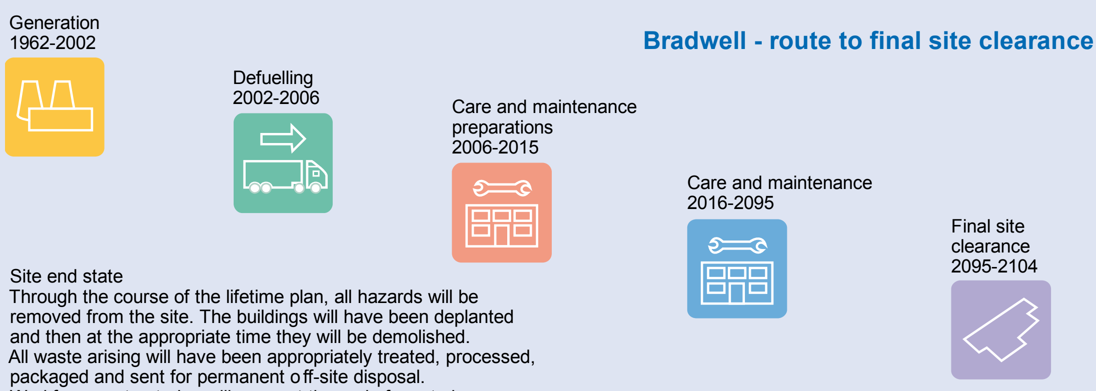
Strategic planning for remediation should be started at the same time as planning for decommissioning as it is an integral part of the process. However, because of uncertainties, the development of a remediation plan is not always straightforward and therefore an adaptive approach is recommended (see Section 3.2.1). Uncertainty is commonly experienced with respect to understanding the source distribution and contaminant behaviour, as well as the response to a remediation action, (see Section 3.2). The key to a successful remediation plan is therefore to make it a living plan, one that is updated in an iterative and adaptive manner during operation, decommissioning and remediation. The use of a living remediation plan, along with a phased approach, means that if the situation deviates from the plan due to new information or due to uncertainty in a particular aspect, the plan can be modified using an adaptive approach, to ensure that the plan considers the revised situation.

Early detection of contamination can prevent the situation from getting worse and hence reduce the scale of the remediation that is required. It is therefore important to think ahead and to have measures in place that will enable any contamination to be identified as early as possible; an example is installing a strategic monitoring network on the site. Thus, the appropriate remediation actions can be put in place promptly if contamination is found. This detection and mitigation approach will be part of the operating plan, but additional strategic measures may be required during the decommissioning phase so this should also be specified in the remediation plan.

One important aspect of planning for decommissioning and site remediation is identification of the waste and material streams and the available waste storage and disposal options. It may be necessary to plan an interim state with a waste store until a waste disposal facility is available. This approach is being taken in Canada, France and the United Kingdom, see Figure 4.1 for example.

Figure 4.1 Exemplary elements of a strategic plan for final site clearance

In the United Kingdom, a care maintenance stage is part of the strategic plan. This is a period of storage of radioactive waste and contaminated structures to allow radioactivity levels to decay and to allow for the development of a disposal facility for intermediate-level waste.



Site end state
Through the course of the lifetime plan, all hazards will be removed from the site. The buildings will have been deplanted and then at the appropriate time they will be demolished.
All waste arising will have been appropriately treated, processed, packaged and sent for permanent off-site disposal.
Workforce restructuring will occur at the end of most phases.

Source: Reproduced from NDA, 2006. This plan is currently under review.

Remediation may involve processes that take place over a long timescale and this adds additional uncertainty (e.g. future site use, remediation timescale) that has to be considered. It is important to understand that uncertainty is always present.

Frequently, several different authorities have a role to play in the development of the remediation plan, e.g. environmental and nuclear authorities, and therefore both environmental and nuclear safety aspects need to be considered and the overall optimum remediation approach selected. Furthermore, there is a strong interface between site remediation, decommissioning and waste management. An overarching strategy that considers these interfaces is very helpful.

There will often be a mixture of conventional (e.g. solvents) and radioactive contaminants, and the situation can change across the site and over time. It is necessary therefore to understand the spatial distribution and temporal evolution of contamination, the dynamics of contaminant transport and the impact of remediation measures.

> Optimisation is searching for the best implementation of remediation plans and alternatives to reach an end state, noting that even the end state is part of the optimisation process.

There can be many reasons for optimising the remediation plan as the decommissioning and remediation progresses (NEA, 2014a). For example, as decommissioning progresses sources of risk are removed so it is possible to modify the amount of monitoring that is done by performing an optimisation study. Another reason for optimising the plan may be that the remediation may be more expensive than originally envisaged. As described in Chapter 3, the site end state itself is part of the optimisation and may need to be amended to minimise the environmental impact of the remediation required to achieve it. Optimisation of the plan can be linked to the series of steps in the remediation journey, e.g. the interim states or milestones: the plan for each step is optimised when the time comes to implement it. As discussed in the CPD report (NEA, 2014a), other important aspects of optimising the plan are prevention of contamination in the design of new plant/systems; asset management; integration with facility management plans and development control; early characterisation; monitoring; and ensuring prompt remediation (where appropriate) thereby minimising the spread of radioactive waste via contamination of land and/or groundwater.

The content of the remediation plan is described in Section 4.1. Further details of important components of the plan (site characterisation, conceptual site model, the integrated approach to decommissioning and remediation, choosing remediation technology options and risk management) are given in Sections 4.2 to 4.6. The adaptive approach to remediation is described in Section 4.7, knowledge management in Section 4.8, prioritisation of remediation in Section 4.10, research and development in Section 4.9, and scheduling of remediation work in Section 4.10.

4.1. Content of the remediation plan

The remediation plan contains details of the remediation actions to be taken and the associated interim states or milestones. It also contains details of the monitoring needed to confirm understanding of the site. A number of different strategic and technical factors are taken into account.

4.1.1. Site description

The remediation plan includes a description of the site and the relationship to other site projects (see Section 4.4), the site history (including events), the results of the radiological and chemical characterisation, the inventory (see Section 4.2), and a description of the conceptual model (see Section 4.3). The groundwater situation and subsurface soils have a great impact on the remediation plan and on the possible end states.

4.1.2. Remediation goals and the strategy for implementing remedial actions

The end states and remediation goals, and the sequence of remediation activities and milestones required to enable the goals to be realised, are an element of the remediation plan. The timescale and prioritisation of remediation actions has to be described (see Section 4.10). These actions address radioactive contamination and other (e.g. chemical) contamination. It also includes measures to deal with unpredictable eventualities (e.g. unexpected cracks and leakages, unexpected location of underground structures or difficult accessibility) since these are of high importance for remediation projects. Key performance indicators are established.

4.1.3. Management system for remediation

The remediation plan must describe:

- the organisational structure;
- quality assurance and document preparation arrangements;
- arrangements for staff qualifications and training;
- a stakeholder engagement plan (see Section 4.6.3);
- work control procedures;
- a project management approach including contract management;
- a knowledge management plan (see Section 4.8).

The work control procedures are the link between the strategic planning level and the work that is undertaken as part of the remediation actions; they are an important instrument that enables the remedial activity to be consistent with the updated i.e. current version of the plan.

4.1.4. Conduct of remediation actions

Technologies and methodologies that will be used for the remediation approach (see Section 4.5) must be specified in the remediation plan. This includes the supporting infrastructure (e.g. treatment plants) as well as measures to prevent spread of contamination and recontamination.

4.1.5. Waste and material management

A description of the waste management and waste classification arrangements that will be applied, including the clearance levels and clearance procedures, is included in the remediation plan. The amount of material and waste is difficult to predict and therefore it is important to be flexible regarding the planned capacities and logistics for the management of materials and waste (see Section 4.5.2).

4.1.6. Financial resources

Good strategic planning needs good cost estimates. The first requirement is an estimate of the likely cost of the planned remediation approach (this is an important factor in determining the remediation strategy). In cases where nuclear site remediation is part of decommissioning, remediation should be considered in the financial reserves set aside for the decommissioning project. In addition, contingency plans and costs should be included. These are obtained by identifying the assumptions underlying the risk assessments that form the basis for the decommissioning and remediation plan, and translating them into contingency plans and costs. Contingency is also required for unexpected contamination: consideration can be given to early release of part of the decommissioning funds to allow remediation prior to transition to decommissioning in special circumstances. Experience suggests that final costs are always a little more than the planned costs so the provision of contingency is important. Storage, transport and disposal are typically the largest portions of the cost of remediating a site. The effort and cost needed to confirm the final site status is a significant contribution and should not be underestimated.

Good practice is to subject cost estimates to independent peer review so that the subsequent discussions will improve understanding of the key issues.

4.1.7. Radiation protection and chemical hazard protection

On many sites, substances with chemotoxic hazards may be present in radioactive waste or may be co-located with radioactive contaminated land. Indeed, radioactive wastes may themselves have adverse chemotoxic properties. The chemotoxic component of radioactive waste or of contaminated land or groundwater has the potential to provide a greater hazard than the radioactivity. As such, the national remediation strategy will expect each site to consider both radiological and non-radiological contaminants.

There is little information available on international approaches to the assessment of contaminated land and disposal of radioactive waste containing both radioactive and chemotoxic substances. The assessment of exposure to multiple contaminants, and synergistic or antagonistic effects relating to the co-location of radioactive and chemotoxic substances, is subject to ongoing studies. The limits and opportunities for harmonisation of assessment of risk to mixtures of chemical contaminants are the subject of discussion by the World Health Organization (WHO, 2009), and examples of approaches to the assessment of exposure to multiple chemicals are available (Kienzler et al., 2014; ITRC, 2015). Work on multiple stressors, including ionising radiation, has been performed for non-human biota (Vanhoudta et al., 2012; STAR, n.d.). There is also uncertainty around the regulatory frameworks and expectations. Thus, in most cases radiological and non-radiological effects are considered independently.

The radiation and chemical hazard protection principles and objectives that will be applied, and the monitoring, control and surveillance that will be carried out, are parts of a remediation plan.

4.1.8. Safety assessment

A description of the safety assessment that demonstrates that the planned remediation activities can be conducted safely for the workers and the public is an integral part of the remediation plan (see Section 4.6.1). The level of detail in the safety assessment should be commensurate with the type of risks and hazards and their potential consequences (following a graded approach). Account should be taken of uncertainty about the state of the site.

4.1.9. Environmental impact assessment

An environmental impact assessment that assesses the discharges during decommissioning and site remediation, and presents the impact of the planned measures to the public and the environment (see Section 4.6.1), is required for planning of decommissioning and remediation. Radiological, other hazards, and nuisance impacts (e.g. noise, vibration, visual, transport) have to be assessed.

4.1.10. Emergency arrangement

The provisions for emergency preparedness (emergency plan and appointment of responsibilities) are described in the remediation plan.

4.1.11. Physical protection

The remediation plan includes a description of physical protection measures (security, responsibilities) and of the main site modifications to ensure physical protection for long-lasting site remediation.

4.1.12. Final radiological and chemical survey

A description of plans for the final site survey and future requirements for monitoring (timescale and extent of survey) is required in the remediation plan.

4.1.13. Implementing planned end state

The planned end state, institutional control requirements and preparations for applications of institutional control and handover to the relevant authority (if necessary) have to be specified in the remediation plan. Possible restrictions on-site use and long-term stewardship monitoring requirements are also described. For some sites it might not be possible to complete remediation for many decades, for example because of timescales for decommissioning. In these cases, the definition of remediation goals (site end states) should take account of associated uncertainties, e.g. uncertainties of site condition (incomplete characterisation), potential changes in societal needs over the decades or potential changes of regulation.

4.2. Site characterisation and determination of the inventory of contaminants

Characterisation of the nuclides and chemical hazards present, the activity concentration of all contaminants and their distribution and movement in the soil and groundwater on the site is key to the appraisal of the problem and development of a remediation plan. This characterisation enables the inventory of radionuclides in the soil and groundwater to be determined, and this inventory is an important component of the site conceptual model (see Section 4.3).

This inventory information is obtained through knowledge of the operational history and through characterisation of the site using one of the many techniques available (NEA, 2014a). An evaluation of the radiological and chemical situation is often not possible until excavation, when contamination may be uncovered, because the contamination routes are subject to a degree of uncertainty. As a consequence the radiological and chemical characterisation has to be considered throughout the overall decommissioning and remediation process.

Before beginning characterisation it is essential to define the objectives and strategies of the characterisation in terms of:

- quality and quantity of data;
- phasing;
- planning;
- health and safety;
- sampling and analysis;
- quality assurance plan;
- data management plan;
- project management.

Sampling, and associated measurements, is a vital element for the assessments of risks, remediation costs, waste storage and the choice of waste routes (disposal, etc.). The aim is to be able to draw up a sound description of the contamination on the site and to select the remediation strategy to be carried out. Sampling carried out at the start of the remediation project defines the initial state of a potentially contaminated zone, informs sentencing during remediation work and in the final stages of a project it contributes to the site release file.

Characterisation takes time and is resource expensive so it is important to use resources efficiently. It is important to make sufficient measurements and to take sufficient samples, but to avoid duplicative or overly precise data (see data quality objectives [DQO] process). Typical site characterisation efforts use a graded approach that starts with the historical site assessment. This is an investigation to collect existing information describing a site's complete history (including events) from the start of site activities to the present time, its functions and any existing data. This information may, or may not, be already available. It is used to determine the type of characterisation programme that is required. A poor historical and functional analysis (due to a very limited amount of documents for a very old site, for example) results in a more extensive characterisation campaign. Many tools exist to enable the optimum characterisation plan to be developed (NEA, 2014a). In many cases, the site is divided into zones in order to be able to take the required decisions with a reasonable confidence level.

The characterisation plan should be developed at an early stage but will be refined as new areas become accessible during decommissioning and remediation activities. An example of this occurred for a German research site with underground storage structures for solid and liquid waste, which had been used for collecting the effluents and wastes from the reactors. The soil was contaminated not only near the surface, but also at depth, e.g. because of leakage of underground pipes. The remediation plan described an approach where concrete structures are left in the ground after radiological clearance and this plan was followed for a storage structure for solid waste. However, for a retention basin for radioactive waste water, the complete removal of the basin structures was necessary because of unexpected detection of conventional toxic substances (polycyclic aromatic hydrocarbons), which could enter the local groundwater. Hence, the remediation plan had to be optimised to include the several thousand cubic metres of soil that were excavated and then required radiological clearance measurements to be carried out before it could be used for subsequent backfilling of the excavation.

> An evaluation of the contamination of underground structures is not always possible before excavation and stepwise decontamination of the structures.

There are already a number of national and international groups that provide guidance on characterisation (e.g. the Infrastructure Transitions Research Consortium [ITRC], SAFEGROUNDS, UK Nuclear Decommissioning Authority [NDA] group, US Environmental Protection Agency [EPA], ISO). The Environmental Radiation Survey and Site Execution Manual (EURSSEM, http://eurssem.eu/) has been developed to provide a consistent consensus approach and guidance for the conduct of all actions at radioactively contaminated and potentially radioactively contaminated sites and/or groundwater up to their release for restricted or unrestricted (re)use. Further international discussions to consolidate this good practice guidance would be beneficial. The *Multi-Agency Radiation Survey and Site Investigation Manual* (MARSSIM) (EPA, 2000a) is the most used approach (sometimes with local adaptations) for final (verifying) characterisation surveys.

The DQO process (see Figure 4.2) is a series of planning steps based on the scientific method for establishing criteria for data quality and developing survey designs (EPA, 1994, 1987a and 1987b). This is often used for the planning of the characterisation phase. The level of effort associated with planning is based on the complexity of the survey. Large, complicated sites generally receive a significant amount of effort during the planning phase, while smaller sites may not require as much planning effort.

Planning site characterisation using the DQO process can improve the survey effectiveness and efficiency, and thereby the defensibility of decisions. It also can minimise expenditure related to data collection by eliminating unnecessary, duplicative, or overly precise data. The use of the DQO process ensures that the type, quantity, and quality of environmental data used in decision making will be appropriate for the intended application. It provides systematic procedures for defining the criteria that the survey design should satisfy, including when and where to perform measurements, the level of decision errors for the survey, and how many measurements to perform.

Figure 4.2 Data quality objectives process

The DQO process consists of seven steps:

Step 1. State the problem.

Step 2. Identify the decision (goals of the study).

Step 3. Identify inputs to the decision (information inputs).

Step 4. Define the study boundaries.

Step 5. Develop decision rules.

Step 6. Specify limits on decision errors.

Step 7. Optimise the design for obtaining data.

At the international scale, a very varied approach for site characterisation is observed. Geostatistics is one of several tools that can help to reduce the uncertainties, particularly during characterisation.

4.3. The conceptual site model

A good conceptual site model (CSM) is required to give confidence in remediation decision making, and can be an important tool in stakeholder involvement. It facilitates a common understanding of the site, and models of the site, enabling evaluation of the strategic options.

According to American Society for Testing and Materials standards (ASTM, 2014), a CSM is "a written or pictorial representation of an environmental system and the biological, physical, radiological and chemical processes that determine the transport of contaminants from sources through environmental media to environmental receptors in the system".

The information gained through the site investigation is used to characterise the physical, biological, radiological and chemical systems existing at a site. The processes that determine contaminant releases, contaminant migration, and environmental receptor exposure to contaminants are described and integrated in the CSM.

Development of the CSM is critical for describing potential exposure routes (for example, ingestion and inhalation) and for evaluating possible effects of the contaminants on human health and the environment. Uncertainties associated with the CSM need to be identified clearly so that efforts can be taken to reduce these uncertainties to acceptable levels. Early versions of the CSM, which are usually based on limited or incomplete information, will identify and emphasise the uncertainties that should be addressed. A case study is presented in Annex G.

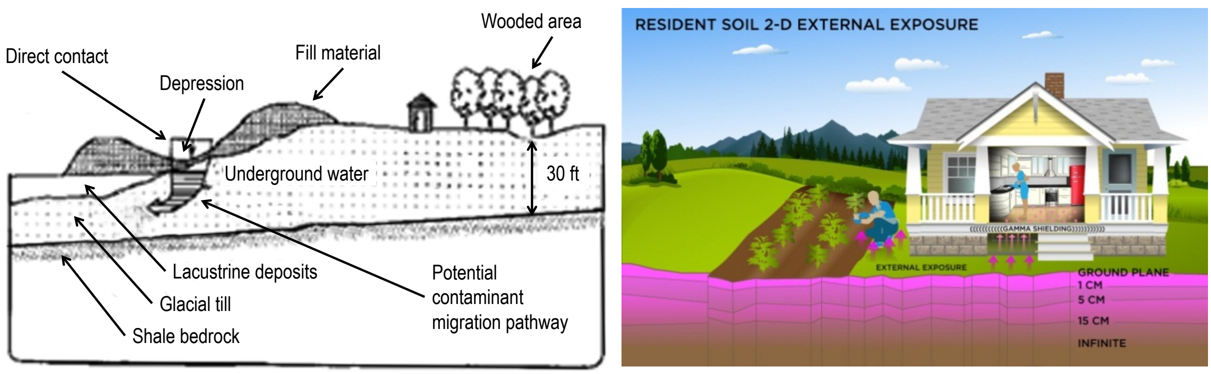
A preliminary CSM can, and should, be developed prior to the beginning of any intrusive site investigations. This can be undertaken as soon as an understanding of the physical layout of a site, as well as its historical land-use information, has been obtained, and should ideally form part of the initial site history review.

Although its complexity will be at least partly dependent on the scale and complexity of the site, each CSM should address several fundamental areas:

- site definition and background information (e.g. geology and hydrogeology);
- sources of contamination and contaminants of potential concern;
- sensitive receptors, including the presence of designated ecological sites;
- migration pathways and exposure routes.

In some cases a good CSM can eliminate the need for additional investigations if it shows that the source-pathway-receptor linkage is broken e.g. exposure does not occur.

Figure 4.3 Examples of conceptual site models



Source: EPA.

The level of detail incorporated in the CSM can vary, from a high-level picture (e.g. Figure 4.3) to detailed process models. In some cases, it may be useful to describe the site and factors that affect contaminant fate and transport by listing features, events, and processes (FEPs) that are important to consider as part of a systematic understanding of the site and for design of mitigation measures. Good practice is to involve stakeholders in development of the CSM, together with their technical experts, to get good dialogue on the CSM and deeper understanding. Five potential purposes for a conceptual site model are summarised below:

- Depiction of the site, remediation/mitigation measures, monitoring systems, and key elements affecting remedy/mitigation selection, implementation, and performance. An important element of a conceptual site model is showing the spatial relationships of site infrastructure, monitoring systems, and remediation/mitigation measures in relation to the key hydrogeologic system features. A geographic information system (GIS) is a typical and useful means of organising this information. This type of conceptual site model depiction is primarily useful for communication and to organise the site data.

- Baseline contamination and risk assessments. Exposure pathway descriptions and/or diagrams are used as an initial high-level visualisation of a site to support risk assessments and to identify the focus for remediation efforts.

- Systematic understanding of the site and factors affecting contaminant fate and transport. A high-level description of the important system components is a key communication tool that helps describe a systematic understanding of the site and factors affecting contaminant fate and transport. In addition, this type of conceptual site model is a starting point from which more detailed aspects of the conceptual site model and associated numerical modelling or mitigation measure design efforts can be identified and put into context.
- Identification of characterisation and monitoring data needs. CSMs can be used to map known information and identify any characterisation data gaps. CSM elements can be depicted in block diagrams, as a list of FEPs, or in a "cartoon" diagram. Available data can then be compared with data needs to identify potential data gaps. Approaches are discussed in an NEA radiological characterisation report (NEA, 2013). Using codified standards and guidance is good practice. It is important to understand the credibility of the approach. Good practice is to use the DQO process to identify key conceptual site model elements, available data, and data gaps (EPA, 2006: 7-8). Other structured approaches can be equally valid but they generally have less credibility.
- Compilation of information in support of a numerical model configuration. Numerical models require information to set boundary and initial conditions, and to spatially configure subsurface flow and transport parameters. Three-dimensional hydrogeologic models generated from interpolation of site borehole data are a common approach to generating a numerical model grid. Hydrogeologic units are identified with their corresponding flow and transport properties. The hydrogeologic model and supporting information coupled with descriptions of boundary and initial conditions are important for communicating the way in which the site is represented for contaminant migration simulations.

4.4. Integrated approach to decommissioning and site remediation

On some operating sites there will be ongoing operations, decommissioning and remediation all occurring at the same time. An additional consideration when remediating on an operating site is the safety case aspect: remediation can be difficult as it is still necessary to maintain the operating safety case functions.

Decommissioning tasks are fundamentally different from operational tasks. Rules and procedures for site operations are intended for facilities that are built to last and for processes that are intended to work for a long time whereas in decommissioning the facility or process does not have to run forever. Operating sites' rules and procedures will have to be amended to allow decommissioning to proceed effectively and efficiently.

A master plan is needed to drive the priorities on an operating or partially operating site otherwise operational considerations will dominate and remediation will only be opportunistic and potentially inefficient. An example is to reroute services to allow the part of the site originally providing the services to be decommissioned. The master plan must also consider the necessity to protect subsurface structures still required for the operating facilities from damage, e.g. by covering of buildings and protection of cables and pipes during excavation works.

Many sites have old and new installations on the same site, managed by the same operator. Different licences may be held by the same organisation: one for operation and one for decommissioning. Often operational purposes (e.g. electricity generation) are viewed as more important than decommissioning, although not always e.g. at Sellafield. Clearly identifying the area to be remediated, and defining it as a separate zone from the operating zone, can improve the management of the remediation process.

In the United Kingdom, the entire site is licensed under one nuclear site licence and different areas or zones may be operating or being decommissioned.

Although there may be a clearly defined remediation area on an operating site, remediation and operational staff are often from same organisation. There may be two different managers, each responsible for the relevant operating or decommissioning licence present on the same site. Some specialists, e.g. radiation protection staff, may be centralised under the employer and part sent to each area. In other sites, for instance in Italy, all services are common, but operate under two different licences. The work activities may be totally different in the different areas and, hence, classification of the areas is different and physical protection measures can vary. The regulator is usually the same organisation for both the operating part of the site and the decommissioning part of the site, but supervision may be performed by different departments of the regulator.

The decommissioning site may be a hosted site, in other words the decommissioning area is effectively a guest on an operating site, e.g. in France at Chinon. Decisions will then go through the host governance system and this will add another layer of management to environmental remediation issues.

In the establishment of remediation plans for sites undergoing decommissioning it is important to implement an integrated approach to decommissioning and site remediation rather than to consider them as separate stages (IAEA, 2009). Non-integrated approaches may result in decommissioning end points that have ignored the overall aims of site remediation – particularly with respect to the potential impacts on human health and the environment from any residual contamination after the facility itself is decommissioned. These oversights can be costly in terms of site remediation – particularly with respect to the ability to:

- remediate surface and subsurface contamination while the decommissioning workforce is still mobilised and the project management infrastructure is in place;
- use existing site infrastructure that is required to support remedial actions (liquid and solid waste processing facilities and other “enabling” facilities);
- realise potential revenues from reusing parts of the site early by remediation to a “fit-for-purpose” end point when a particular facility is decommissioned, as opposed to waiting for all facilities to be decommissioned before remediating the entire site so that it can be reused.

Further, the completion of facility decommissioning activities without consideration of the site remediation goals can, in some circumstances, result in degraded environmental conditions (e.g. enhanced contaminant mobility), resulting in increased remediation requirements and possibly rendering some site reuse options non-feasible (in turn resulting in potential revenue losses).

4.5. Selection of remediation technology options

This section discusses strategic considerations and lessons learnt for the selection of the appropriate remediation technology option(s), including aspects of storage and disposal of waste. It also gives three examples of different approaches that have been taken.

Remediation technology options include:

- Excavation/retrieval of the contaminated material and disposal off-site, or in a disposal facility elsewhere on-site (dig and dump).
- Characterisation, sorting and segregation of the material after excavation (including clearance of excavated material). Segregation may be required because of non-radiological aspects of the material e.g. organic fraction.

- *In situ* disposal (e.g. installation of a cover system).
- *In situ* treatment – for soil remediation (e.g. solidification/stabilisation, soil flushing, phytoremediation or electrokinectics) and groundwater remediation (e.g. pump and treat systems or permeable reactive barriers).
- Monitored natural attenuation.

These options are also supported by monitoring.

4.5.1. Selection of remediation approach

Sustainability, and environmental and radiation protection principles imply that it is important to consider a wide range of factors, not just the risks to human health, when selecting the overall remediation approach and the remediation end state (see Section 3.4). Factors affecting the choice of the optimum remediation technology, include the volume of contaminated material, the accessibility of the contaminated material, the presence or absence of a local population, the exposure pathways and the level of contaminants present. Following a sustainable remediation approach, the waste generated by a remediation technique and the waste management implications also need to be explicitly addressed, together with wider social and economic issues.

In selecting the technical option or combination of options, the goal is to adopt best practice and the following are important strategic considerations:

Factors that should be taken into account in selection of the remediation technique (IAEA TECDOC 1086, Vienna, 1999):

- the ability of the technology to reduce or avert risk to the health and safety of the public and to the environment (e.g. performance);
- the reliability and maintenance requirements for the technology;
- the associated cost of implementing the technology;
- the infrastructure available to support the technology;
- the ease of accessing the technology and associated services (e.g. availability);
- the risk to workers and public safety during the implementation of the technology;
- the environmental impacts of the technology;
- the ability of the technology to meet regulatory acceptance;
- the ease of obtaining community acceptance of the technology.

Even though the technology selected will, in most cases, be site specific, the NEA CPD (NEA, 2014a) and IAEA offer some general guidance about which technologies tend to be suitable in certain situations (IAEA, 2014). Detailed guidance on remediation technologies is available, see References.

4.5.2. Waste management and disposal

The waste management programmes of many countries include a variety of storage and disposal concepts, which have an influence on remediation planning. Generally, the more hazardous the waste is, in terms of radioactivity and chemical toxicity, the more rigorous the storage and disposal requirements are. The national waste management context is important and may mean that it is necessary to adapt the approach to managing land, e.g. spending more money in clean-up or disposal. This is a strategic question at national level.

Storage and disposal facilities are available in most countries and it is important to plan to use them, and feedback requirements into the national infrastructure. An example is the UK's 2007 low-level radioactive waste (LLW) policy (Defra, 2007), which is based on the waste management hierarchy described in the Waste Framework Directive (EU, 2008), and introduces a range of waste management and disposal options for LLW.

Most countries dispose of remediation waste in near-surface facilities. The range of disposal facilities includes conventional landfill sites and purpose built disposal sites. These facilities can be also used for non-radioactive wastes. If a disposal facility is not available, wastes are managed in an interim storage facility until disposal is available. Most European countries have national radioactive waste inventories and national radioactive waste management plans (EU, 2011). The inclusion in these national inventories of accurate estimates of volumes of contaminated land that may need to be managed as radioactive waste in the future represents good practice. This allows for integrated waste management planning.

Even if disposal facilities are available, other factors may need to be considered when deciding if remediation wastes have a disposal route:

- site location and distance to a disposal facility (proximity principle);
- facilities serving the site and disposal facility (rail, truck, vessel);
- types of waste (not radioactive, mixed chemical and radioactive waste, LLW, intermediate-level waste [ILW]);
- volume of waste;
- properties of the waste (physical characteristics, hazardous/non-hazardous characteristics);
- appropriate permits and licences in place at the disposal facility to accept the waste;
- timing and status of disposal facility approval;
- local and national policies.

Storage, transport and disposal are typically the largest portions of the cost to remediate a site. Costs are generally driven by the first five factors listed above. Savings can be realised by minimising the volume of waste to be disposed of through characterisation, sorting, clearance and segregation, i.e. by applying the waste management hierarchy. Where available disposal space is sufficient and facilities accept a wide range of wastes, with little need for segregation, the amount of waste segregation and handling can be reduced, resulting in greater worker safety and less costs.

The remaining three factors listed above can, however, be the deciding criteria for whether the waste can be disposed of. They can be the most difficult to define and can pose the most risk to schedule and costs.

If a country does not have disposal facilities available, remedial activities that generate large quantities of waste may have to be postponed or it may be necessary to store the wastes in temporary storage facilities (as in Germany). In Canada for example, large-scale remediation of old waste sites has been delayed until disposal facilities are available (see Section 4.5.3).

A special challenge is managing the logistics for the accruing soil and concrete masses which, experience shows, often exceed the amount planned for. The quantity of radioactive waste and residual material that has to be handled may be greater than was originally envisaged. The limited capacities of waste sentencing and clearance measurement devices and interim storage facilities, and the limited availability of transport can cause considerable delay and/or additional costs.

The cost effectiveness of storage vs disposal, and the effectiveness of decay storage in reducing radioactive waste disposal volumes should also be considered in order to obtain the most sustainable approach, i.e. the approach that gives the overall best solution taking due account of the availability of resources, safety, environmental and ethical aspects.

Clearance, the removal of radioactive material or waste originating within authorised practices from any further regulatory control that is applied for radiation protection purposes, is an important concept that can be applied to waste and materials from remediation in many countries. Waste and materials can be considered for clearance if they have activity concentration levels that represent acceptable (low) radiological risks in all conceivable circumstances. The material remains within the radiation protection regulatory control until the decision on clearance is made. Non-radiological properties are still to be considered when deciding on the potential disposal or reuse of the waste or material that has been cleared. Various terms are used in different member states to describe this concept, e.g. “free release”, “out of scope”, and internationally agreed sets of clearance levels exist (EU, 2013; IAEA, 2014). Specific clearance, e.g. clearance for a specific process (recycling) or disposal route (landfill), may also be specified and corresponding specific clearance levels may be applied.

4.5.3. Examples of remediation approaches

Four examples are given below to illustrate the range of approaches.

a) Taking the long-term view

In Canada, where final disposal facilities are not available, Canadian Nuclear Laboratories (CNL) has taken the strategic approach to delay the large-scale remediation of many of the contaminated areas on the Chalk River Laboratories (CRL) site. Ongoing monitoring is in place to detect any changes in conditions and risk assessment has determined that current conditions do not pose a risk to human health and that the risk to the environment (on the CRL site) is small and manageable. In some instances, CNL has proceeded with near-term remedial activities where higher risks are present (i.e. radioactive liquid wastes stored without secondary containment). In these situations CNL has addressed the liquid component of the waste but often left the waste burial structure and any associated solid waste in place to be remediated in the future with other similar solid wastes nearby. This saves on interim radioactive waste storage space and takes advantage of efficiencies during the large-scale recovery/processing and final disposal stage. It also avoids double handling of wastes. In making the decision to leave contaminant source areas in place, CNL must manage the environmental impact of groundwater plumes emanating from the source areas. Both pump and treat systems and passive reactive barrier systems are used on the CRL site. This is an example of taking a long-term view of remediation.

At many former legacy nuclear mine and mill sites in Canada, especially in Northern Canada, logistical difficulties may prevent the efficient, large-scale transfer of waste materials to an off-site receiving facility. Under these circumstances, the majority of waste materials must be managed on-site through various engineered means; with the possibility of removal of minimal amounts of hazardous waste materials leaving site for off-site disposal.

b) Sustainable approach

Recently, in the United States at the Savannah River site, the US Department of Energy (DOE) has transitioned from the standard pump and treat systems to an innovative, passive, enhanced attenuation remedial approach. The original pump and treat systems were proving unsatisfactory in meeting environmental management programme needs, and local regulatory requirements, for both effectiveness and cost. The new passive system works with the natural geology and groundwater flow at the site, with some minor engineering of the flow system, and replaces the continuous pumping and treating operation with a once a year injection of the chemicals forming the reactive barrier to stabilise the contaminants in place. This is an example of a sustainable approach, using a passive system that uses less energy.

c) Integrated with waste management

As discussed above, national strategies for waste management and site remediation should be integrated. The same need exists at a site-level. An important aspect is therefore to pursue appropriate ways to minimise the wastes to be generated by the remediation process, taking account of the overall optimisation of the remediation activities and the wider sustainability factors discussed earlier. Minimising waste volumes will reduce transport requirements, thereby limiting any consequent environmental impact, as well as the total costs associated with contaminated material management. According to the IAEA (2001), the main elements of a waste minimisation strategy can be grouped into four areas: source reduction (keep the generation of radioactive waste to the minimum possible or practicable), prevention of contamination spread (contain it as much as possible), recycle and reuse valuable components from existing and potential waste streams, and waste management optimisation. This is consistent with the waste management hierarchy shown in Figure 2.1.

d) Reuse of excavated material

In Italy, recent remedial work on solid waste trenches has used a combination of remedial approaches. Sampling of the cover soil and screening against clearance levels has enabled the reuse of suitable soil in the backfilling of the trenches. The waste material itself and soils not meeting the clearance level have been collected and transferred to an interim storage facility. The sampling of the cover soil reduces the volume of material that must be moved to and stored in the interim storage facility. This combination of approaches considers the availability of waste disposal facilities and also demonstrates waste minimisation principles.

4.6. Risk management

Risk management is the process of identifying, evaluating, selecting, and implementing actions to reduce risk to human health and to ecosystems. The goal of risk management is scientifically sound, cost-effective, integrated actions that reduce or prevent risks while taking into account social, cultural, ethical, political, and legal considerations (EPA, 1997). Often, individuals associated with risk management decisions come from different entities that may have different perspectives on the definition of risk and on clean-up.

Other risks, for example programme risks, should be considered so that mitigating actions can be prepared. These programme risks include the consequences from the unexpected findings as a result of the uncertainties present, for instance the uncertainties that may arise from, or associated with, the characterisation results. Other programme risks exist, for example the risk of losing funding. This is – among others – an area where IAEA has an ongoing project, International Project on Decommissioning Risk Management (DRiMa), due to finish at the end of 2015.

4.6.1. Risk assessments

Risk assessment is an organised process used to describe and estimate the likelihood of adverse health outcomes from environmental exposures. The four steps are hazard identification, dose-response assessment, exposure assessment, and risk characterisation (EPA, 1997). The use of risk assessment in the clean-up process depends on the regulatory agency, regulatory programme, purpose of the risk assessment, and phase of the project.

The risk assessment evaluates the potential health effects and environmental impacts from the situation. In the case of site remediation it has two main purposes: firstly to understand the situation at the start of the remediation process, and secondly, to understand the residual risk after implementation of each option. There are three main components: the risk assessment for the contamination in the absence of any remediation option being implemented (initial risk assessment), the risk assessment for the proposed remediation option (option risk assessment), and the risk assessment for the situation after the remediation option has been implemented (residual risk assessment). The initial risk assessment uses the conceptual site model (see Section 4.3) to identify the likelihood of potential health effects or ecological impacts arising from the contamination. The option and residual risk assessments identify the impacts and benefits arising from implementing the remediation option. These three aspects are then used in the optimisation study to identify the remedial option which leads to the overall optimum result.

There may be remedial options that have such negative impacts on the environment (e.g. groundwater) that they are not justified and should be discounted.

The risk assessment is reviewed and updated when new data are available or the conceptual model changes, as part of an iterative process.

Different options will have different levels of uncertainty associated with them and it is important to identify this and present them openly to enable well-founded decisions to be made. The risk assessment should therefore acknowledge the uncertainties present and make an attempt to address them. This could be by systematic uncertainty analysis or sensitivity analysis to identify which parameters have the most influence on the risk results. This analysis can be made using single values of the parameters, giving a single value of risk, or using ranges, giving a distribution of risk values. There are many ways of dealing with uncertainties in decision making, such as taking a conservative approach to identify key parameters, or taking small steps to try to resolve the uncertainty and hence refine the risk assessment.

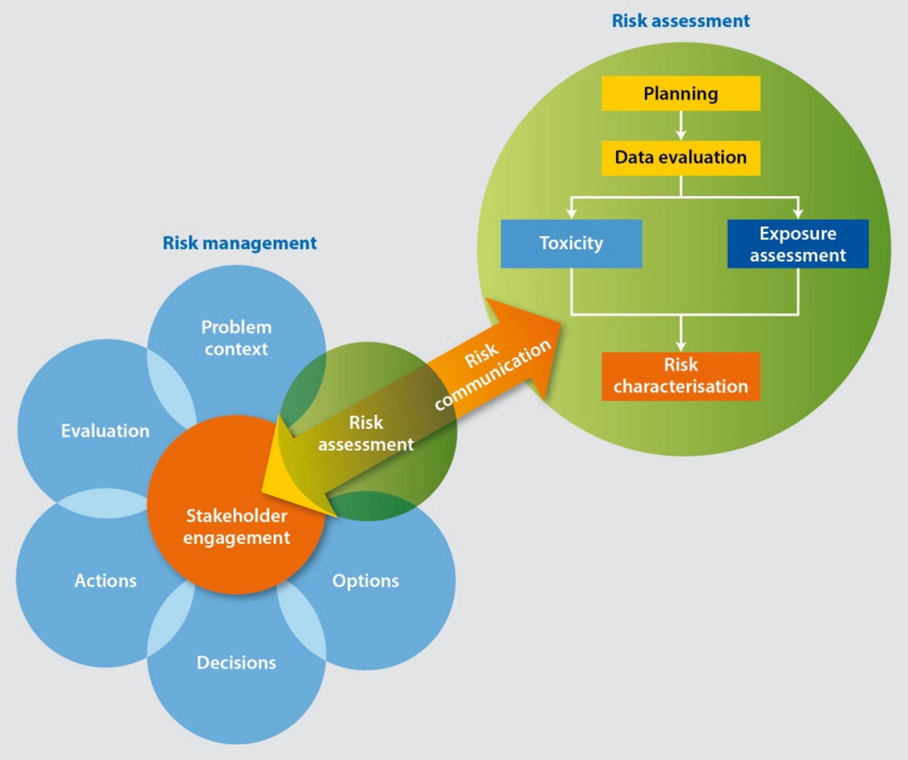
The radiological risk assessment can be used to calculate the dose or radiological impact from the activity concentration. It can also be used to determine activity concentrations corresponding to a given dose or risk criterion. In real life both approaches will be used.

It is also important to consider other conventional contaminants (toxic substances) that are present and to perform risk assessments for them too. Common examples are asbestos, oils and polychlorinated biphenyls (PCBs). There are many risk assessment methodologies, models, and guidance documents available (see References).

4.6.2. Risk characterisation

Risk characterisation provides an understanding of the results of the risk assessment. The risk characterisation integrates information from the risk assessment and synthesises an overall conclusion about risk that is complete, informative and useful for decision makers (EPA, 2000b). The challenge of the risk characterisation is refining the data gathered and clear communication of the key findings and the context of those findings (ITRC, 2015).

Figure 4.4 Using risk assessment to inform risk management



Source: Adapted from EPA, 1997.

4.6.3. Risk communication

Risk communication is the formal and informal process of communication among and between regulatory agencies and organisations responsible for site assessment and management, and the various parties who are potentially at risk from or are otherwise interested in the site (the stakeholders).

It is very important both to identify the stakeholders and to start meaningful engagement with them early on in any remediation project. In many jurisdictions, stakeholder engagement and the duty to consult are legally mandatory. It may also be worthwhile considering integration of stakeholder knowledge into the project.

Involvement of stakeholders for remediation projects should give attention to the site (e.g. planned measures and end state), as well as related waste management (e.g. transport and storage). Stakeholder engagement on a waste management issue may lead to a review of the remediation plan to take into account the new information. An example could be the importance of a particular radionuclide or method of transport which may lead to a change in the transport and storage requirements for waste generated during the remediation.

As stated earlier, stakeholder involvement is a basic requirement of any decision-making process. It is not a one-off occurrence but a continuous process that must take place throughout the lifetime of the project. However, typically stakeholder involvement is focused at decision points where a number of options need to be evaluated and therefore it is important that they understand the context of the decision. To ensure stakeholder involvement is effective, the decision maker needs to be informed by the views of the stakeholder, while the stakeholders need to have confidence that their input is considered, and has and effective and demonstrable impact on the decision-making process.

4.7. Adaptive approach to remediation

> Adaptive management of remediation would include implementing remedy decisions for approaches that maintain protectiveness (e.g. institutional controls, targeted actions for exposure pathways), reduce future risk, and provide information to evaluate subsequent actions. This leads to a series of interim endpoints.

Remediation is itself a multi-phased activity consisting of identifying the problems, gathering information in order to make decisions about how to solve the problems, planning and carrying out the remediation project that will solve the problem, and verifying and documenting that the solution has in fact been achieved (NEA, 2014a). Many solutions may not have a defined end time as they may require monitoring or care and maintenance for an extended period of time, or even in perpetuity.

A single remediation project may not lead to a final remedy that fully meets remediation goals, as suggested by EPA's Groundwater Road Map (EPA, 2011); the EPA's Groundwater Remedy Completion Strategy (EPA, 2014); and the US National Academy of Sciences (NRC, 2013). Thus, some sites may need to consider whether sequences of remediation steps are appropriate. In this case the steps in the process can be adaptive to account for changing conditions and improved understanding as additional data about the site are obtained, for example, through remedy implementation and monitoring (e.g. NRC, 2003).

The sequences of steps may also reflect the different requirements for the contaminated land (and groundwater) over different timescales, for example clean-up to be suitable for a specific use of the land in the near future and for unrestricted use of the land at a later stage.

This adaptive approach leads to a series of **interim endpoints**. In this context, an interim endpoint is an intermediate remediation target or an intermediate point on the path to an ultimate end state. The advantage of using an adaptive approach with interim endpoints is that it enables uncertainty to be taken into account. A structured approach may facilitate planning, optimisation and the determination of end states for nuclear site remediation. An interim endpoint enables the establishment of a path for clean-up that may include intermediate remedial milestones and transition points and/or regulatory alternatives to standards-based remediation. Interim endpoints must be scientifically and technically defensible and based on systematic, objective understanding of the contamination issue and impact of proposed solutions.

A crucial aspect when planning an environmental remediation project is to begin with the end state in mind. As such, it is essential to determine the preferred end use(s) or future use(s) of a site, and the destination of material that will be removed from the site, early in the planning stages of a remediation project. This will help the key participants to form a clear understanding of the project, avoiding unnecessary processes and activities. The resulting collaborative and iterative process facilitates communication among different stakeholders and allows remediation practitioners to achieve regulatory goals and maximise the integration of sustainability parameters during the remediation process (Holland et al., 2011). However, not all sites can have clear preferred end or future uses determined in the early stages of planning and in these cases an iterative collaborative process must be maintained to balance the value of the remediated site options against the emerging technical and financial challenges of achieving them.

The gap between the end state and the existing conditions will guide what remedial actions should be taken.

4.8. Knowledge management

4.8.1. Records management

Preserving information is critical to knowledge management given the complexity and long time frames over which remediation can take place. Key information for long-term retention should be identified early in the process. Key information should include explicit official company records as well as tacit information in the form of personal knowledge and experiences or data that is not formalised and captured as records.

Key information to keep in the records:

- general project background;
- remedial design and configuration;
- construction and commissioning of facilities;
- operations, events and accidents;
- health, safety and environmental information;
- licensing, legal or other governing documents;
- final site status information;
- waste storage and disposal.

For long-term remediation, the method of record capture is important as it determines the usefulness of the record in the future. Over time, record keeping methods change, and the number of knowledgeable personnel decreases along with the opportunities to capture the knowledge of the remediation experience.

In the United States, three sets of key records have been identified: records that are essential for planning the remediation activities, records that are generated during the remediation process itself, and records that are generated after remediation is complete. These records are collected in a project data package that contains a high-level summary of the key results, lessons learnt and other documents and events in the life of the completed project. Data records generated after remediation is complete may include data collected to demonstrate regulatory compliance or monitoring data associated with long-term stewardship. The DOE Legacy Management Business Centre (LMBC) (formerly known as the LM Records Storage Facility) in West Virginia contains up to 150 000 cubic feet of non-classified records from the Cold War nuclear legacy. The records are accessible to researchers, former contractor employees, and other authorised persons both in on-site records research facilities and via an electronic record keeping system.

At CNL in Canada, federal regulations require nuclear facilities to maintain records after receiving a licence to abandon the facility. An information management group has been established to implement the strategy for the long-term preservation of decommissioning and environmental remediation information. In addition to the company-wide database, a customised database for decommissioning, environmental remediation and waste management provides easy and quick access to key information, including photographs, historical records and external sources of information.

On behalf of the UK government, the NDA are setting up the National Nuclear Archive in a purpose built facility at Wick in Scotland. The facility will provide long-term storage of records and other archive material from civil nuclear sites in the United Kingdom.

The most common challenges for records and information management are:

- late realisation of the need to start compiling key records to support remediation;
- loss of institutional records (and institutional knowledge) critical to the success of the remediation process;
- inability to access records owing to changes in records-storage technology;
- maintaining duplicate records in at least two separate secure locations;
- the definition and identification of records that constitute the project data package to document the process used for the successful completion of the remediation project;
- records where the quality, completeness and integrity of the information is compromised.

4.8.2. Qualified personnel

It is important to ensure that people with the appropriate skills and experience are available when needed. Continuity of staff is particularly important for planning of remediation and there are advantages in using internal personnel. In addition, it is important to have a strategic approach to ensuring that the correct standards and guidance are being used and to keep them up to date. The long timescales involved in decommissioning and site remediation (which can extend beyond the working life of a single individual) mean that it is important to have a strategic approach to managing the training and availability of suitably qualified personnel, and the maintenance of knowledge of all periods of the remediation project.

The IAEA recognises the loss of nuclear knowledge as a threat to future nuclear programmes. The IAEA supports information management internationally by:

- maintaining a nuclear knowledge portal that integrates existing nuclear data and information bases in the IAEA as well as in member states;
- promotion of networking of institutions for nuclear education and training;
- developing guidance documents on the preservation of nuclear knowledge;
- designing and implementing outreach activities to improve general knowledge;
- implementing targeted preservation of knowledge projects;
- expanding the International Nuclear Information System (INIS) by providing online access to documents.

4.9. Research and development

Sites, particularly complex sites, occasionally present a remediation problem which has no currently available solution. The solution may be at an early stage of technical development, or there may be knowledge gaps that have been identified and need to be filled before a remediation option, or set of options can be selected. Research may also be necessary to improve the effectiveness of existing techniques, to transfer techniques from different settings and to introduce innovative approaches that deliver step changes in effectiveness and efficiency. Hence, it is important to have a structured approach to identifying the state of technical readiness and an approach to keeping the status under review, see for example the NDA's Research and Development Strategy (NDA, 2011) and Guide to Technological Readiness Levels (NDA, 2014).

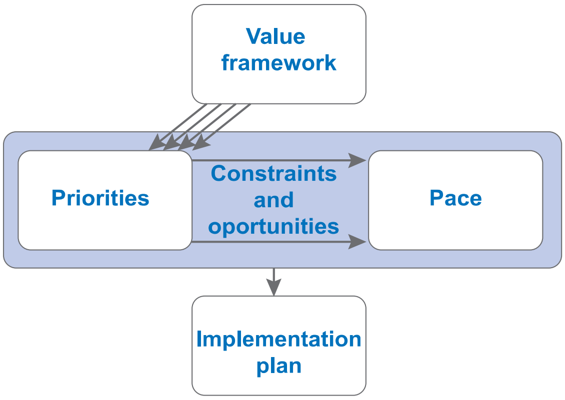
It is also important to ensure that funding is available to undertake the necessary research and development in order to finalise the choice of remediation option. Failure to implement a strategic approach to maintaining research and development funding and commitment will lead to difficulties in achieving the planned remediation solution. The NEA CPD on nuclear site remediation (NEA, 2014a) and the NEA report on research needs for decommissioning (NEA, 2014b) both give an overview of research priorities for environmental remediation.

4.10. Prioritising remediation

The remediation plan describes a series of activities and the scheduling of these activities is informed by the ranking or ordering of these activities according to agreed criteria or factors. In some cases prompt remedial action may be necessary but in most cases whether and when remediation should be undertaken will need to be balanced with other priorities, the views of stakeholders on end use, and the risks to people and the environment. For example, the potential harm from an inventory may drive the priority attached to specific projects, with greatest hazards being identified for earliest remediation. Other influencing factors may be accessibility, the availability of appropriate staff and the availability/throughput of the waste management route. It is often difficult to set the scheduling of different actions in advance because of unexpected contamination that occurs or is found during decommissioning. As described earlier, the remediation plan should be integrated into the decommissioning plan and should adapt to new information as the decommissioning progresses. In the United Kingdom, the concept of "pace and priority" has been developed to formalise the decisions on scheduling and to aid communication of the factors which influenced the decisions, see Figure 4.5 and Annex F.

In Canada, in the province of Saskatchewan, much of the prioritisation for remediation planning focuses on turning a uranium site back to provincial jurisdiction for entry into an institutional control programme (ICP). Conceptual planning, operational decommissioning planning, decommissioning design, progressive decommissioning and reclamation (operating sites), and monitoring are all conducted strategically with the end goal of handing the site back to provincial government control. Much of the priority for remediation is determined by the proponent of the sites. It is in the proponent's best interest to remediate their site as efficiently as possible in order to divest the properties back to the province and recover any monetary guarantees.

Figure 4.5 Pace and priority (UK approach to prioritisation)



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5. Discussion, conclusions and recommendations

5.1. Discussion

The following observations were made during the discussions related to the preparation of this report:

- The term "remediation" can be used in a generic sense, as is done in this report, to describe clean-up actions designed to reduce the impact of contaminated land and groundwater on humans and the environment to acceptable levels. However, it is increasingly being used in a more specific sense, namely to address situations where widespread contamination has occurred as the result of an accident or in the case of an unregulated or abandoned nuclear site: this is the sense in which it is now used by the International Atomic Energy Agency (IAEA). This type of situation corresponds to the International Commission on Radiological Protection (ICRP) concept of an "existing exposure situation". The IAEA uses the term "clean-up" for sites undergoing decommissioning, not "remediation", since this corresponds to the ICRP concept of a "planned exposure situation" and the radiological criteria that are applied to the two different situations are different, though they both require optimisation. Therefore, it is important that the context and meaning of the term remediation is made clear.
- Clean-up levels for an abandoned nuclear site or a site contaminated as the result of an accident will be different to those for sites being decommissioned since the balance of benefits and impacts will be different.
- It is important that environmental and radiological principles are fully integrated and embedded in national policy and guidance.
- Prevention is generally better than cure, and good practice is to have a comprehensive multi-barrier approach to control radioactivity. However, as plants age, weaknesses in design, events or poor operation will result in potential issues with contamination of groundwater and land. Preventative action, enabling a problem to be identified and acted upon early, is good practice since experience shows that it reduces the environmental and safety risks and also the overall remediation costs.
- Ensuring funding is available for preventative action is essential. This can be an initial amount that will grow with time. There are recognised issues of pressures on available funding from other high-priority activities. Consideration should be given to early release of part of the decommissioning funds to allow remediation prior to transition to decommissioning in special circumstances.
- Any remediation action has associated environmental, social and economic drawbacks and benefits, both in the short term and in the long term. Sustainable remediation is a holistic approach to remediation that considers these wider impacts and aims to balance net effects. Sustainable remediation also simultaneously encourages the reuse of remediated land and enhanced long-term financial returns on investments. Though the potential benefits are enormous, there is often a lack of awareness regarding the methods for selection and implementation of sustainable remediation options.

- Outcome or performance-based regulation offers advantages over more prescriptive approaches in many cases. In some cases, prescriptive clean-up levels are leading to remediation solutions that cannot be considered as sustainable since they create unnecessary waste management burdens that are transferred to other locations.
- Good decision making depends on early and continuous engagement with the affected stakeholders and on considerations concerning future stakeholders. Experience from the United States suggests that it is good practice for stakeholders to appoint their own trusted technical representatives. There should be funding arrangements to take into account such factors, and site operators/owners should consider funding experts as they help local communities place the environmental risks in context, challenge assumptions and inform optimised remediation solutions.
- Waste management needs to be integrated in both decommissioning and remediation planning. Storage, transport and disposal of waste are typically the largest portions of the cost to remediate a site. The waste management hierarchy will influence remediation decisions, and waste disposal options will need to be planned. In some cases, there will be institutional control of land and disposal facilities on the same site. Consideration will need to be given to ensuring the integrated protection of people and the environment, recognising the differences in hazard from the two sources.
- Remediation starts at the definition of the problem. Indeed, identifying that there is a problem can be the first problem. It would be useful to collate case studies of how site authorities first realised they had groundwater problems and the actions that were taken. This will help site authorities ensure that they understand the potential vulnerabilities, and refine conceptual models and groundwater monitoring arrangements.
- An adaptive approach provides flexibility that in turn allows a sustainable remedial option to be achieved and prompt decisions to be made.
- To follow a sustainable remediation approach, it is helpful to think in terms of “end states” rather than simply in terms of “end uses”. An end state describes the remedial goal in a more holistic way, e.g. it considers the characteristics of the site and of the affected off-site areas following the clean-up, environmental restoration and waste management actions, as well as the end use. Following the holistic, sustainable approach, the end state should protect people and the environment (including groundwater) from radioactive and non-radioactive (e.g. chemical) contamination, taking into account wider social and economic factors. Thus, for a particular land use, several possible end states may be considered. These alternative end states should be assessed and the sustainable option selected.
- Remediation does not necessarily imply removal of all contamination if that is not the sustainable approach. On complex or more contaminated sites it is also helpful to consider interim end states, and also to divide the site into zones.
- Determination of the sustainable option requires assessment against appropriate performance indicators. Some sustainability performance indicators are suggested in this report (Annex C), but there is an opportunity for these to be developed further through exchange of experience in sustainable remediation. In determining the sustainable option, long-term institutional control may or may not be considered as an undue burden for future generations, depending on the exact circumstances.
- Where contamination levels are low, it will be practicable to reach early agreement with stakeholders on interim and final end states for these sites, which allow early

and preventative remediation. On some sites where contamination levels are higher and there are uncertainties over subsequent use of the site, it is more problematic. A zoning approach may provide more flexibility. Narrowing down the potential or credible future uses will also allow earlier interim state agreement.

- Long-term institutional controls contain inherent risks. A proposed land use change that takes place in the future may mean that it will be necessary to achieve higher levels of clean-up before this change is possible. "Trusts" could also be proposed allowing land owners to consider new uses of land due to pressures resulting from scarcity or local needs, or allowing for remediation if monitoring shows that modelling assumptions were misleading.
- Clean-up levels for sites that are being decommissioned are risk-based and vary from country to country. This is not a problem within sustainable remediation systems as many site remediation solutions are site-specific and influenced by local stakeholders. Hence communication of clean-up levels and the reasons for the different levels is important.
- Remediation is an integral part of decommissioning, but on many sites it has been left to the end of the decommissioning process. It is vital that remediation be integrated into the decommissioning plan at an early stage (see Section 4.4).
- A master plan is needed to drive the priorities on an operating or partially operating complex site so that remediation work can progress in a timely manner, following the principles of sustainability (see Section 4.4). The remediation plan is a flexible, living document that can be adapted to revised situations. It is supported by the site's conceptual model and the safety assessment, both of which are developed in an iterative manner and are updated when new data is available.
- The long timescales in remediation projects mean that strategic planning is required to ensure that appropriately trained and knowledgeable staff, together with the relevant information, are available at the appropriate times. Once remediation is completed, maintaining of knowledge on the site over the long term may be required. Hence, knowledge management and the maintaining of knowledge applies both during the remediation project and after the remediation project has been completed. Key information to be maintained over the long term should be identified early in the remediation process. Information on methods for records management and access should be shared so that lessons can be learnt.

5.2. Conclusions

This report introduces and promotes the concept of sustainable remediation of contaminated land and groundwater in the context of the decommissioning of nuclear sites. It uses the term "remediation" in the generic sense, referring to actions to reduce the impact of the contamination on people and the environment.

Remediation of contaminated land and groundwater is often left until the end of the decommissioning process. However, as illustrated in this report, it is not the best approach as remediation should be integrated into the decommissioning plan at an early stage. It would be useful to collate case studies of how site authorities first realised that they had groundwater problems and the actions that were taken to address these problems. This will help site authorities ensure that they understand potential vulnerabilities, and refine conceptual models and groundwater monitoring arrangements.

Any remediation action has associated environmental, social and economic drawbacks and benefits, both in the short term and in the long term. Sustainable remediation is a holistic approach to remediation that considers these wider impacts, and aims to balance the net effects. Sustainable remediation also simultaneously encourages the reuse of remediated land and enhanced long-term financial returns on investments. Though the potential benefits are enormous, there is often a lack of awareness of methods for selection and implementation of sustainable remediation options. This report identifies important principles and approaches related to sustainability, describes the decision framework and gives some examples of sustainable remediation projects.

Following a sustainable remediation approach will mean that it is not always optimum to remove all contamination or to clean up sites to be fit for any use. The optimal remedial approach may be to include administrative controls (long-term stewardship) to break the pollutant linkage. Management arrangements need to be made to ensure that these controls are reviewed periodically.

Examples of sustainable approaches to the remediation of contaminated land resulting from industries other than the nuclear industry could provide useful lessons learnt.

An adaptive approach provides the flexibility that allows a sustainable remedial option to be achieved and prompt decisions to be made.

Regulators need to ensure adequate flexibility in regulation to allow the most sustainable approach to be taken. Regulators could, for example, review the various approaches to achieving safety and environmental protection goals, including those for the different industries. A case study approach and sharing of experience could be facilitated using the IAEA web portal CONNECT. CONNECT is a web-based platform that enables collaboration and sharing of information and experience between IAEA network participants, whether within or among networks. The IAEA networks include the International Decommissioning Network (IDN), the Environmental Management and Remediation Network (ENVIRONET), the Nuclear Knowledge Management Network (NKM) and the International Low Level Waste Disposal Network (DISP).

Remediation of radioactive contamination on nuclear sites should, as far as reasonably practicable, be consistent with approaches to the management of non-radioactive contaminants in land and groundwater, management of off-site contamination and waste disposal.

Good examples exist of sustainable nuclear site remediation across many countries. However, substantial challenges remain for remediation of large and complex sites where many different facilities have existed and various processing activities have taken place. Some countries have relatively straightforward remediation challenges, but the increasing pressures on disposal facilities and increasing stakeholder interest means that careful strategic planning is required. The development of performance indicators for the assessment of the sustainable option is at a very early stage, and it is recommended that these are developed further through the exchange of experience in sustainable remediation between countries.

International fora, such as the NEA or the IAEA, have an important role to play in promoting the exchange of information and experience in nuclear site remediation, and will continue to be useful sources of recommendations for good practice and further research and development. It is recommended that organisations promoting nuclear decommissioning conferences and seminars introduce sessions on the remediation of contaminated land and groundwater at nuclear sites to ensure increased awareness on strategic and practical considerations. This will encourage operators to integrate the remediation plan with the decommissioning plan and lead to optimised solutions.

Many nuclear sites contain a mixture of radioactive and chemotoxic substances in contaminated land or groundwater, and therefore consideration of the effects of multiple contaminants is required. The assessment of exposure to multiple contaminants is the subject of ongoing studies and an internationally agreed approach has not yet been developed. It is therefore recommended that the NEA organise a conference to address the risk assessment of such radioactive and chemical contaminant mixtures.

The Task Group on Nuclear Site Restoration has provided participating countries with a valuable opportunity to discuss the remediation (clean-up) of land and groundwater contaminated by radioactive materials on nuclear sites, and to identify strategic considerations and good practice. There are many topics that would benefit from further consideration, for example: the integration of site remediation, facility decontamination/clearance levels and on-site disposals; the derivation of site clean-up levels; *in situ* disposal of foundations and facilities; and consideration of both chemical and radiological risks. A long-term strategic approach to the lifecycle design and operation of nuclear facilities could also be developed that takes into account waste management, decommissioning and site remediation, as well as the reuse of sites. It is recommended that the task group continue in the future to provide a forum for exchange of information on the remediation of land and groundwater and to develop guidance on some of the topics listed above.

5.3. Recommendations

This report introduces and promotes the concept of sustainable remediation of contaminated land and groundwater in the context of the decommissioning of nuclear sites and makes some recommendations, including the following:

- Integration of remediation of contaminated land and groundwater into the decommissioning plan at an early stage. Drafting of a collation of case studies on how site authorities first realised that they had groundwater problems, and the actions that were taken to address these problems.
- A review by regulators of the various approaches to achieving safety and environmental protection goals, including those applied in non-nuclear industries. A case study approach and sharing of experience could be facilitated using the IAEA web portal CONNECT.
- The development of performance indicators for the assessment of sustainable options through the exchange of experience in sustainable remediation between countries, building on good examples of sustainable remediation existing across many countries.
- The development of a long-term strategic approach to the lifecycle design and operation of nuclear facilities, which takes into account waste management, decommissioning and site remediation, as well as the reuse of sites.
- The introduction of the remediation of contaminated land and groundwater at nuclear sites as specific topics in conferences and seminars addressing nuclear decommissioning. This will ensure increased awareness on strategic and practical considerations.
- The organisation of a conference on the risk assessment of radioactive and chemotoxic contaminant mixtures as the first step in the development of an internationally agreed approach. The NEA or the World Health Organization could be suitable host organisations.
- The continuation of the Task Group on Nuclear Site Restoration, initially established by the NEA Co-operative Programme on Decommissioning (CPD), to provide a forum for exchange of information on the remediation of land and groundwater, along with further consideration of topics identified in this report, and development of guidance and good practice.

Annex A. Glossary

Definitions (except those marked*) are taken from *IAEA Safety Glossary: 2007 Edition* and/or *IAEA Radioactive Waste Management Glossary: 2003 Edition*.

Accident	Any unintended event, including operating errors, equipment failures and other mishaps, the consequences or potential consequences of which are not negligible from the point of view of protection or safety.
Activities	Include: the production, use, import and export of radiation sources for industrial, research and medical purposes; the transport of radioactive material; the decommissioning of facilities; radioactive waste management activities such as the discharge of effluents; and some aspects of the remediation of sites affected by residues from past activities.
Authorisation	The granting by a regulatory body or other governmental body of written permission for an operator to perform specified activities. Authorisation could include, for example, licensing, certification or registration. The term authorisation is also sometimes used to describe the document granting such permission. Authorisation is normally a more formal process than approval.
Clean-up	Actions taken to reduce the level of contamination in soil and groundwater in the context of decommissioning of nuclear facilities. See *remediation*.
Clearance level*	A value, established by a regulatory body and expressed in terms of activity concentration and/or total activity, at or below which regulatory control for radiation protection purposes may be removed from a source of radiation.
Contamination	Radioactive substances on surfaces or within solids, liquids or gases (including the human body), where their presence is unintended or undesirable, or the process giving rise to their presence in such places.
Conceptual model or conceptual site model (CSM)	A set of qualitative assumptions used to describe a system.
Decommissioning	Administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility (except for a repository or for certain nuclear facilities used for the disposal of residues from the mining and processing of radioactive material, which are “closed” and not “decommissioned”).

Data quality objectives*
These are an established set of qualitative and quantitative criteria, including acceptable tolerance levels, to specify the quality and quantity of data necessary to support a given decision (e.g. conformance with acceptable clearance screening levels). ANSI/HPS N13.12-2013, 6 May 2013 "Surface and Volume Radioactivity Standards for Clearance".

Environmental assessment*
Assessment of the dose(s) to an individual or group of people from radionuclides in the environment. Can also include assessment of doses to non-human biota. An environmental assessment model is a type of model specifically designed to address questions formulated in the context of an environmental assessment. Environmental assessment models are usually less complex mathematically than models used as tools in research (NCRP Report N. 123).

Exposure
The act or condition of being subject to irradiation. Exposure should not be used as a synonym for dose. Dose is a measure of the effects of exposure. Exposure can be divided into categories according to its nature and duration or according to the source of the exposure, the people exposed and/or the circumstances under which they are exposed.

End state
A predetermined criterion defining the point at which a specific task or process is to be considered completed. Used in relation to decommissioning activities as the final state of decommissioning.

End use
A desired use of the site after the End state has been achieved. One end state may have multiple end uses, likewise multiple end states may have the same end use.

Facility
Includes: nuclear facilities; irradiation installations; some mining and raw material processing facilities such as uranium mines; radioactive waste management facilities; and any other places where radioactive material is produced, processed, used, handled, stored or disposed of – or where radiation generators are installed – on such a scale that consideration of protection and safety is required.

Institutional control
Control of a radioactive waste site by an authority or institution designated under the laws of a state. This control may be active (monitoring, surveillance, remedial work) or passive (land use control) and may be a factor in the design of a nuclear facility (e.g. near-surface repository). *i)* Most commonly used to describe controls over a repository after closure or a facility undergoing decommissioning. *ii)* Also refers to the controls placed on a site that has been released from regulatory control under the condition of observing specified restrictions on its future use to ensure that these restrictions are complied with. The term institutional control is more general than regulatory control (i.e. regulatory control may be thought of as a special form of institutional control). In particular, institutional control measures may be passive, they may be imposed for reasons not related to protection or safety (although they may nevertheless have some impact on protection and safety), they may be applied by organisations that do not meet the definition of a regulatory body, and they may apply in situations which do not fall within the scope of facilities and activities. As a result, some form of institutional control may be considered more likely to endure further into the future than regulatory control.

Interim end point	A predetermined criterion defining the point at which a specific task or process is to be considered completed, that marks a level of progress towards the end state.
Knowledge management	An integrated, systematic approach to identifying, managing and sharing an organisation's knowledge and enabling groups of people to create new knowledge collectively to help in achieving the organisation's objectives. In the context of management systems, knowledge management helps an organisation to gain insight and understanding from its own experience. Specific activities in knowledge management help the organisation to better acquire, record, store and utilise knowledge. The term "knowledge" is often used to refer to bodies of facts and principles accumulated by humankind over the course of time. Explicit knowledge is knowledge that is contained in, for example, documents, drawings, calculations, designs, databases, procedures and manuals. Tacit knowledge is knowledge that is held in a person's mind and has typically not been captured or transferred in any form (if it were, it would then become explicit knowledge). Knowledge is distinct from information: data yield information and knowledge is gained by acquiring, understanding and interpreting information. Knowledge and information each consist of true statements, but knowledge serves a purpose: knowledge confers a capacity for effective action. Knowledge for an organisation is the acquiring, understanding and interpreting of information. Knowledge may be applied for such purposes as: problem solving and learning; forming judgements and opinions; decision making, forecasting and strategic planning; generating feasible options for action and taking actions to achieve desired results. Knowledge also protects intellectual assets from decay, augments intelligence and provides increased flexibility.
Long-term monitoring	1. The measurement of dose or contamination for reasons related to the assessment or control of exposure to radiation or radioactive substances, and the interpretation of the results. Includes environmental monitoring. The measurement of external dose rates due to sources in the environment or of radionuclide concentrations in environmental media. 2. Continuous or periodic measurement of radiological or other parameters or determination of the status of a structure, system or component. Sampling may be involved as a preliminary step to measurement.
Naturally occurring radioactive materials (NORM)	Material containing no significant amounts of radionuclides other than naturally occurring radionuclides. The exact definition of "significant amounts" would be a regulatory decision. Materials in which the activity concentrations of the naturally occurring radionuclides have been changed by human made processes are included. These are sometimes referred to as technically enhanced NORM (TENORM).
Optimisation	Measures for improving the operation of an ongoing remediation taking into account hazard reduction, security, safety, environmental and socio-economic and costs. Optimisation may be carried out using a structured decision-making process such as MAUA or more qualitative approaches.

Pace* Rate at which decommissioning/remediation is progressed and resulting start and end dates.

Remediation Any measures that may be carried out to reduce the radiation exposure from existing contamination of land areas through actions applied to the contamination itself (the source) or to the exposure pathways to humans.

The term is used here to represents the generic remedial actions that can be applied to nuclear sites that are undergoing decommissioning. IAEA now use the term “remediation” only to refer to sites that are contaminated as a result of an accident, an unregulated site or abandoned site, reserving the term “clean-up” for nuclear sites undergoing decommissioning. Hence the term “remediation” in this report is synonymous with the IAEA term “clean-up”. Remediation does not necessarily imply complete removal of the contamination or returning the site to its background conditions, something that may be neither practicable nor necessary. Other terms that are sometimes used include site clean-up, decommissioning, and restoration. Long-term stewardship may also be considered as a remediation action.

Remediation plan* Planning for remediation is an integral part of decommissioning planning. The remediation plan is a living document, one that is updated in an iterative manner during decommissioning and remediation.

Risk assessment* An evaluation of the risk to human health or the environment by hazards. Risk assessments may look at either existing hazards or potential hazards. This will normally include consequence assessment, together with some assessment of the probability of those consequences arising. EPA Radiation Glossary (www.epa.gov/radiation/glossary/term qr.html#r).

Site* A licensed or regulated location that includes one or more *i)* facilities designated for the use of radioactive materials or radiation generating devices or *ii)* radiologically controlled or restricted areas. ANSI/HPS N13.12-2013, 6 May 2013 “Surface and Volume Radioactivity Standards for Clearance”.

Legacy sites* Sites on which radioactive materials have been left or where contamination occurred due to activities in the past, and for which there is no longer any operator or the former operator cannot any longer be held responsible for remediation. In general the state has taken over responsibility from previous operators.

Annex B. Advantages and disadvantages of different regulatory systems

The main text discusses the fact that the regulatory system can influence whether it is straightforward to follow a sustainable remediation approach. For example, a prescriptive approach specifying unrestricted use can force unsustainable remediation by requiring removal of everything from the site. The advantages and disadvantages of a prescriptive system and a performance-related system are given in the following tables.

Table B1: Advantages and disadvantages of a prescriptive regulatory system

Advantages	Disadvantages
• Rules are clearly set out in legislation/regulation. • Operator requirements for internal inspections, audits and monitoring are clearly described in legislation, regulations, standards and guidelines. • Regulatory inspectors have a clear set of rules by which to evaluate an operator's compliance. • Progressive enforcement rules are clearly defined. • The system generally has a formal mechanism for appeal	• A significant level of operator effort is required to understand requirements. • A significant level of operator effort and funds is required to satisfy requirements. • It often applies "one rule fits all" criteria that may not be appropriate for all operations. • There is limited flexibility for operators to suggest alternatives to meeting the intent of a legislated requirement. • Regulatory inspectors have limited flexibility when evaluating operator compliance, which can lead to a frustrating and adversarial interaction between the operator and the regulator. • Progressive enforcement escalates quickly and may not allow adequate time for an operator to come into compliance. • Because of the clearly defined rules, appeals are generally not successful.

Reproduced from the 2013 IAEA report, *Overcoming Barriers in the Implementation of Environmental Remediation Projects*.

Table B2: Advantages and disadvantages of a performance-based regulatory system

Advantages	Disadvantages
• Rules set out in legislation/regulation are generally less detailed than in a prescriptive system. • Operator requirements for internal inspections, audits, monitoring, etc., can be developed in operation-specific licences (permits). • Regulatory inspectors have significant flexibility by which to evaluate an operator's compliance. • There is increased flexibility for operators to suggest alternatives to meeting the intent of a requirement. • Progressive enforcement escalates slowly, which generally allows adequate time for an operator to come into compliance. • There is generally a less formal mechanism for appeal.	• The system requires more understanding on the part of the operator to be able to interpret the intent of the rules. • It may require more effort on the part of the operator to develop the operation-specific licences (permits). • Regulatory inspectors may have limited internal guidance by which to ensure consistency of regulatory oversight. • Operators who have multiple facilities may encounter significant differences in how inspectors evaluate compliance. • Progressive enforcement rules are less clearly defined. • Because the rules are often less clearly defined, appeals may be successful where an operator can show that their efforts meet the "intent" of the rules

Reproduced from the 2013 IAEA report, *Overcoming Barriers in the Implementation of Environmental Remediation Projects*.

Annex C. Sustainability principles and indicators

In 1992, the UN defined 27 key principles of sustainable development and the UN General Assembly has subsequently developed sets of sustainable development goals covering a broad range of sustainable development issues (including ending poverty and hunger, improving health and education, making cities more sustainable, combating climate change, and protecting oceans and forests). The most recent set of goals was agreed in September 2015, and are described in the 2030 Development Agenda titled "Transforming Our World" (UN, 2015).

The key principles have remained unchanged since 1992 and those that apply to remediation are presented in Table C1. The concepts of **conserving natural resources,** improving **energy efficiency** and the **waste hierarchy** also reflect these principles in that it is better to avoid or reduce the consumption of finite raw materials and to avoid or reduce the generation of waste.

Table C1: UN principles of sustainable development relevant to site remediation

Sustainable development principle number	Title	United Nations description	Commentary
2	Prevention	States have … the sovereign right to exploit their own resources pursuant to their own environmental and developmental policies, and the responsibility to **ensure that activities within their jurisdiction or control do not cause damage to the environment** of other states or of areas beyond the limits of national jurisdiction.	It is clearly better to prevent pollution occurring at all than to have to remediate after the fact. This principle is more relevant to new nuclear facilities than to closed facilities.
3	Intergenerational equity	The right to development must be fulfilled so as to equitably meet developmental and environmental **needs of present and future generations**.	When considering restricted use the needs of present generations to reuse land and those of future generations to have choice about the use of land will need to be balanced.
4	Environmental protection	In order to achieve sustainable development, **environmental protection shall constitute an integral part** of the development process and cannot be considered in isolation from it.	Emphasises the need to integrate planning for decommissioning and environmental remediation.
7	Conserve, protect and restore ecosystems	States shall co-operate in a spirit of global partnership to **conserve, protect and restore the health and integrity of the earth's ecosystem**. …… The developed countries acknowledge …. the pressures their societies place on the global environment and of the technologies and financial resources they command.	Remediation needs to take account of the needs of people and biota.

Table C1: UN principles of sustainable development relevant to site remediation *(cont'd)*

Sustainable development principle number	Title	United Nations description	Commentary
9	Use best available knowledge	States should co-operate to strengthen endogenous capacity-building for sustainable development by **improving scientific under-standing** through exchanges of scientific and technological knowledge, and by **enhancing the development, adaptation, diffusion and transfer of technologies**, including new and innovative technologies.	This NEA report contributes to nuclear site sustainable remediation capacity.
10	Involvement of citizens	**Environmental issues are best handled with the participation of all concerned citizens**, at the relevant level …. shall facilitate and encourage public awareness and **participation by making information widely available**. Effective access to judicial and administrative proceedings, including redress and remedy, shall be provided.	The report emphasises the need to encourage the participation of stakeholders in remediation decision making.
13	Liability and compensation	States shall develop national law regarding **liability and compensation for the victims of pollution and other environmental damage**. States shall also co-operate … to develop further international law regarding liability and com-pensation for adverse effects of environmental damage caused by activities within their jurisdiction or control to areas beyond their jurisdiction.	See earlier discussion on policy and principles.
15	Precautionary	In order to protect the environment, **the precautionary approach shall be widely applied** by states according to their capabilities. Where there are threats of serious or irreversible damage, **lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation**.	In the face of uncertainty a cautious approach should be taken. The pre-cautionary principle therefore encourages the use of the best available techniques. This principle is particularly relevant to old sites where contamination has occurred and prompt actions should be taken to protect the environment.
16	Polluter pays	National authorities should endeavour to promote the internalisation of environmental costs and the use of economic instruments, taking into account the approach that **the polluter should, in principle, bear the cost of pollution**, with due regard to the public interest and without distorting international trade and investment.	The polluter is therefore expected to pay for all the necessary remediation. Some counties may decide to be more flexible and provide subsidies or grants to reduce polluter liability.

Sustainable approaches to remediation that provide a net benefit to the people and the environment involve:

- minimising or eliminating energy consumption or the consumption of other natural resources;
- reducing or eliminating releases to the environment;
- harnessing or mimicking a natural process rather than engineering against nature;
- reusing land and application of the waste management hierarchy to reuse or recycle waste materials, with due consideration of radiation protection.

There could be two stages in identifying the sustainable approach: a discussion about the most sustainable site end state and then a discussion about what is the most sustainable remediation approach. Planning, actions and resources dedicated to remediating a site should align and add value to the preferred end use(s) or future use(s) from the inception of the project.

Sustainability indicators

Many opportunities exist within the remediation industry to integrate sustainability parameters (Butler et al., 2011) as a way to generate higher value. Although fewer opportunities exist for generating value from incorporating sustainability parameters later in the remediation project, value can still be derived from integrating sustainability parameters at any phase.

A starting point for sustainability indicators for remediation will be a balanced selection of performance questions. Once the questions are established practitioners and stakeholders can collaborate on indicators that are site specific. It is recommended that the selection of appropriate, site-specific indicators (including metrics) is an iterative collaboration between the remediation practitioner and stakeholders throughout the remediation process to ensure that the metrics reflect critical outcomes and future site use.

Below we set out some considerations that will help this process:

- Overall net benefit.
- Consumption of energy or natural resources – what are the potential impacts on energy or resources?
- Harnessing natural processes rather than engineering against them.
- Application of the waste management hierarchy.
- Cost effectiveness.
- Adaptive approach.
- Application of best available knowledge.
- Reducing or eliminating releases to the environment (from the site and any waste management processes associated with the remediation actions).
- Remediation of the environment.
- Reuse of land.
- Groundwater quality.
- Graded approach.

- Polluter pays.
- Prevention of contamination – what is the level of confidence that contamination will be avoided now and in the future?
- Early action to identify potential problems: are contingency arrangements in place to ensure prompt corrective action can be taken? Is there a risk-based prioritisation of unavoidable burden transferred to society to ensure the most pressing problems are addressed?
- Risks to health from radioactive and non-radioactive materials and waste.
- Prompt action to prevent environmental degradation.
- Reducing reliance on human actions.
- Stakeholder participation.
- Social equity or intragenerational equity: will society realise an equitable benefit or exposure to risk?
- Intergenerational equity – how to ensure that a broad perspective of stakeholder values are incorporated into decisions that may have longer-term implications and potential transfer of burden?
- Long-term stewardship.
- Dealing with uncertainty.
- Durability of the solution.

References

Butler, P.B. et al. (2011), "Metrics for integrating sustainability evaluations into remediation projects", *Remediation*, Vol. 21, p. 81-87, www.sustainableremediation.org/library/guidance-tools-and-other-resources/Metrics-20290_ftp.pdf.

UN (2015), "Transforming Our World: the 2030 Agenda for Sustainable Development", A/RES/70/1, https://sustainabledevelopment.un.org/post2015/transformingourworld.

Annex D. Country-specific example: United States

The majority of decommissioning activities in the United States occur in two sectors: facilities licensed by the Nuclear Regulatory Commission (NRC) or agreement states and sites that come under the purview of Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), including Department of Energy (DOE) and Department of Defense (DOD) sites.

This section discusses the federal regulatory framework and policies relevant to site clean-up of radioactive contamination being addressed under CERCLA. Clean-up activities may occur under other statutes such as the Atomic Energy Act (AEA).

Clean-up standards under CERCLA and the National Contingency Plan

Under CERCLA, the Environmental Protection Agency (EPA) has primary responsibility for implementing a key US law providing broad authority for clean-up of hazardous waste sites. Other federal and state agencies may have the lead for response actions conducted under CERCLA at a particular site. Congress established the Superfund Program in 1980 to, among other things, locate, investigate, and clean-up the worst hazardous waste sites nationwide. First published in 1968, the National Contingency Plan (NCP) is the federal government's blueprint for responding to both oil spills and hazardous substance releases. It was broadened to cover releases at hazardous waste sites requiring emergency removal actions following the passage of Superfund legislation in 1980.

Radioactive contamination is generally addressed in the same manner as other hazardous substances at CERCLA sites and normally should follow the same remedy selection process. EPA provides guidance for addressing radiologically contaminated sites that is consistent with its guidance for addressing chemically contaminated sites, taking into account the technical differences between radionuclides and chemicals. The EPA guidance has been developed to facilitate clean-ups that are consistent with the NCP at radiologically contaminated CERCLA sites.

DOE-owned and -operated or NRC-licensed facilities are generally subject to those agencies' authorities under the AEA. EPA's involvement under CERCLA in decommissioning facilities normally arises as part of clean-up actions designed to address contamination at a site. The general manner in which sites, including facilities, follow the CERCLA clean-up process is described in this section.

Clean-up process under Superfund

Generally, response actions under CERCLA are either removal or remedial actions. Removal actions are generally short-term response actions taken to abate or mitigate imminent and substantial threats to human health and the environment. They may be classified as emergency, time-critical or non-time-critical, and often primarily address surface or soil contamination. In comparison, remedial actions are generally longer term (and hence less time-sensitive), do not pose an imminent threat to human health and the environment, and are usually more costly than removal actions. Further, federally funded remedial actions can be taken only at sites on EPA's National Priority List (NPL), unless the site is a federal facility. Removal actions may be used to address some threats at remedial sites. The Superfund remedial clean-up process typically begins with site discovery or notification to EPA of possible releases of hazardous substances, pollutants, or contaminants. Sites may be discovered by various parties, including citizens, state agencies, and EPA Regional offices. Once discovered, sites that are to be addressed by the CERCLA remedial process are entered into the Comprehensive Environmental Response, Compensation, and Liability Information System (CERCLIS), EPA's computer system used to track potential and confirmed hazardous waste sites brought to the attention of the EPA Superfund Program. EPA then typically evaluates a site through steps in the Superfund clean-up process. Other federal and state agencies may have the lead for response actions conducted under CERCLA at a particular site. The steps of the Superfund clean-up process are as follows:

- Preliminary assessment/site inspection (PA/SI) – investigations of site conditions and surrounding area to determine whether a site poses a threat to human health and the environment.
- Hazard ranking system (HRS) – screening mechanism using information obtained by EPA during the PA/SI to determine whether a site should be placed on the NPL.
- NPL – list of the most serious sites identified for possible long-term clean-up.
- Remedial investigation/feasibility study (RI/FS) – detailed study of the nature and extent of contamination, associated risks to human health and the environment, and clean-up alternatives.
- Record of decision (ROD) – selection of a clean-up alternative to be used at the site.
- Remedial design/remedial action (RD/RA) – preparation and implementation of plans and specifications for achieving site clean-up.
- Construction completion – the date on which all components of the remedy are operational and functional.
- Post-construction completion – long-term stewardship to ensure that Superfund response actions provide for the protection of human health and the environment, which may include long-term response action, operation and maintenance (O&M), institutional controls, five-year reviews, remedy optimisation (RO), and NPL deletion.

Releases that require immediate or short-term response actions are addressed under the emergency response programme of Superfund.

Preliminary remediation goals

Generally, preliminary remediation goals (PRGs) under the NCP are developed as risk-based concentrations, usually derived from standardised equations combining exposure information assumptions with EPA toxicity data. Normally, they are considered by EPA to be protective for humans (including most sensitive groups) over a lifetime. However, these risk-based PRGs may not always be used at a particular site.

Generally, PRGs should be established using a risk level of 10^{-6}. PRGs are identified early in the CERCLA process and may be modified as needed at the end of the remedial investigation or during the FS based on site-specific information from the baseline risk assessment. Ultimately, a preferred alternative with protective remediation levels should be selected through the use of the nine NCP remedy selection criteria.

PRGs generally can be used to screen sites and as initial clean-up goals in appropriate circumstances. PRGs are not designed to serve as *de facto* clean-up standards and should not be applied as such. PRGs can be used in site screening to help identify areas, contaminants, and conditions that do not require further federal attention at a particular site. Generally, at sites where contaminant concentrations fall below PRGs, no further action or study is warranted under Superfund so long as the exposure assumptions at a site match those taken into account by the PRG calculations. Chemical concentrations above the PRG do not automatically designate a site as "dirty" or trigger a response action. However, exceeding a PRG suggests that further evaluation of the potential risks that may be posed by site contaminants is appropriate. PRGs are also useful tools for identifying initial clean-up goals at a site. In this role, PRGs can provide long-term targets to use during the analysis of different remedial alternatives. By developing PRGs early in the decision-making process, project managers may be able to streamline the consideration of remedial alternatives.

A detailed discussion of PRG tools for risk assessment is provided in Annex E.

The hazard index

To help assess the potential for cumulative non-carcinogenic effects posed by multiple contaminants, EPA has developed a hazard index (HI). Generally, the HI is derived by adding the non-cancer risks for site contaminants that have the same target organ or mechanism of toxicity. When the HI exceeds 1.0, there may be concern for adverse health effects due to exposure to multiple contaminants.

Combining radionuclide and chemical risk

Excess cancer risk from both radionuclides and chemical carcinogens should be summed to provide an estimate of the combined risk presented by all carcinogens. Exceptions would be cases in which a person cannot reasonably be exposed to both chemical and radiological carcinogens. Similarly, the chemical toxicity from uranium should be combined with that of other site-related contaminants in calculating the HI.

There are generally several differences between cancer slope factors (the cancer risk [e.g. proportion affected] per unit of dose used in EPA's Integrated Risk Information System chemical files) for radionuclides and chemicals. However, similar differences also occur between different chemical slope factors. In the absence of additional information, it is reasonable to assume that excess cancer risks are additive for purposes of evaluating the total incremental cancer risk associated with a contaminated site.

"To-be-considered" materials (TBCs)

TBCs generally include criteria, advisories, guidance, and proposed standards that are not legally enforceable but contain information that may be helpful in determining the level of protectiveness in the remedy selection and implementation process. Because TBCs are not applicable or relevant and appropriate requirements (ARARs), their identification and use are not mandatory.

Guidance outside the risk range

Guidance that provides for clean-ups outside the risk range (greater than 10^{-4}) is generally not consistent with CERCLA and the NCP and should not be used to establish clean-up levels. Thus, dose-based guidance for developing clean-up levels generally is inconsistent with CERCLA and the NCP's risk range approach for reasons that include the facts that *i)* estimates of risk from a given dose estimate may vary by an order of magnitude or more for a particular radionuclide and *ii)* dose-based guidance generally begins an analysis for determining a site-specific clean-up level at a minimally acceptable risk level rather than the 10^{-6} point of departure set forth in the NCP. Where radiological and non-radiological (chemical) contaminants are present at a CERCLA site, they should both be addressed using the risk range approach regarding risk from carcinogens. For further information see EPA, 2014: 12, 28.

Removal actions

This section focuses on non-time-critical removals since most decommissioning and decontamination (D&D) activities under CERCLA at DOE sites are conducted as non-time-critical removals. Non-time-critical removal actions are those where the lead agency determines, based on the site evaluation, that a removal action is appropriate but a planning period of more than six months is available before on-site activities must begin. Non-time-critical removal actions typically involve a secure site, no nearby population centre, storage containers in stable condition, and a dangerous concentration of chronic toxic substances. Non-time-critical removal actions provide an important method of moving sites more quickly through the Superfund process because they can address priority risks.

Section 300.415(b)(4)(i) of the NCP requires an engineering evaluation/cost analysis (EE/CA) for all non-time-critical removal actions. An EE/CA is intended to accomplish the following:

- satisfy environmental review requirements for removal actions;
- satisfy administrative record requirements for documentation of removal action selection;
- provide a framework for evaluating and selecting alternative technologies.

The EE/CA identifies the objectives of the removal action and analyses the effectiveness, implementability, and cost of various alternatives that may satisfy these objectives. Thus, an EE/CA serves an analogous function to, but is more streamlined than, the remedial investigation/feasibility study conducted for remedial actions. The non-time-critical removal should be conducted to ensure that all risk assessment activities are consistent with any future remedial action that may occur to achieve consistent risk goals. The results of the EE/CA and EPA's response decision are summarised in an action memorandum (AM). For further information see EPA, 1993a.

Background radiation in facility clean-up

Background radiation should be considered when developing remediation goals. Background and site-related levels of radiation are generally addressed as for other contaminants at CERCLA sites. For risk-based (10^{-4} to 10^{-6} or HI) clean-up levels, background levels of the contaminant typically are included in the risk estimate. If background levels of a contaminant exceed the acceptable risk goal (e.g. 10^{-4}, HI of 1), then background is generally used as the clean-up level. In general, CERCLA clean-ups do not go below background.

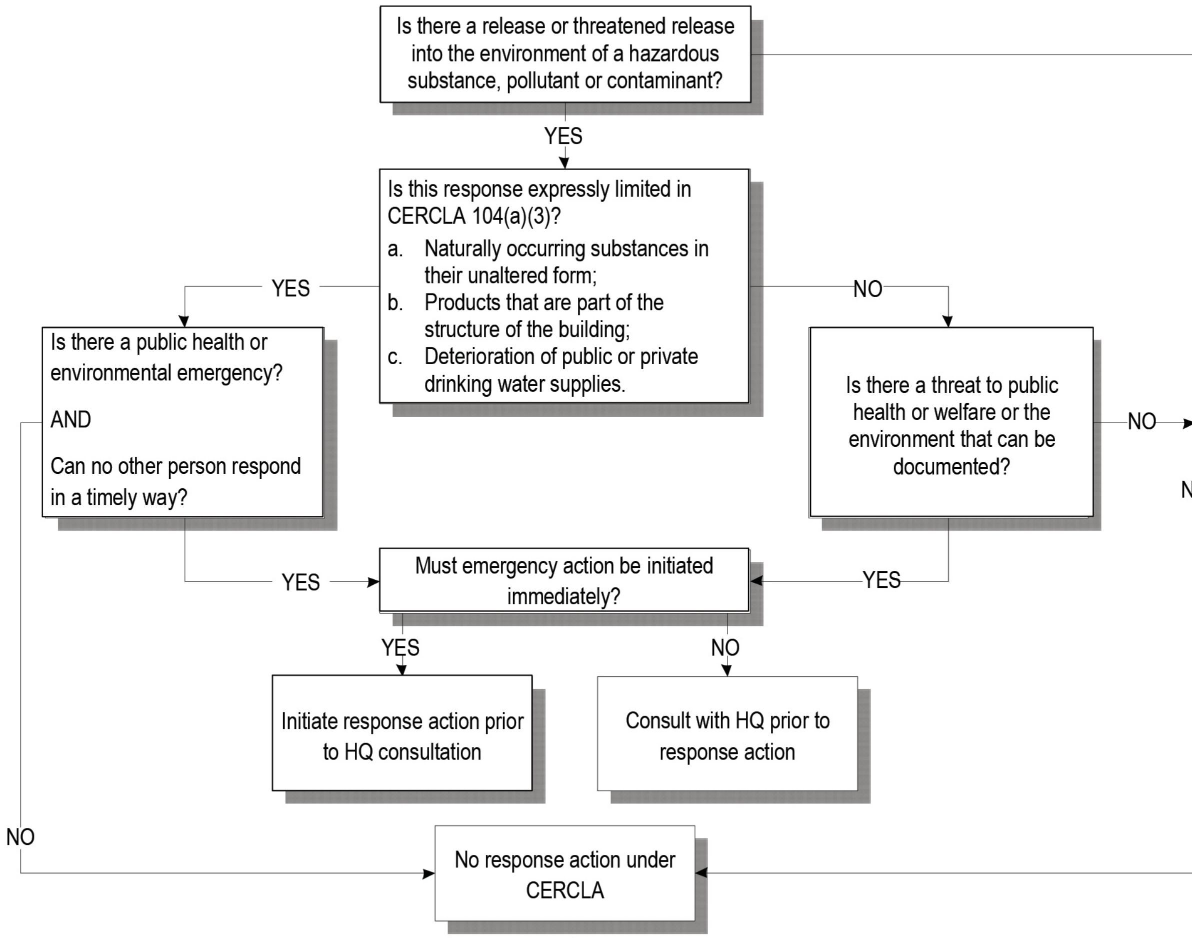
It should be noted that certain ARARs specifically address how to factor background into clean-up levels. For example, some radiation ARAR levels are established as increments above background concentrations. In these circumstances, background normally should be addressed in the manner prescribed by the ARAR where that approach leads to a protective clean-up level. For further information see EPA's guidance (EPA, 2002).

Additional information on radioactive materials present in building materials can be found in Hobbs, 2000.

CERCLA response actions at sites with contamination inside buildings

Under certain specific circumstances, CERCLA response authority can be used to address releases of hazardous substances, pollutants, or contaminants that are found within buildings. OSWER Directive 9360.3-12 provides useful guidance on this subject (EPA, 1993). (Figure D.1 is a flow chart of recommended steps for action in this guidance.)

Figure D1. Indoor contamination: Steps for action



Release or threat of release

CERCLA authorises response to a release or threatened release into the environment of a hazardous substance, pollutant, or contaminant. The authority to respond to a release of a pollutant or contaminant applies to situations where there may be an imminent and substantial danger to the public health or welfare. The terms "hazardous substance" and "pollutant or contaminant" are defined very specifically in CERCLA (see US Code, Title 42, Chapter 103, Subchapter I, § 9601). In general, a release or threat of release from a building may exist if at least one person or the environment outside of the building may be exposed to the release. For example, if the hazardous substance, pollutant, or contaminant can migrate through a window or through the foundation or building structure into the soil, creating exposures to persons or hazards to the environment, a sufficient basis may exist to show that there is a threat of release into the environment that may justify the clean-up of the interior of the building. A release or threat of release of a hazardous substance, pollutant, or contaminant may also exist where contaminated articles, clothing, or even parts of the structure itself may inadvertently be removed from the building.

Indoor contamination also may be the direct result of a release into the environment from a non-natural source that migrates into a building or structure. For example, contamination in a yard may be transported into a building on the feet of the residents or workers, or may migrate into the building through an open window or basement walls. In this situation, a release into the environment may be occurring and can cause a building to become contaminated with the hazardous substance, pollutant or contaminant.

Limited vs. non-limited authority

If a release or threat of release is present, the next step generally is to determine whether the qualified limitation on response authority provided for in CERCLA Section 104(a)(3) is triggered; this determination corresponds to the uppermost "YES" decision in Figure 3.1. In brief, this provision may limit the authority to respond under CERCLA for a release or threat of release:

- "of a naturally occurring substance in its unaltered form, or altered solely through naturally occurring processes or phenomena, from a location where it is naturally found;
- from products which are part of the structure of, and result in exposure within, residential buildings or business or community structures; or
- into public or private drinking water supplies due to deterioration of the system through ordinary use."

CERCLA Section 104(a)(4) provides exceptions to this limitation of response authority.

Under these three circumstances, a CERCLA response action may be appropriate if there is a "public health or environmental emergency, and no other person with the authority and capability to respond" in a timely way is available. When these three circumstances are not present, CERCLA Section 104 response authority is not affected.

Land use/institutional controls under CERCLA

The concentration levels for various media that correspond to the acceptable risk level established for clean-up typically depend in part on land use at the site, in particular the reasonably anticipated future land use of the facility undergoing D&D (e.g. demolished and taken down, reused for some industrial/commercial purpose). Land uses that will be available following completion of a remedial action may depend on the remedy that has been selected (considering the reasonably anticipated future land use, along with other remedy selection factors).

EPA's policies for how to consider reasonably anticipated future land use in the CERCLA remedy selection process are discussed in EPA, 1995.

In certain cases, in spite of the acceptable land-use scenarios and due to other limitations, an interim D&D process could be in place until those limitations are eliminated over time.

Generally, institutional controls may be included as a supplemental component to the remedy selected at a CERCLA site, not as a substitute for treatment, containment, or other remedial action. Institutional controls typically are non-engineering measures, usually legal controls, intended to affect human activities in a way that prevents or reduces exposure to hazardous substances. Institutional controls usually restrict land use to prevent unanticipated changes in use that could result in unacceptable exposures from residual contamination. At a minimum, institutional controls are normally intended to alert future users to the residual risks and the need to monitor the site in light of potential changes in land use. Engineering controls may be employed with institutional controls. Inside buildings, different methods have been employed to shield contamination from occupants, such as shielding or distance regulations.

EPA's CERCLA policy states that if a site cannot be cleaned up to a protective level (e.g. generally within the 10^{-4}-10^{-6} risk range) for the "reasonably anticipated future land use" because it is not cost effective or practicable, then a more restricted land use should be chosen that will meet that protective level (EPA, 1995: 9).

When waste is left on-site at levels that do not allow unlimited and unrestricted use, CERCLA requires that reviews be conducted at least every five years to ensure the remedy remains protective; monitoring the site for any changes in land use can be part of the five-year review process. Such reviews usually analyse the implementation and effectiveness of the remedy, including any institutional controls where they are relied upon. Should land use change in spite of the institutional controls, it may be necessary to evaluate the implications of that change for the selected remedy and whether the remedy remains protective.

Preliminary remediation goal tools for decommissioning

EPA developed two risk assessment tools that can be particularly relevant to decommissioning activities conducted under CERCLA authority: the preliminary remediation goals for radionuclides in buildings (BPRG) for radionuclides electronic calculator and the preliminary remediation goals for radionuclides in surfaces (SPRG) electronic calculator.

EPA developed the BPRG calculator to help standardise the evaluation and clean-up of radiologically contaminated buildings at which risk is being assessed for occupancy. BPRGs are radionuclide concentrations in dust, air, and building materials that correspond to a specified level of human cancer risk. The BPRG calculator recommends assessing contamination in building materials both on the surface and volumetrically. The BPRG calculator includes two standard default land-use scenarios – residential and indoor worker. The BPRG calculator is available at http://epa-prgs.ornl.gov/radionuclides/.

The intent of SPRG calculator is to address hard, outside surfaces such as building slabs, outside building walls, sidewalks and roads. SPRGs are typically radionuclide concentrations in dust and hard, outside-surface materials. The SPRG calculator recommends assessing contamination in hard, outside-surface materials both on the surface and volumetrically. The SPRG calculator includes three standard default land-use exposure scenarios – residential, indoor and outdoor worker. The SPRG calculator is available at http://epa-sprg.ornl.gov. Tables are provided with both the BPRG and SPRG calculators to show generic PRG concentrations. Both calculators are designed to help provide the ability to modify the standard default BPRG/SPRG exposure parameters to calculate site-specific BPRGs/SPRGs. However, to set radionuclide-specific BPRGs/SPRGs in a site-specific context, assessors should answer fundamental questions about the site. Information on the radionuclides present on-site, the specific contaminated media, land-use assumptions, and the exposure assumptions behind pathways of individual exposure is generally necessary to develop site-specific BPRGs/SPRGs.

To facilitate compliance with dose-based ARARs while conducting decommissioning activities under CERCLA, EPA developed two electronic calculators. These are the radionuclide building dose clean-up concentrations (BDCC) and the radionuclide outside hard surfaces dose clean-up concentrations (SDCC) electronic calculators. Both of these ARAR dose calculators are set up in a manner similar to the BPRG and SPRG calculators. They include the same exposure scenarios. Also, the equations in the scenarios are essentially the same except the ARAR dose calculators use dose conversion factors instead of slope factors and a year of peak dose instead of risk over a period of exposure such as 30 years. The BDCC and SDCC calculators are available at http://epa-bddc.ornl.gov/ and http://epa-sdcc.ornl.gov/.

References

EPA (2014), "Radiation Risk Assessment at CERCLA Sites: Q&A", OSWER Directive 9200, pp. 4-40.

EPA (2002), "Role of Background in the CERCLA Clean-up Program", OSWER 9285.6-07P, pp. 13, http://rais.ornl.gov/documents/bkgpol_jan01.pdf.

EPA (1995), "Land Use in the CERCLA Remedy Selection Process", OSWER Directive No. 9355.7-04, www2.epa.gov/sites/production/files/documents/landuse.pdf.

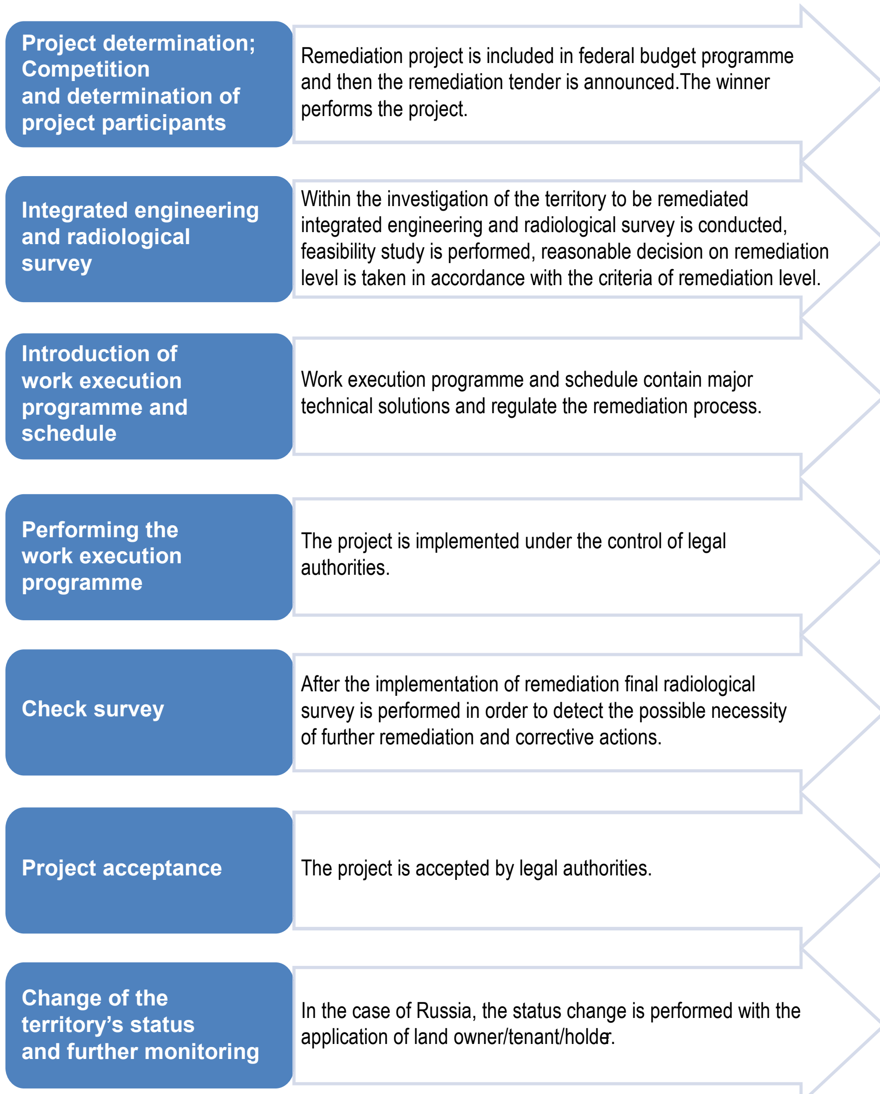
EPA (1993a), "Guidance on Conducting Non-Time critical Removal Actions Under CERCLA", PB93-963402, EPA540-R-93-057, OSWER Directive 9360.0-32, www2.epa.gov/enforcement/guidance-conducting-non-time-critical-superfund-removal-actions.

EPA (1993b), "Response Actions at Sites with Contamination Inside Buildings", OSWER Directive 9360.3-12, PB94-963269.

Hobbs, T.G. (2000), "Radioactivity measurements on glazed ceramic surfaces", *Journal of Research of the National Institute of Standards and Technology*, Vol. 105, p. 275-283. http://nvlpubs.nist.gov/nistpubs/jres/105/2/j52hob.pdf.

Annex E. Country-specific example: Russia

Principal project stages within territory remediation



Remediation process in Russia is regulated on different levels, the principal documents are the following:

- Federal Law 190-FZ "On Radioactive Waste Management and Amendments to Dedicated Regulations of the Russian Federation".
- Federal Law 92-FZ "On Specific Ecological Programs for Rehabilitation of Radioactive Contaminated Territories".

- Russian Federation Government Decree of 02/27/2004 No. 112 “On Management of Lands that Underwent Radioactive and Chemical Contamination, Performing Reclamative and Land Clearance Operations, Establishment of Protective Zones and Conservation of Land Facilities”.
- Radiation Safety Regulations (NRB-99, SP 2.6.1.758-99).
- Basic Sanitary Rules for Radiation Safety (OSPORB-99, SP 2.6.1.79-99).
- Sanitary Rules for Radioactive Waste Management (SPORO-2002, SP 2.6.6.1168-02.).

As described in the main text, the term “remediation” is not used in the regulations of Russia, thus within the present document we understand remediation to be rehabilitation of land degraded as a result of radioactive contamination. (According to the Law No. 92-FZ of 07/10/2001 “radioactive contaminated area of the territory is an area being hazardous for the population health and the environment which undergoes rehabilitation after radioactive contamination as a result of man-induced actions or decommissioned highly hazardous facilities located on this territory”). The character and level of land contamination is evaluated in accordance with the regulations for sanitary and epidemiological welfare of the population, radiation safety and environmental protection. When it comes to practice, the following approach is generally accepted: depending on land purpose (cadastral land category) it is remediated up to 0.6 $mSv\ y^{-1}$ (industry), or up to 0.3 $mSv\ y^{-1}$ (accommodation), and financial matters are very important. Ecological programmes are financed preferably from the federal budget, though lately there has appeared the experience of joint financing involving landowners.

As described in the main text, remediation of territories up to background values is costly, main criteria for determining the appropriateness and completeness of the conducted decontamination are:

- equivalent dose of gamma radiation;
- the specific activity of man-made and effective specific activity of natural nuclides;
- exposure quotas of the population in the territory after rehabilitation;
- permitted levels of residual specific activity and content of toxicants: in soil, surface and ground water, sediments.

The decision must be based on the economic approach, which defines a mechanism for assessing the costs and the identification of key economic indicators that determine the cost structure.

In Russia, the responsibility for the industrial activities of prior years is poorly regulated. Despite this fact, territories and facilities connected with ionising radiation are traditionally strictly controlled, and radioactive waste contaminated territories are mostly identified and investigated. The main task of categorising the territories (facilities) which underwent radioactive and chemical contamination is to detect, evaluate and analyse the existing hazards with reference to contamination in order to work out, compare and introduce actions for their safe operation under present-day conditions. The main criterion for categorising the territories that underwent radioactive and chemical contamination is the level of their potential hazard for the population and environment.

The following types of contaminated territories exist:

- Territories contaminated as a result of radiation accidents: Protection applies – there are criteria for intervention in areas contaminated as a result of radiation accidents (presented in the form of the calculated dose limits).

- Territories with local radioactive contamination: Protection applies – there are intervention criteria for local radioactive contamination (intervention levels are presented as the calculated dose limits).
- Territories that have operating nuclear facilities: Safety applies – regulation of the total annual emissions and discharges from the nuclear facility (adoption of a standard annual maximum permissible emission for each nuclear facility).

Over the past decades, contaminated industrial territories were taken out of service by changing their category (for example, industrial lands were transferred to land reserve). This approach does not intend further rehabilitation. On the other hand, requirements for the reclamation of disturbed lands have been introduced (e.g. by mining or other operations disturbing land surface), but the occurrence of such reclamation was limited.

The above-mentioned approaches have been reflected in legislation. For example, Federal Law "On Changing Land Category" of 12/21/2004 No. 172-FZ reads that transfer of industrial, energy, and transport lands is performed with no limitations. But in case of degradation or contamination of these lands the transfer is performed with an approved project of land remediation and reclamation. The Government Decree No. 112 places contaminated territories into three categories depending on type and level of contamination:

- lands due to be transferred to reserve lands for conservation if opportunity to provide safety for population health and proper quality of production does not exist, and also if there is a lack of efficient rehabilitation technologies;
- lands exploited according to the intended purpose with determination of specific conditions and mode;
- lands exploited according to the intended purpose without determination of specific conditions and made in case the contamination indices do not exceed the specified standards.

The data on contaminated territories are kept by State Corporation Rosatom in accordance with the form "the territories contaminated with nuclides", which includes the following fields:

- the name of the site;
- cadastral number of the plot;
- plot code;
- the area of the contaminated territory, m^2;
- the average and maximum dose rate of gamma radiation, $\mu Sv\ h^{-1}$;
- average contamination density, $Bq\ m^{-1}$;
- alpha-emitting nuclides;
- beta-emitting nuclides.

Unless the territory is remediated to 0.1 $mSv\ y^{-1}$ it remains in the current database.

Evaluation of the type and level of contamination as well as determination of indices of harmful influence on the health of population or environment, caused by contamination, are performed on the basis of standards introduced in accordance with regulations by Russia in the sphere of sanitary (health) and epidemiological wellness of the population, radiation safety and environmental protection.

Remediation-aimed evaluation is based on a radiation dose approach. In this sense, the Russian approach to legislation addressing radiation safety mostly coincides with the international practice of remediation based on the risk evaluation concept.

The criteria for evaluation of radioactive contaminated territories are the present regulations for providing safety of people on this territory from the influence of radiation of artificial or natural origin.

The main criterion for evaluation of radioactive contaminated territories from the risk point of view is the level of socially acceptable risk provided that principle radiation safety standards are obeyed taking into consideration the categories (purposes of use) of radioactive contaminated land, based on method of socially acceptable risk and multiple exposure pathways.

Health risks to the population on contaminated territories can arise in the following ways: direct consumption of soil; dust inhalation; consumption of drinking water contaminated as a result of radionuclide migration to aquifers through soil; skin contamination; consumption of local products; migration of radioactive gases to the basements of buildings; external exposure by radionuclides contained in soil.

There exist three groups of standards for group A employees, group B employees and population:

- major dose limits;
- acceptable levels of multifactorial influence: limits for annual exposure, acceptable average annual activity concentration, average annual specific activity, etc.;
- control limits (doses, activity levels, etc.).

Major dose limits do not include doses from natural or medical exposure and doses caused by radiation emergencies (these types of exposure are separately regulated). By simultaneous influence of external and internal exposure annual effective dose shall not exceed the dose limits provided by NRB-99. For population, these limits equal 1 mSv y^{-1} on average for every successive five years, but not above 5 mSv y^{-1} in any one year. Acceptable levels of multifactorial influence for each category of people and for each exposure pathway are determined in such a way that the amount of dose equals the annual limit averaged over five years. Control levels are determined in such a way to guarantee that major dose limits are not exceeded and to minimise exposure doses.

For drinking water, the criterion is also an acceptable concentration (action level) for contents of contaminants. According to NRB-99, remediation is not needed for drinking water contents of natural and artificial radionuclides that give rise to a dose of less than 0.1 mSv y^{-1}.

In Russia, the risk concept became popular in the sphere of radiation protection after performing a range of projects for testing the international method of risk evaluation and appearance of the Decree "On Using the Method of Risk Evaluation for Environment and Population Health Management in the Russian Federation". The method analyses each type of influence and evaluates its role in risk generation. Direct consumption of soil, dust inhalation and water consumption are the most widespread ways of receiving a radiation dose in residential areas. Additional pathways for soil contaminants, such as skin contamination, consumption of local products and migration of gases to the basement of a building can also add health risk. An important source of radiation exposure is external radiation from radionuclides in soil. In some cases evaluation of risks caused by consumption of natural products (fish, mushrooms, berries, etc.) is needed. Apart from that it is important to keep in mind that radiation exposure risks are to coincide not only with profits, but rather with risks of non-radiation origin.

In the attachment below, the most recent remediation projects are introduced to illustrate the remediation process in Russia.

Site remediation

Reason/warrant/contract

Remediation of tailing sites after the operation of the processing plant of former Novotroitsk mining department and the area (Novotroitsk, the Zabaikalye territory).

Project description

The present project is performed by the own efforts of Federal State Unitary Enterprise RosRAO, starting with radiation control of the contaminated areas and finishing with total deactivation and transfer of the areas to the local government to get used for intended cadastral purpose.

In order to reach such a result the following works are performed:

- soil sorting on the areas under deactivation;
- decontamination of buildings and constructions;
- dismantlement of buildings and constructions;
- arrangement of storage for contaminated soil;
- radioactive waste collection and containerisation;
- radioactive waste transportation to specific stores of RosRAO.

Services provided/works implemented

RosRAO is acting as principal contractor for the implementation of full range of site rehabilitation activities.

Types of services provided:

- design documentation development;
- performing of integrated engineering and radiological survey;
- risk analysis and project safety estimation;
- process operation development for the decommissioning of hazardous nuclear and radiation facilities and site rehabilitation;
- engineering documentation development;
- project management and control;
- project implementation and documentation control;
- licensing support;
- contract management;
- decontamination and dismantlement of constructions;
- radioactive waste management and long-storage;
- final expert examination.

Customer

Russia in the person of State Corporation Rosatom

Location

Novotroitsk, the Zabaikalye territory, Russia

Commencement

February 2013

Implementation

November 2015

Total cost of the project

EUR 15 000 000.00

Project manager

Alexey Zakharov

Contact customer representative

Alexey Zakharov

ROS RAO

A SC "ROSATOM" COMPANY

Decommissioning of nuclear and radiation hazardous facilities and site rehabilitation

Reason/warrant/contract

Full range of site rehabilitation of land parcel on the territory of JSC Mosrentgen.

Project description

The present project has been implemented «turn-key ready» starting with performance of an integral radiological examination until the receipt of the decision of regulatory authorities proving the purity of the facility and its shift from the government control. For these purposes the following works have been implemented:

- dismantlement of temporary biological defence of solid radiactive waste storage facility;
- decontamination of buildings and constructions;
- dismantlement of buildings and constructions;
- radioactive waste collection, sorting and containerisation;
- radioactive waste transportation to specific storages of Federal State Unitary Enterprise RosRAO.

Services provided/works implemented

RosRAO acts as a principal contractor for the implementation of a full range of activities aimed at decommissioning of nuclear and radiation hazardous facilities on-site, including final dismantlement of constructions and site rehabilitation.

Types of services provided:

- design documentation development;
- performance of integrated engineering and radiological survey;
- risk analysis and project safety estimation;
- process operation development for the decommissioning of hazardous nuclear and radiation facilities and site rehabilitation;
- engineering documentation development;
- project management and control;
- project implementation and documentation control;
- licensing support;
- contract management;
- decontamination and dismantlement of constructions;
- radioactive waste management and long-storage;
- final expert examination;
- assistance in relationships with regulatory authorities.

Customer

Russia in the person of State Corporation Rosatom, JSC Mosrentgen

Location

Moscow, Russia

Annex F. Country-specific example: United Kingdom

In this annex we discuss in more detail two concepts underlying scheduling of decommissioning and remediation activities in the United Kingdom: the Nuclear Decommissioning Authority (NDA) value framework, and the concepts of pace and priority as developed in the United Kingdom.

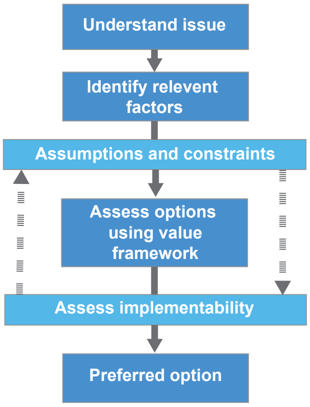
The Nuclear Decommissioning Authority value framework

To ensure transparency when comparing and assessing options, the NDA has established an approach to the way it values its business, recognising that value comes in many forms. These values have been gathered together as a value framework. This value framework supports NDA's aim to deliver safe and sustainable solutions to the challenge of nuclear clean-up and waste management, and enables a structured discussion with a clear line of sight between any activity and the NDA's overall strategic objectives.

At the heart of the NDA value framework lies a list of factors that are grouped under seven headings: health and safety, security, environment, risk or hazard reduction, socio-economic impacts, finance and enabling the mission (see Figure F1).

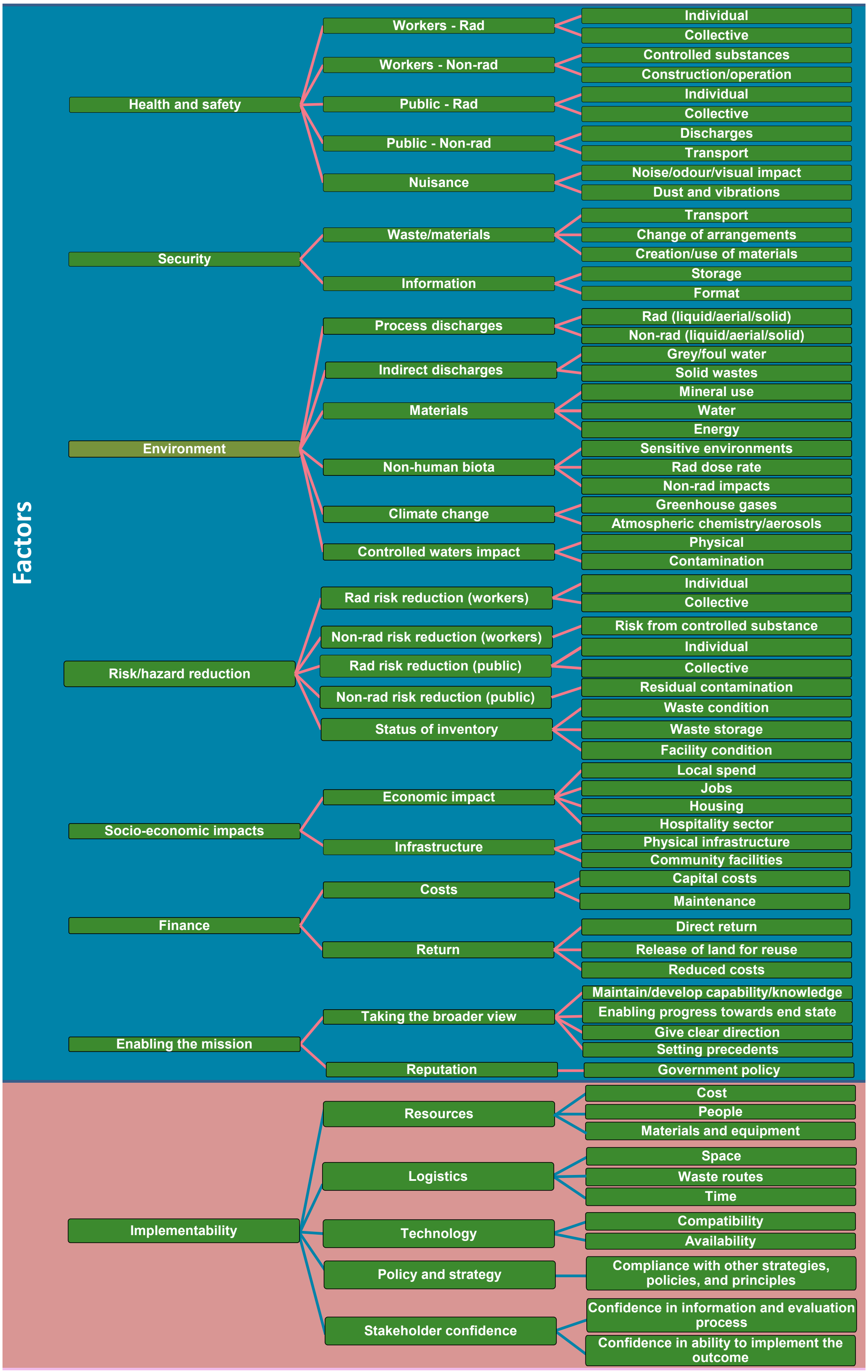
Discussion of these factors is a key part of the assessment process used to identify a preferred option. However, the value framework is not intended as a mandatory checklist, only relevant factors should be considered and the approach should be proportionate to the issue being addressed. These assessments may vary in complexity, and consequent time and effort involved. In each case, the purpose is to present an evidence-based comparison of alternative options to identify a preferred option. Real-life situations are often complex with many areas overlapping. As such, the value framework encourages assessors to take a broad view of options under consideration, and to evaluate options against longer-term objectives.

This approach enables learning from experience, provides the opportunity to demonstrate leadership, and allows a much broader discussion than if attention were focused solely on short-term impacts and risk or hazard reduction. For example, clean-up of land contamination and partial site de-designation may demonstrate progress and promote good community relations.



The value framework also emphasises the necessity to consider the full ramifications of implementing any option both in the present and in the future. Thus, the full lifecycle implications of an option should be considered, including the impact of doing the work and the impact of the work having been done. For example, the environmental impact of doing remediation (such as energy use) should be considered against the environmental impact of the completed decommissioning project (land released for future use).

Figure F1. The NDA value framework tiered approach



Application of the value framework is not a simple flow process model, rather it requires careful consideration of the details of the problem at all times in relation to the desired objectives. As such, knowledge of assumptions and constraints surrounding the options assessment are essential. An ideal solution is often not possible and it is necessary to balance the ideal with the attainable. In particular, some constraints may be absolute, whereas other constraints may be conditional and subject to challenge and modification as the decision-making process develops (for example, as further information becomes available).

Thus, a number of factors may constrain the range of options that are considered practicable. Conversely, assumptions may be required to underpin the practicability of implementing one or other option. For example, if residual contamination exists within a small area bounded by the site boundary and operational areas of the site. In this case, the size of the site constrains the approaches that can be implemented. However, all remedial technologies would be listed at the options-identification stage, including those that require more space than is currently available.

If, in this example, the site area cannot be increased it is considered to be a fixed factor, it can be said to be an **absolute constraint**. Absolute constraints can be used as screening criteria because options that do not meet these constraints are considered unfeasible.

If the site area can be increased, for example through moving or closing an operational area, options could be reassessed. In this case, the site area would form a **conditional constraint** and the factors that could amend the assessment would require clear identification. Conditional constraints may present significant challenges to implementation, but may be subject to modification as the decision-making process develops (for example, as further information becomes available).

In turn, this approach requires an understanding of the degree of the uncertainty surrounding the problem. Uncertainty may be manifest both in the problem definition (such as the level of contamination), and the solution outcome (will the implemented option be successful?). In both cases, uncertainty can arise from a lack of knowledge, incomplete information or from inherent variability within a system. While uncertainty can often be reduced, it is likely that information may remain incomplete or reflect real variability. As such, the significance of any information gaps should be determined, and the tolerability of the options assessment to uncertainty considered. As new information becomes available, assumptions may be modified as knowledge develops, and assessments should be updated to reflect these findings. In many cases, this modification of the assumptions will correspond to a reduction of uncertainty.

Pace and priority

The NDA's remit is to deliver timely reduction of risk and hazard across its estate in a safe, secure and cost-effective way while protecting the environment for the present and future generations. Recognising that we cannot do everything immediately, we need to prioritise our activities. We recognise that, even after preferred options have been identified using our *value framework*, finite time and resources mean that both the pace (i.e. the realistic achievable timescale) and the priority (i.e. the relative importance of these preferred options in comparison to one another) of implementing actions needs to be considered at both the site and national level. That is why we separate the options assessment process from the decision-making process.

Assessment of pace and priority

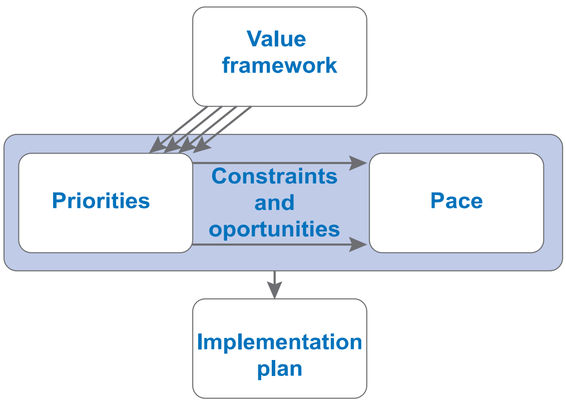
We give the highest priority where risks to people or the environment are identified as *intolerable*. At the same time, whatever initial priority is attached to a programme, it must be recognised that doing nothing may have consequences. In particular, a risk that is currently tolerable or broadly acceptable may degenerate if no action is taken to maintain the status quo.

The pace at which an activity is implemented reflects both the start date (i.e. when the activity is scheduled to commence) and the rate at which that activity is progressed (i.e. the total duration of the activity).

Sometimes, even a high-priority activity cannot be progressed rapidly, and the pace may be determined by a number of constraints. For example, a facility or waste inventory may present a high risk, and thus be identified as a high priority for risk reduction. However, establishing a waste retrieval or disposal route, to ensure that a higher risk is not incurred during recovery operations, may mean that the activity can only proceed slowly. Consequently, we may take the opportunity to simultaneously progress, and complete, a lower priority activity where there are fewer constraints.

Combining our evaluation of options with an understanding of site and national priorities, and the recognition of both constraints and opportunities to progress activities, results in the process shown in the figure below.

NDA pace and priority process



This process can be broken into the main steps described below.

Step 1: Identify priority

This is the identification of the ideal order in which activities (portfolios, programmes, projects or tasks) should be carried out. The NDA's first priority is always the reduction of risk and hazard across its estate. However, establishing the level of risk or hazard reduction that can be achieved, and the broader implications of doing so, requires consideration of a range of factors, as laid out in our *value framework*. Consideration of these factors requires evaluation of uncertainty, assumptions and constraints relating to the identified preferred options, as well as assessing the confidence that the option can be implemented successfully.

The main output from this step is to identify an order in which the activities assessed should be considered.

Step 2: Identify constraints

Establishing the priority in which initiatives or projects should be implemented represents an "ideal world" position. In reality, there may be constraints that restrict what is achievable, or determine the order in which programmes can actually be pursued.

Failing to understand "real world" constraints can give a false impression of what is achievable and can result in delays to implementation and a slowdown in overall risk reduction across the site and across the estate.

It is important both to identify constraints and to evaluate them to determine whether they can be resolved or whether alternative approaches will be required. Resultantly, in the *value framework* a distinction is made between absolute constraints (these are barriers that mean another way must be found) and conditional constraints (these are challenges that may be resolved).

The output from this step is expected to be a series of preferred options which progress through hazard reduction at a pace that is achievable.

Step 3: Identify opportunities

Progressing a higher priority activity may establish opportunities to progress other activities. For example, the suitability of a new approach to decommission a high-risk facility may be established by first decommissioning a low-risk facility. Alternatively, delivering a high-risk reduction programme may mean that facilities and trained staff are available, enabling other lower risk reduction programmes to be driven forward ahead of the time that would otherwise have applied (i.e. apparently moving them up in priority). This makes best use of resources and enables the overall site or estate risk to be reduced in the most cost-effective manner.

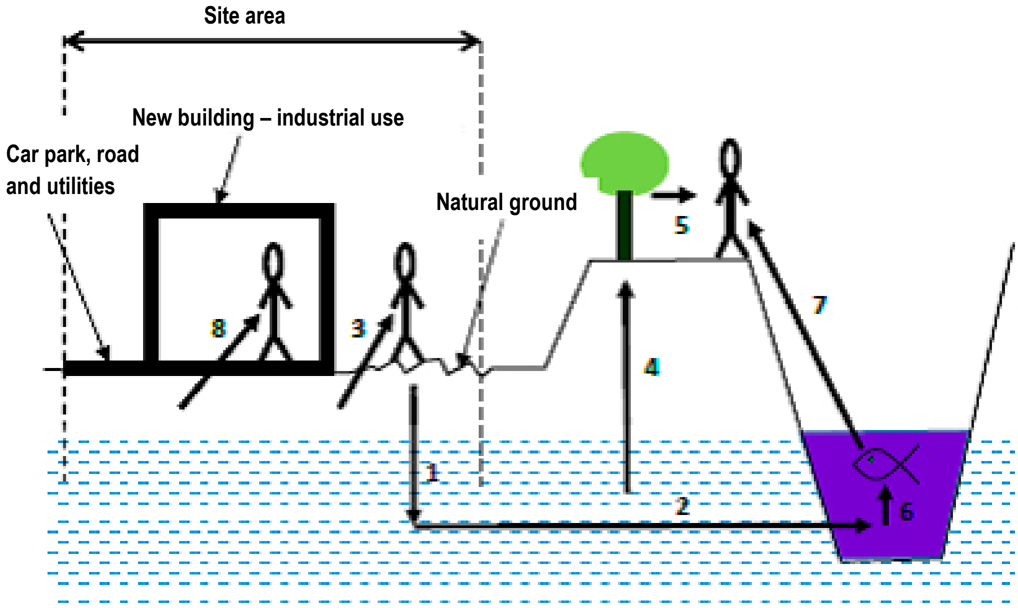
Step 4: Review and implement

As always, decision-making rests with the role of an identified decision maker. Having established the pace and priority at which programmes can be progressed, and any associated opportunities for other programmes, an overall schedule must be compiled, reviewed and approved for implementation.

Annex G. Country-specific example: French conceptual site model

A conceptual site model (CSM) was developed at Grenoble in France even though remediation goals were pre-set by the regulator. A CSM is needed to assess physical site characteristics even if there are pre-mandated clean-up criteria. Knowledge of where the contamination is or has gone is still needed, so that completion of clean-up activities can be verified, and to check nothing has been missed.

Figure G1. Conceptual site model: Grenoble



1. Contamination of ground water by soil or ground;
2. Contamination of the river by ground water;
3. Contamination or irradiation of workers by soil or ground (naked or coated, e.g. car park);
4. Contamination of terrestrial ecosystems by ground water;
5. Contamination by ingestion of terrestrial ecosystems products;
6. Contamination of aquatic ecosystem in the river from the ground water;
7. Contamination by ingestion of aquatic ecosystem products;
8. Contamination or irradiation of workers by ground through a building slab (irradiation and/or gas).

Annex H. Management approach in France

The general principles governing the management of sites polluted by radioactive substances were defined jointly by the French nuclear safety authority (ASN) and the General Directorate for Risk Prevention at the ministry responsible for ecology.

They are primarily based on the polluter pays principle defined by article L. 110-1 of the Environment Code. In accordance with the principles of the Public Health Code (Article L.1333-1), the exposure of persons to ionising radiation as a result of site management operations, must be kept to a level that is as low as reasonably achievable given current technical knowledge and economic and social factors (ALARA principle). The cost/benefit analysis of the various possible management options for the site must be such as to justify this optimisation by limiting residual exposure, but also by guaranteeing the robustness and permanence of the final management solution proposed.

Validation of the clean-up project and targets by the public authorities concerned is necessary prior to implementation of the chosen solution. It is important to remember that there is no release or clean-up level in France. The management values are those defined by the public authorities to ensure the general protection of the population and the environment.

The values to be considered can define either a level of quality for a biotope and a given usage, or a level of exposure. Thus, concerning water intended for human consumption, the orders of 12 May 2004 and 11 January 2007 set guideline values for total α, total β and tritium activity levels and for an exposure indicator called the total indicative dose (TID). From the radiological viewpoint, water with activity of less than 0.1 Bq l^{-1} total alpha, 1 Bq l^{-1} total β or which is associated with a TID of less than 0.1 mSv y^{-1} is considered to be suitable for consumption. In addition to the previous regulatory requirements, with regard to the uranium concentration, the assessment of the degree of pollution may also be based on the guideline value of 30 µg l^{-1} recommended by the World Health Organization (WHO) for drinking water.

Moreover, depending on the context, more restrictive management values than those previously mentioned could be adopted by the public authorities.

The management approach is described in the French methodological guide to the management of sites potentially polluted by radioactive substances (ASN-IRSN-MEDTL December 2011) (see Figure H1). The management approach adopted in the guide reinforces the management approach according to the usage, introducing a clear distinction between two types of situations:

- Those for which it is possible to influence both the condition of the site and the uses, which can be chosen or adapted. This is the case with the cessation of activity or conversion of former industrial sites.
- Those for which the uses are already established. The uses are qualified as "established" when the polluted zone is home to clearly defined activities (industrial, commercial, residential, agricultural, etc.) and there are no redevelopment projects which could entail their modification. This is, for example, the case when the activity at the origin of the pollution is still ongoing or when it has ceased and new uses have been developed on the site without adequate clean-up having been performed.

Figure H1. Management approach – French methodological guide to the management of sites potentially polluted by radioactive substances (ASN-IRSN-MEDTL, December 2011)

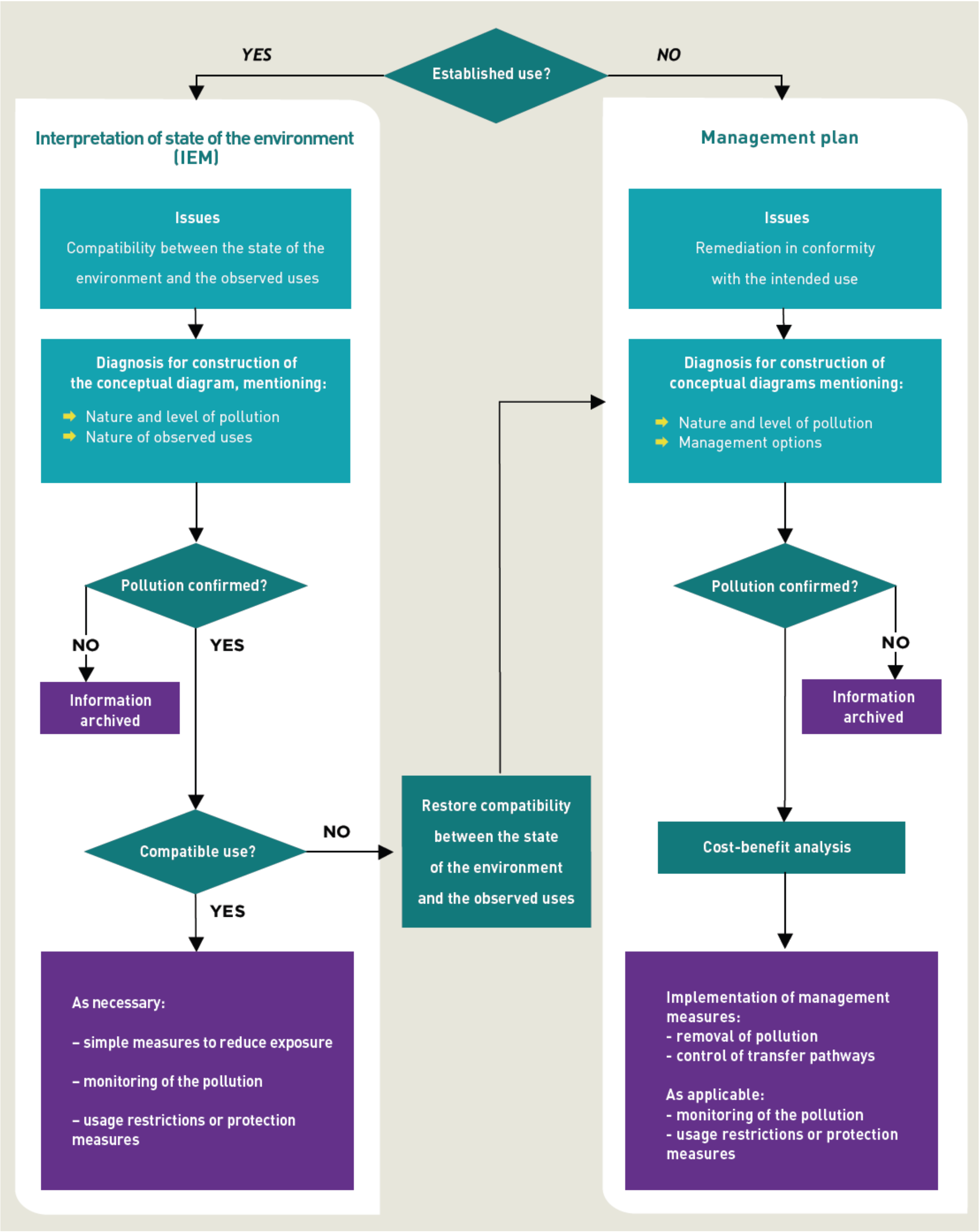
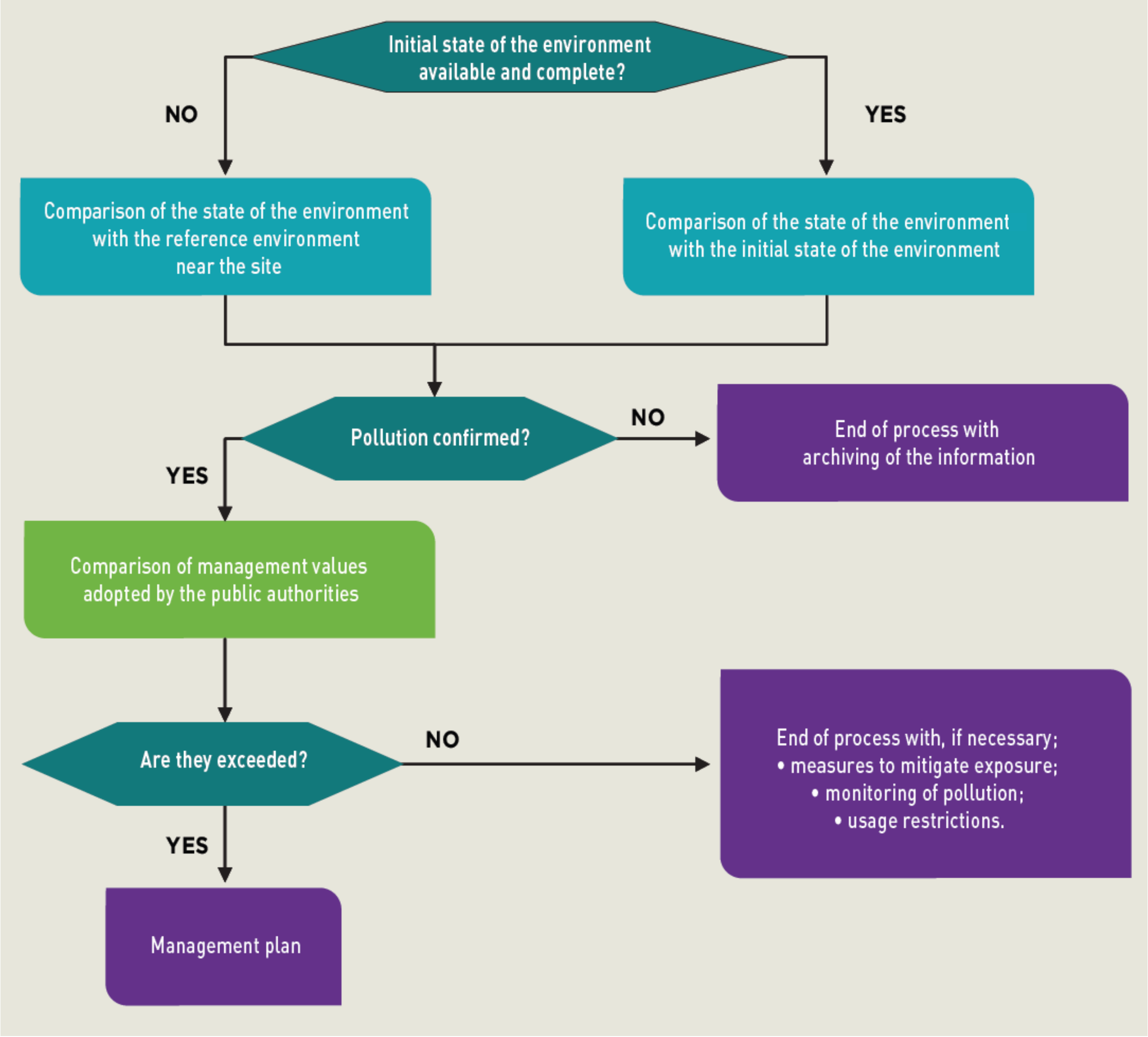


Figure H2. Flow chart for interpretation of the environment



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Strategic Considerations for the Sustainable Remediation of Nuclear Installations

Nuclear sites around the world are being decommissioned and remedial actions are being undertaken to enable sites, or parts of sites, to be reused. Although such activities are relatively straightforward for most sites, experience has suggested that preventative action is needed to minimise the impact of remediation activities on the environment and the potential burden to future generations. Removing all contamination in order to make a site suitable for any use generates waste and has associated environmental, social and economic drawbacks and benefits. Site remediation should thus be sustainable and result in an overall net benefit.

This report draws on recent experience of NEA member countries in nuclear site remediation during decommissioning in order to identify strategic considerations for the sustainable remediation of subsurface contamination – predominantly contaminated soil and groundwater – to describe good practice, and to make recommendations for further research and development. It provides insights for the decision makers, regulators, implementers and stakeholders involved in nuclear site decommissioning so as to ensure the sustainable remediation of nuclear sites, now and in the future.

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