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Standard**

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**Remediation techniques applied at
contaminated sites**

Techniques de dépollution appliquées aux sites pollués

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Foreword

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Introduction

In the context of contaminated land, if unacceptable risks associated with a site are identified following a risk assessment and should be managed, remedial actions are required to prevent, minimise, remedy or mitigate the effects of the unacceptable risks. The choice, implementation and verification of remediation techniques require detailed site characterization and risk assessment.

A remediation strategy should be set up encompassing these actions by implementing technical and organisational actions on contaminant source(s), transport and exposure pathways and/or receptors, aiming to control the unacceptable impacts and associated risks that have been established following the investigations and risk assessment. Amongst these actions are the implementation of individual, or combinations of, remediation techniques aiming to address contaminants that can be present within the soil, water, soil gas or ambient air, including non-aqueous phase liquids (NAPL).

This document provides requirements and guidance on key aspects for effective implementation of individual or combinations of in situ and on-site remediation techniques. It was developed in response to demand for minimum specifications for the selection and verification of remediation strategies to manage the risks from contaminated sites.

It is intended to inform practitioners and stakeholders about the main characteristics of commonly used remediation techniques. It can also help practitioners to select technically feasible approaches within the options appraisal phase, based on the state of the art of remediation technologies.

NOTE 1 Some of the on-site techniques presented in the document can also be used within off-site treatment facilities but the latter are not covered (e.g. this document covers incineration on-site, but not incineration at a permanent off-site installation).

NOTE 2 There is a continuous development of remediation techniques. It is possible that this document does not reflect all knowledge that is gained as techniques are improved.

NOTE 3 Not all available techniques are covered. Those not covered include: electrokinetic methods to remove contaminants or to improve the effectiveness of other methods (e.g. electrokinetic enhanced bioremediation), and phytoremediation.

Remediation techniques applied at contaminated sites

1 Scope

This document provides requirements and guidance on key aspects of remediation techniques. It describes the principles, main characteristics, advantages and limitations to be considered in the selection within an option appraisal of individual or combinations of in situ and on-site remediation techniques, including:

- the type of contaminants to be dealt with;
- current and/or intended site use;
- local legal, policy, socio-economic and environmental contexts.

This document is applicable to the remediation of contaminated sites, i.e. where soil, or soil gas, ambient air or groundwater are contaminated. It identifies which phase/matrix can be targeted by a technique, e.g. fluid (groundwater, gas, non-aqueous phase liquid) or solid, and which contaminant it can be applied to. This document also provides information on hazards that can be associated with the implementation of remediation.

This document does not provide:

- an exhaustive list of remediation techniques;
- guidance on sites contaminated with radioactive substances, pathogenic or infectious agents, or “pyrotechnic devices” (e.g. unexploded ordnances);
- guidance on ex situ techniques that are set up off-site;
- a framework that covers all individual situations, or prescribes which technique(s) to use in a specific context.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1

contaminant linkage

presence and relationship established between contaminants, preferential pathways and receptors

3.2

engineering-based technique

civil engineering technique (e.g. excavation, containment, hydraulic control) used to remove the contaminant source or soil material or to modify pathways without necessarily removing, destroying, or modifying the source

Note 1 to entry: Some of these techniques can be considered when implementing protective measures.

[SOURCE: ISO 11074:2015, 6.2.1, modified — in the term, “methods” has been changed to “technique”; Note 1 to entry has been added.]

3.3

environmental medium

soil, underlying material, sediments, surface water, groundwater, soil gas, and ambient air that can contain contaminants

[SOURCE: ISO 21365:2019, 3.4, modified — “ambient” has been added before “air”.]

3.4

ex situ treatment technique

treatment technique applied to medium to be treated (e.g. soil, groundwater) after extraction from the ground

[SOURCE: ISO 11074:2015, 6.2.2, modified — in the term and the definition, “method” has been replaced by “technique”.]

3.5

hazard

property of a substance or material or situation that in particular circumstances can lead to harm or pollution

[SOURCE: ISO 11074:2015 5.2.15]

3.6

in situ treatment technique

treatment technique applied to medium to be treated (e.g. soil, groundwater) without extraction from the ground

Note 1 to entry: The remediation installation is built on-site and the treatment of the contaminants is applied directly to the subsurface.

[SOURCE: ISO 11074:2015, 6.2.3, modified — in the term and the definition, “method” has been replaced by “technique”; Note 1 to entry has been added.]

3.7

off-site treatment

treatment applied away from the site to be remediated

[SOURCE: ISO 11074:2015, 6.2.4]

3.8

on-site treatment

treatment applied on the site being remediated

Note 1 to entry: In the case of contaminated ground, treatment is applied after extraction of *environmental medium* (3.3) material from the ground.

[SOURCE: ISO 11074:2015, 6.2.5, modified — Note 1 to entry has been added.]

3.9

remediation

process of dealing with contaminated soil, groundwater, or site to eliminate, reduce or control *risks* (3.12) to human health or the environment

Note 1 to entry: A remediation can rely on an individual remediation technique or a combination of remediation techniques.

[SOURCE: ISO 11074:2015, 6.1.17, modified — “reduce” has been added after “to eliminate”; Note 1 to entry has been added.]

3.10

remediation strategy

remedial design

one or more *remediation* (3.9) technologies and associated works that meets specified contamination-related *risk* (3.12) reduction objectives

Note 1 to entry: The choice of methods can be constrained by a variety of site-specific factors such as topography, geology, hydrogeology, underground services, propensity to flood and climate.

[SOURCE: ISO 18504:2017, 3.5, modified — the admitted term “remedial design” and Note 1 to entry have been added.]

3.11

sustainable remediation

elimination, reduction and/or control of unacceptable risks in a safe and timely manner whilst optimising the environmental, social and economic value of the work

[SOURCE: ISO 18504:2017, 3.10, modified — “reduction” was added after “elimination”.]

3.12

risk

combination of the probability or frequency of occurrence of a defined *hazard* (3.5) and the magnitude of the consequences of the occurrence

[SOURCE: ISO 11074:2015, 5.2.24]

3.13

unacceptable risk

level of *risk* (3.12) that requires *remediation* (3.9)

Note 1 to entry: The level of risk may be evaluated by comparison to a relevant numeric threshold or by benchmarking against a narrative definition. Different levels of risk are deemed unacceptable in different countries or even by different laws within a country.

[SOURCE: ISO 11074:2015/Amd 1:2020, 6.5.10]

4 Abbreviated terms

BTEX	benzene toluene ethylbenzene xylene-isomers
COD	chemical oxygen demand
DNAPL	dense non-aqueous phase liquid
DPLE	dual pump liquid extraction
ECH	electric conduction heating
EHS	environment health and safety
EISB	enhanced in situ bioremediation
ENA	enhanced natural attenuation
FAG	funnel and gate
GAC	granular activated carbon

HDPE	high density polyethylene
HRC®	hydrogen release compound
ISC	in situ combustion
ISCO	in situ chemical oxidation
ISCR	in situ chemical reduction
ISTD	in situ thermal desorption
ISTR	in situ thermal remediation
LCA	life cycle assessment
LNAPL	light non-aqueous phase liquid
MNA	monitored natural attenuation
MPE	multi phase extraction
MTBE	methyl ter-butylether
NOD	natural oxidant demand
NSZD	natural source zone depletion
ORC®	oxygen release compound
ORP	oxydation reduction potential
P&T	pump-and-treat
PAH	polyaromatic hydrocarbon
PBDD	polybrominated dibenzo-p-dioxin
PBDF	polybrominated dibenzo furan
PCDD	polychlorodibenzodioxines
PCDF	polychlorodibenzofuranes
PCBs	polychlorobiphenyls
PCE	perchloroethylene or tetrachloroethylene
PFAS	per-and polyfluoroalkyl substances
PRB	permeable reactive barrier
PVC	polyvinyl chloride
POPs	persistent organic pollutants
ROC	return on capital
RoC	radius of capture
ROI	return on investment

RoI	radius of influence
RZ	reactive zone
S/S	stabilization/solidification technique
SVE	soil vapour extraction
TCE	trichloroethylene
TCH	thermal conductive heating
TPH	total petroleum hydrocarbon
VB	vertical barrier technologies
VOC	volatile organic compounds
ZVI	zerovalent iron
UXO	unexploded ordnance

5 Overview

5.1 Structure of this document

The remediation techniques dealt with in [Clause 9](#) are listed in [Table 1](#).

Table 1 — Remediation techniques presented in this document

9.1	In situ chemical oxidation (ISCO)
9.2	In situ chemical reduction (ISCR)
9.3	Enhanced in situ bioremediation (EISB)
9.4	Monitored natural attenuation (MNA)
9.5	Incineration
9.6	In situ thermal remediation (ISTR)
9.7	On-site thermal desorption
9.8	Soil vapor extraction (SVE)
9.9	Air-sparging
9.10	Multi-phase extraction (MPE)
9.11	Dual pump liquid extraction (DPLE)
9.12	Hydraulic techniques for groundwater remediation
9.13	Soil washing (ex situ)
9.14	Biopiling
9.15	Landfarming
9.16	Vertical barrier technologies (VB)
9.17	Cover systems
9.18	Permeable reactive barrier (PRB) systems
9.19	Immobilisation techniques for soil and solid materials
9.20	Excavation
9.21	Off-gas treatment technologies and wastewater treatment technologies

For each technique in [Clause 9](#), this document provides:

- a) remediation principle;
- b) scope and applicability of the technique (i.e. operating window);
- c) technology description (i.e. how is the technology realized/implemented);
- d) design considerations and dimensioning;
- e) key monitoring parameters;
- f) advantages and limitations;
- g) specific EHS aspects
- h) possible other remediation/containment techniques to be combined.

Guidance is provided as follows.

- [Clause 6](#) describes the principles for carrying out an option appraisal.
- [Clause 7](#) provides generic recommendations for selecting remediation techniques within an option appraisal process.
- [Clause 8](#) presents generic information on hazards and risks prevention to consider when implementing a remediation strategy on a contaminated site.
- [Clause 9](#) provides specific description and recommendations for a range of individual techniques that can be considered in an option appraisal (the possible combination of techniques and supporting techniques are also described in this clause).

[Clause 7](#) should be read prior to using information from [Clause 9](#).

NOTE All techniques are illustrated in [Annex C](#).

5.2 Generic concepts associated with remediation

A remediation strategy aims to control the unacceptable impacts and associated risks that have been established following the investigations and risk assessment (including cases where the elimination of concentrated contamination is technically complex and financially disproportionate). This strategy relies on the conceptual site model (CSM) which should be developed according to ISO 21365.

In the context of a point source contamination, the remediation strategy usually focuses, as a priority, on identifying the source of contamination and removing it and stabilising and/or confining and/or limiting the spread of the contamination arising from this source. The remediation strategy can consist of using treatment techniques that individually or combined within a treatment train destroy, transform, remove or stabilize contaminants present in the environmental medium. A remediation strategy can also help to manage diffuse contamination.

The production of a remediation strategy relies, among other things, on an options appraisal. This permits decisions to be made about which possible remediation options to adopt, for any particular contamination linkage, in order to address the unacceptable risks. A combination of several techniques can improve the efficacy of a remediation strategy. Consequently, the option for combining techniques in a treatment train should be considered in the options appraisal. Supporting techniques (whether chemical and/or physical) can also be used to improve the effectiveness of extraction techniques. This is the case for example for the thermal-enhanced soil vapour extraction technique.

Remediation should not introduce significant new risks and should be enduringly sustainable over the period in which the contamination risks need to be managed. Sustainable remediation encourages considering site reuse from the beginning of a remediation project. This can enable project leaders to exploit synergies of the redevelopment process while minimizing costs and environmental impacts associated with bringing

sites back to beneficial use, according to, amongst other things, sustainable remediation principles outlined in ISO 18504.

Remediation techniques can be categorised in many ways, for example according to their treatment location, the nature of the process(es) on which the treatment relies (physical, thermal, chemical, biological, etc.), the nature of contaminants being treated or the matrix being targeted.

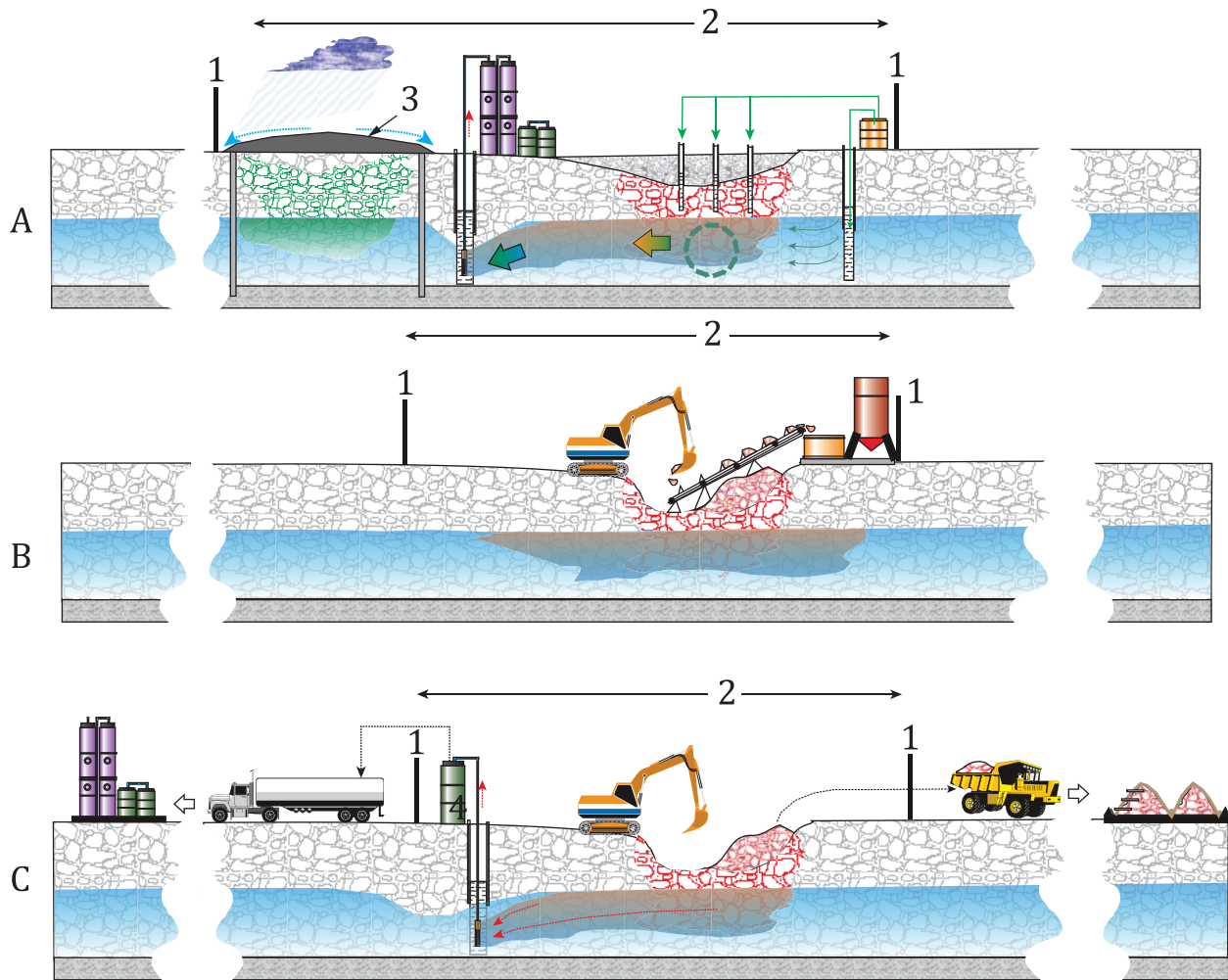
If categorised according to the remediation location, there can be the following distinctions amongst treatment techniques that can be chosen for a remediation strategy ([Figure 1](#)).

- All in situ treatment techniques that can be applied within the ground and that are physical engineering-based techniques, such as containment or hydraulic control techniques. These techniques treat contaminants directly in or from the ground or remove the contaminant from the environmental medium matrix (without post treatment). For the in situ treatment techniques, the treatment installation is built on-site and the treatment of the contaminants is applied directly to the ground. They can be referred to as in situ remediation techniques. They are applied to the medium and contaminants within the site's boundary.
- All ex situ treatment techniques can be applied to the extracted environmental medium (medium and or contaminant to be treated). Physical engineering-based techniques such as extraction are a prerequisite before applying the ex situ treatment. If the treatment occurs on site, they are referred to as on-site techniques (e.g. the soil is excavated or the groundwater is pumped, then treatments occur in the mobile units set up within the site premises). If the treatment occurs off-site, they are referred to as off-site techniques (e.g. contaminated soils or groundwater are excavated and delivered to a regular and authorized unit).

NOTE Off-site techniques are not covered by this document. They rely on off-site technologies which can be considered as “waste treatment technologies”, with also very specific local/national requirements regarding treatment targets and possibility in the reuse of the treated soil.

Treatment techniques can also be categorised according to whether they rely on transformation or destruction of contamination, whether in situ or ex situ (see [Annex B](#)).

A remediation plan is generally included in a legal authorization plan specific to each country and site.



Key

- A in situ techniques
- B on site (ex situ) techniques
- C off site (ex situ) techniques
- 1 fence
- 2 site
- 3 capping and vertical barrier
- 4 tank

NOTE Only on-site and in situ techniques are covered in this document.

Figure 1 — Schematic representation of in situ, on site (ex situ), and off site (ex situ) treatment techniques

6 Good practice for carrying out a strategies appraisal prior to implementing remediation strategy

6.1 General

When a decision has been made to remediate, strategy appraisal becomes necessary. The contaminant linkages identified through risk assessment become “relevant contaminant linkages”. They represent the unacceptable risks to the identified receptors. Strategy appraisal should be conducted by experienced and skilled expert(s), able to have a global overview of the analysed situation. At the end of a strategy appraisal

phase, a strategy appraisal report should be produced. Sustainability should be a driving issue in strategies evaluation and strategy development.

6.2 Identifying feasible remediation strategies

This first stage relies on identifying and producing a shortlist of feasible remediation strategies. It consists of a first selection of remediation strategies by screening all possible techniques that are relevant to the contaminant linkages and the site's context. Remediation techniques can be selected depending on the environmental medium that is being impacted by contamination and depending on the contaminants involved (whether organic or inorganic). The remediation strategy objectives can be considered as criteria to help in this selection, for example:

- need for protection measures and cut-off of the contaminant pathways;
- need to remove or destroy or transform the targeted contaminants within the source of contamination;
- need to treat groundwater (on site);
- need to treat off-gases (on site).

Overall, the choice of feasible remediation strategies shall consider the following questions as a prerequisite (see [Annex A](#)).

- Can the treatment technique treat the contaminant type being considered (see [Annex B](#))?
- Can the treatment technique target the environmental medium (or matrix) that needs to be treated (e.g. soil, groundwater, soil/solid matrix, soil gas matrix)?
- Can the treatment technique be compatible with the site's condition (access, topography, etc.)?
- Can the technique implementation allow the time necessary for the remediation objectives (e.g. expected abatement of contamination in the medium)?
- Can the expected order of magnitude of the required abatement be achieved by the technique?
- Can the implementation of the treatment technique achieve the remediation objectives (i.e. in terms of expected abatement of contamination in the medium)?
- Does the technique need to be combined with other techniques (e.g. as part of a treatment train) in order to achieve the remediation objectives?

In some cases, the nature of the remediation can also be a criterion to consider (physical, chemical, biological). In addition, the “remediation techniques” versus “contaminants that can be treated or targeted” matrix can be used to help in the selection of the most relevant techniques at this stage (see [Annex B](#)). The site information shall be up to date for this exercise. However, such a supporting matrix cannot replace specific studies required to fully characterise the site.

Objectives and possible responses to any regulatory controls that can be needed when remediation starts should be identified at this stage.

NOTE Some countries have developed publicly available on-line tools, which are similar to the concepts provided in [Annex A](#), to facilitate this selection.

6.3 Detailed evaluation of strategies appraisal

This second stage comprises evaluating the strategies chosen at the previous stage and deciding which are the most suitable for dealing with each relevant contaminant linkage in the short-term and long-term.

The evaluation required is a comparative assessment of the different possible remediation strategies considering the advantages and disadvantages associated with each strategy. Criteria are needed to conduct this evaluation and then to make the comparison. A holistic set of criteria should be agreed by stakeholders early in the process to reflect all three dimensions of sustainable remediation: environment, society and

economy (see ISO 18504). Technical and organizational criteria and legal and regulatory criteria can also be considered ([Table 2](#)).

A remediation technique that appears to be the most appropriate solution for a given contaminant linkage, can also have positive and negative effects on the environment or society beyond the site being considered. Taking these effects into account leads to the need to include sustainability criteria in the choice of the most appropriate remediation techniques for a given site. When a sustainable approach is followed, it can help to ensure that the benefit of doing the remediation is greater than its negative impact.

The strategy appraisal should enable the identification of the optimal economical and sustainable strategy, from the range of available ones. It should enable practitioners to weigh the economic and sustainability impacts of each available remediation strategy, to guide decision-makers in identifying and selecting the strategy that best addresses the remedial objectives.^[5] When aiming at addressing sustainable remediation, the relative ability of each strategy to achieve the remedial objectives in a safe and timely manner should be considered while optimising the environmental, social and economic value of the work.^[2]

ISO 18504 highlights different possible approaches for a detailed evaluation of strategies. These approaches can be based on a qualitative analysis (e.g. narrative analysis, non-parametric prioritization), semi-quantitative (e.g. multi-criteria analysis, pairwise comparison), or quantitative [e.g. cost benefit analysis, life cycle assessment, (environmental) footprint assessment, cost-effectiveness analysis]. However, the evaluation approach to be followed should be adapted on a case-by-case basis.^[2]

A minimum of two strategies should be reviewed at this stage. The detailed evaluation stage makes it possible to initiate a comparative discussion of the selected remediation strategies and, if necessary, to provide recommendations for tests and complementary studies.^[2]

In practice, the detailed evaluation of strategies usually consists of a cost benefit analysis. This type of evaluation can result in a summary table presenting the evaluation of the different remediation strategies for each of the chosen criteria. Multi-criteria analysis tools can be used to support this assessment. Five main families of criteria can be considered in accordance with ISO 18504 (see [Table 2](#)).

A plan for restoration of soil health and related soil ecological functions can also be needed (depending on remediation technique and planned land use). After remediation, the soil should be in better health than before and this does not only include removal of contaminants. This aspect should be considered when remediation techniques are evaluated in the appraisal.

Table 2 — Possible criteria to consider in a detailed evaluation assessment

Family of impact criteria	Example of impact criteria
Technical, normative and organizational	— Nature of contaminant — Impacted environmental media or matrix — Depth of the contamination below ground level
Economic	— Direct and indirect costs of remediation actions (including any restrictions of use that would be required, necessary mitigation measures and their possible maintenance)
Environmental	— Overall impact on all ecosystems, including impact on atmosphere, indoor air, soil health and related ecological soil functions, geotechnical properties, groundwater, surface water — Energy consumption — Reduction of the mass of contaminant — Waste production and waste reuse — Contribution to circular land use and construction process
Health/safety and socio-political	— Human health and safety [nuisances from the construction site (visual, noise, olfactory...)] (see Clause 8) — Increase in traffic (also in relation to the above environmental criteria) — Ethics and equality — Communities and community involvement: acceptability of the proposed redevelopment project that is associated with the remediation (expected future use, restrictions of use, rehabilitation objectives and resulting residual contamination)
Legal and regulatory	— Residual constraints — Required subsequent monitoring — Waste management
Source: adapted from ISO 18504.	

6.4 Selecting the final remediation strategy

This stage leads to selection of the final remediation strategy. In some cases, selecting only one strategy is not practical or sufficient. There can be more than one or different types of relevant contaminant linkages. The final selected strategy may comprise a single technique, or a combination of remediation techniques (which can be process-based techniques or engineering-based techniques), together with any necessary protective measures, and any restriction for specific uses within the site.

The techniques identified as appropriate are included in the development of a remediation strategy. If strategies cannot be identified, then the whole process shall be started again and reassessment takes place. Choices shall be validated by conducting treatability and feasibility tests in the laboratory, for complex situations with strong-stakes.

7 Generic recommendations for the selection of remediation techniques

7.1 General

The recommendations that follow are provided to aid the strategies appraisal and development of the remediation strategy, in terms of factors that should be taken into account (key aspects on design/dimensioning, key aspects monitoring, and advantages and limits).

Data collection and proper assessment of the contextual information (situations, site, and techniques) are required to support remedy selection and design.

It is important to recognise the following.

- a) All situations are unique – for example, it can be a crisis, a heated political climate or due diligence intervention where the timeline needs to be short regardless of costs or aggressiveness of the technique, or it can be a more peaceful environment where a full remediation train with trial and error can be carefully designed.
- b) All sites have specific conditions, for example regarding geology, hydrogeological profile, and contaminant situation that limit options regarding what can be done to remediate.
- c) All techniques have their own critical features such as treatable contaminants, timeline, and effectiveness, to be matched with remediation objectives.

Matching situations, sites and techniques is a complex task: remediation becomes then a technological art and as well as science and requires application of varied expertise and experience.

7.2 Considering the site's context

The technique or combination of techniques shall only be kept if they:

- can achieve the remediation objectives with the required effectiveness;
- can achieve remediation objectives within the required timeline (each technique has a specific timeline for its operation, which can be weeks, months, years or decades).

In situ and ex situ techniques may be sorted accordingly. Also, the more urgent the situation, the more aggressive and expensive the technique can be.

Different approaches are possible to define remediation objectives, to appreciate the performance of the technique and the achievement of in situ remediation actions:

- a) compliance with risk-based remedial levels and/or regulatory value for groundwater, drinking water and/or ambient air;
- b) the asymptotic decay of extracted concentrations or mass fluxes and the economical limits of the technique (cost per mass unit extracted) – possible rebound effects shall be taken into account in the remediation achievement process before the definitive closure of the remediation works;
- c) pathways control or reduction;
- d) land use modification to manage exposure.

The performance of remediation techniques varies greatly with order of magnitude reductions covering between 1 decade and 4 decades (from low to very high). The risks of under or oversizing the remediation strategy and to not reach the remediation objectives in the targeted time frame are high.

NOTE 1 For example, for groundwater contaminated with 1 500 µg/l pollutant and a remediation objective of 10 µg/l, the order of magnitude reductions is three (3). In such situations, only a very high efficiency technique can be tested.

One can be reluctant to apply a chemical process because of potential environmental associated impacts. Social and economic criteria (site reputation, residual concentration) can also interfere with a purely mathematical timeframe and efficiency compatible technique. Thus, subjective or imperative interests should be collected and accounted for in the choice of remediation technique.

Also, the remediation does not occur in a vacuum. Some sites already have wells or systems installed for protection measures and cut-off of contaminant migration pathways. Techniques that can use the existing network of wells or site process facilities (e.g. some have water treatment plants) are at an advantage.

NOTE 2 Understanding the geochemistry at the site is especially important for designing metal remediation such as ISCR and for understanding the long-term stability of precipitates and adsorbed species. For example, long-term stability of metal precipitates depends on whether they are stable in relation to the surrounding environment (long-term pH and redox in groundwater zone can be determined by pH in incoming groundwater and redox). It is also important that the feasibility and treatability studies in the laboratory are performed at conditions (e.g. pH, redox) close to those at the site, and that these studies are realistic in terms of possibilities of technical and economic implementation at large-scale.

7.3 Remediation set up on-site

The site shall provide the needed space for the technique to access the contamination. This is a key criterion which can help choice of the most relevant techniques based on their needed space for operation. For example, if a building with underground car park is to be constructed on contaminated ground, the most feasible strategy is likely to be excavation with off-site treatment. Another example, choosing an injection technique using direct-push to install wells would need a fine network of wells covering the whole groundwater plume. Such a set up can be unrealistic if the site is covered by buildings or located in a town centre. Only a small number of recirculation wells with a chemical or biological technique can be used.

Application of a remediation technique needing nearby facilities, such as landfills or activated carbon regeneration facility, is likely to be difficult at sites that are far from major urban and industrial centres. For example, on remote sites, gas treatment shall be oversized (with an on-site oxycatalyser) if there is no possibility of landfilling or regenerating the GAC.

Various data and information are required to support remedy selection and design. It is necessary to identify the source of contamination (and targetable contaminants), the environmental media impacted by contaminants, the geological and hydrogeological settings, and the remediation objectives in order to dimension most remediation techniques for them to be effective.

A remediation action is generally planned for removal, destruction or transformation of the targeted contaminant within the source of contamination. Thus, characterization of the source is paramount. This characterization should aim at establishing a robust conceptual site model, including:

- a) the (hydro)geological setting;
- b) the mass and concentrations distribution (in 3 dimensions) of contamination being considered within the site (i.e. the amount of each contaminant present within the area to be targeted);
- c) the type and nature of contaminant, and depending on the technology foreseen;
- d) the in situ (bio)geochemical conditions.

7.4 Techniques prerequisites

Each technique has constraints in terms of depth of action, soil permeability, groundwater etc. so it is possible to eliminate techniques that do not meet the hydrogeological and source criteria of the site. For example, the MPE 'stinger' technique is limited by the ability to entrain liquids and is unsuitable for treatment of groundwater at depth. Biological treatments can also be pH constrained.

All the technique prerequisites shall be identified prior to choosing between techniques. Each successive component of a remediation train also has prerequisites which shall be accounted for. To conduct in situ remediation operations both process engineering skills and expertise in (hydro)geology are required.

When on-site operations are conducted, contaminant extraction rates depend on local (hydro)geological settings, the properties of the substances and processing capacity. The choice and the design of in situ and on-site remediation technologies often require preliminary laboratory testing (treatability and feasibility tests) and, in some cases, field pilot testing. This is the case for example for ISCO.

7.5 Techniques collateral effects

The effect of different remediation methods on soil health including soil functions is to be noted. For example, techniques such as pump-and-treat do not affect life in topsoil very much while techniques such as ISCO, ISTR or in situ immobilisation techniques can destroy natural organic matter or alter life in the soil material.

7.6 Laboratory testing and pilot tests

The choice and the design of in situ and on-site remediation technologies can require preliminary laboratory testing (treatability and feasibility tests) and, frequently field pilot testing. The evaluation of the technique feasibility can consist of:

- orientation tests which aim to validate the possibility of implementing a specific remediation technique;
- performance evaluation tests, which are used to verify that the objectives can be achieved and to estimate the speed of the planned treatment and its duration.

Dimensioning a remediation technique relies on engineering skills. It comes after the feasibility evaluation.

Considering the likely effectiveness of a remediation technique is important at the strategy appraisal stage. This is especially the case for containment systems. When evaluating the technique effectiveness (both short-term and long-term) it is important to know:

- to what extent the remediation technique will be effective at the time of installation;
- how long after installation the full effect will be realized;
- whether effectiveness will decrease with time (taking into account conditions present at the contaminated site and the design objectives that have been set).

A comprehensive remediation LCA may be realized if needed.^[7]

8 Generic recommendations for managing hazards and risks during remediation

8.1 General

During the remediation and management of a contaminated site, the protection of the health and safety of all people working at, or otherwise involved with, the site is paramount. This includes workers at the site, visitors to the site and third parties such as users of adjoining land, residents, passers-by and sight-seers.

Remediation of contamination presents risks to health and safety that are unique and go beyond those associated with a standard construction site. Many of these hazards are known and predictable, but some are unknown. Health and safety systems shall be designed to handle both situations. Hazards can be distinguished by whether they are related to contaminants already present prior to remediation within the environmental media, or to the remediation operations once they have started. Materials that can present a physical, chemical and/or biological risk can be in solid, liquid, gaseous or dust form. They can be in different matrices such as soil, sediments, groundwater, soil vapour. General hazards can include fires, explosions, confined spaces, underground and above-ground services (e.g. gas lines and electricity), plant, manual handling and slips, trips and falls.^[9] Following the identification of these hazards and the assessment of associated risks, measures can be considered with the help of existing referentials (see for example Reference [9]). As hazards associated with the implementation of remedial actions vary significantly between technologies, health and safety hazards that are specific to the implementation of a particular remediation technique are listed for each technique in [Clause 9](#). All parties should work together to provide a sound management of hazards and risks arising from the application of remediation techniques.

This Clause focuses on specific risks management aspects of remediation projects.

8.2 Risk management process

8.2.1 General

A risk management process provides a framework to assist in decision-making relating to all aspects of work health and safety. Risk management is a process that involves four steps:

- a) identify hazards;
- b) assess risks;
- c) control risks;
- d) review measures.

A remedial health and safety plan should be prepared on every site where remediation is being undertaken. It describes, in particular, tasks designed to minimize or eliminate hazards for the staff performing field activities (incidents and injuries with work), equipment, the environment, and the general public. Stakeholders should always refer to this document, along with recording of risk assessments, reporting incidents and regular reviews of measures put in place.

In most jurisdictions there are regulations and authoritative guidance concerning the hazards listed in [8.2.3](#) to [8.2.21](#) that apply in all work situations.

A risk assessment for health and safety hazards can be conducted using a risk matrix, which assesses the severity of the risk against the likelihood of exposure to the hazard. Each activity has a separate row, and scores (for example see [Table 3](#)) are given for risk both before and after measures. If risk cannot be reduced below an acceptable threshold even with mitigation, the activity is deemed unacceptable and it should be eliminated by finding a different way of working.

Using a matrix can be very helpful for prioritizing actions. It is suitable for many assessments but particularly lends itself to more complex situations. However, accurately judging the likelihood of harm requires a fair degree of expertise and experience. Misjudging risks can result in applying unnecessary controls or, conversely, failing to apply important ones.^[10]

Table 3 — Risk matrix for prioritization of actions (source ISO 18400-103^[10])

Potential severity of harm				
Likelihood of harm occurring		Slightly harmful 1	Harmful 2	Extremely harmful 3
	Highly unlikely 1	Trivial 1	Tolerable 2	Moderate 3
	Unlikely 2	Tolerable 2	Moderate 4	Substantial 6
	Likely 3	Moderate 3	Substantial 6	Intolerable 9

NOTE 1 For further information on this process when applied to site investigation, see ISO 18400-103^[10].

NOTE 2 The higher the score, the higher the risk.

8.2.2 Hazards and controls associated with contaminated soil and groundwater

People can be exposed to chemical contaminants through inhalation (particles, dust, fibres or fumes and vapours), ingestion (soil particles, dust, contaminated food or water) or skin and/or eyes absorption.

Site conditions should be considered when assessing the hazards and risks associated with contaminated soils and ground water, including the toxicity of contaminants, the protective equipment required and the various remediation measures.

8.2.3 Asbestos

Asbestos can be present at a contaminated site as bonded material such as asbestos-containing cement sheeting or linoleum, as friable fibrous lagging such as on pipe work and boilers, or as fibres within the soil. It is frequently present in anthropogenic materials such as fill and made ground. According to the legislation of each country, the safety measures range from simple access restriction to the operation of a controlled atmosphere tent for the removal of asbestos fibres. Appropriate measures should be described in the remediation plan.

8.2.4 Dust

Weather conditions and remediation activities can generate dust. This can lead to concerns about potential health impacts for workers as well as for people in the surrounding community.

Site conditions should be considered when assessing the hazards and risks associated with dust, including for example likely sources of dust generation, distance to nearest sensitive receptors, potential toxicity of the dust (e.g. silica, asbestos, and characteristics of the chemical substances within particulate matter), and remediation mitigation measures such as water sprinklers. Timing of the remediation to a rainy season is likely to minimise dust exposure because of higher soil moisture content, etc.

NOTE Stockpiles can represent a considerable source of dust, due to their height, uncompacted nature, and (frequently) proximity to sensitive receptors.

8.2.5 Offensive or noxious odours

The release to the air of many chemical substances, particularly those associated with petroleum hydrocarbons, gasworks wastes, organic solvents or putrescible wastes, can generate offensive odours or noxious vapours. These can cause varying types and degrees of hazard, such as explosive conditions, toxic environments, unacceptable health risks (either acute or chronic), and objectionable odours. Odours can also cause community concern as the public can perceive odours as posing a poisoning issue.

When dealing with volatile pollutants, an assessment should be made of the need for the regular analysis of atmospheric levels of pollutants (e.g. hydrogen sulfide, ammonia, sulfur dioxide, ethyl and methyl mercaptans, VOCs) on site and at site boundaries to ensure that workers and residents are not being exposed to unacceptable levels that can give rise to adverse health effects.

8.2.6 Contaminated waste

The remediation of a contaminated site very often generates waste that contains residual contaminants (e.g. excavated contaminated soil or pumped groundwater, used PPE, single-use equipment such as tarpaulins that covered stockpiles, or building rubble).

Site conditions should be considered when assessing the hazards and risks associated with contaminated waste, including the toxicity of contaminants, life cycle of contaminants, and life cycle of the waste material, and their implications for waste classification and waste handling, treatment and disposal.

8.2.7 Remediation equipment

Some remediation equipment is highly specialised and carries various hazards during operation (hot surface, pressurised pipes, electric shocks, handling of toxic injection chemical, etc.). Typically, these systems should be managed and overseen by a specialist contractor who is familiar with the operation, potential hazards and appropriate controls. That contractor should have health and safety information pertinent to that equipment which should be included within the site health and safety plan. This information should include risk assessments and hazards and operability studies for process-based equipment. Adequate emergency

stop systems are required and equipments such as a satellite cell phone or a specific isolated worker alert device can be necessary.

Common controls include preventing unauthorised people from being exposed to the hazard (e.g. by using physical barriers) and requiring training prior to operation.

More information on specific hazards posed by remediation equipment can be obtained from the remediation equipment manufacturer.

8.2.8 Unexpected finds

In addition to the contamination known to be on the site, remediation works can uncover areas previously not identified as contaminated, referred to as “unexpected finds”. These can be new areas of contamination similar in nature to that already at the site, a new type of contamination not previously identified at the site or other hazards including UXO. Unexpected finds are special cases that shall be addressed on a case by case basis, commencing with stopping work in the area and investigating the issue. Once the nature and extent of the unexpected find has been determined, the health and safety plan for the site should be updated.

The health and safety plan should have a procedure for handling unexpected finds.

An approach such as last-minute risk assessment (LMRA) can be used to tackle unexpected finds, including in case of simultaneous operations.

8.2.9 Long-term monitoring

In some instances, monitoring of a site long-term is necessary as part of remediation, or validation, or both. The development of long-term monitoring program shall include the risk management process to identify the hazards and assess and control the risks for workers carrying out the monitoring as well as members of the public who can follow them or watch them.

8.2.10 Outdoor work

Many remediation projects involve working outdoors for some or most of the working day. Site conditions should be considered when assessing the hazards and risks associated with outdoor work, including reduced capacity for maintaining personal hygiene, exposure to solar rays, exposure to cold, exposure to wet weather, and biological hazards (e.g. dogs, cattle, snakes, ticks). Proper training should be given based on outdoors and survival specifics.

8.2.11 Remote or isolated working

Some remediation work is carried out in places that are remote or isolated due to the location, time or nature of the work being done. In some situations, a worker can be alone for a short time (e.g. conducting regular boundary monitoring or repairing fences on a large site away from other workers). In other situations, the worker can be on their own for days or weeks in remote locations. Working alone or remotely increases the risks in any job. Proper training can be given including remote place self-medication. Specific operating procedures (registry, fixed calls), and equipment such as satellite cell phone or man down alarms can be necessary.

8.2.12 Underground services and pipelines

One of the major hazards associated with excavation or drilling during remediation activities is potentially striking an underground service, utility or structure, including for examples utility pipelines, underground storage tanks, irrigation systems, basement voids, and mine shafts. Before commencing excavation work, all reasonable steps shall be taken to obtain current underground services information that relates to the site and areas adjacent to the site. Every person carrying out the excavation shall be given this information and it shall be available for inspection by relevant authorities until the excavation is completed.

If any suspect or unexpected structures or damage to a service occurs, the excavation should be halted. Emergency procedures should be enacted if required, such as deploying spill kits, isolating the area

or removing sources of ignition. If safe, the excavation should be inspected, and the service or structure identified. The appropriate utility company or service provider shall be advised as soon as possible, and the excavation shall be left open, suitably fenced, with appropriate warning notices posted.

8.2.13 Ground stability

The vibration from excavation and drilling, from plant, or from the movement of heavily laden trucks can sometimes result in the collapse of pits, or damage to foundations of adjacent structures or to underground services or utilities. Vehicles can also be stuck in loose soils. Site conditions should be considered when assessing the hazards and risks associated with ground stability, including the current or former presence of, for example, mining activity, cellars, underground storage tanks, sub-surface combustion, and unconsolidated soil or fill material.

8.2.14 Excavations

Excavation involving the removal of soil or rock from a site to form an open face, hole, trench, cavity, or similar, using tools, machinery or explosives is very common on remediation sites.

Specific hazards can include a person falling into an excavation, a person working in an excavation being trapped by the failure of excavation wall(s) or struck by moving machinery or something falling on them, instability of an adjoining structure caused by the excavation, hazardous atmosphere in an excavation, particularly if there are volatile contaminants present, plant striking underground or overhead services during excavation (see [8.2.12](#)).

8.2.15 Unexploded ordnance (UXO)

The potential for the site to contain or be affected by unexploded ordnance should be assessed. Measures should be undertaken to mitigate risks during the site investigation that precedes remediation if determined to be necessary by a UXO risk assessment.

NOTE See for example guidance in Reference [\[11\]](#).

8.2.16 Confined space

A confined space is determined by the hazards associated with a set of specific circumstances and not just because work is performed in a remediation tent. Confined spaces are commonly found, for example, in tanks, ducts, sewers or septic tanks, deep trenches and tunnels.

The risks of working in confined spaces can include loss of consciousness, impairment, injury or death due to the immediate effects of airborne contaminants, fire or explosion from the ignition of flammable contaminants, asphyxiation resulting from oxygen deficiency or immersion. These risks can be compounded by the difficulty in rescuing and treating an injured or unconscious person.

It is preferable to alter the work such that entry into the confined space is not required. However, if this is not possible, a suitably trained person should undertake site-specific hazard identification, provide guidance on measures, and undertake the work.

8.2.17 Hazardous chemicals and dangerous goods

During remediation works, it is common to have hazardous chemicals or dangerous goods either being the subject of the remediation or being used during the remediation process. Hazardous chemicals are those that, following worker exposure, can have an adverse effect on health.

Examples of hazardous chemicals are poisons, chemicals that can cause burns or skin and eye irritation, and chemicals that can cause cancer. Examples of hazardous chemicals or dangerous goods that can be encountered on a remediation site are petroleum products (including residues of petroleum products in underground storage tanks), chlorinated hydrocarbons, chemical adhesives, solvents for cleaning or calibrating equipment, or chemicals used as additives for in situ chemical oxidation (permanganate, ozone, other reagents).

There are two broad types of hazards associated with hazardous chemicals:

- a) health hazards linked to the properties of a chemical that have the potential to cause adverse health effects;
- b) physicochemical hazards linked to physical or chemical properties of the chemical, mixture or particle that pose risks to workers other than health risks, as they do not occur because of the biological interaction of the chemical with people.

8.2.18 Hazardous manual tasks

Manual work is common during remediation work, and some manual tasks can be hazardous. A hazardous manual task is any task that requires a person to lift, lower, push, pull, carry or otherwise move, hold or restrain any person, animal or thing, involving one or more of repetitive or sustained force, high or sudden force, repetitive movement, sustained or awkward posture, or exposure to vibration.

Examples of hazardous manual tasks that can be encountered on a remediation site are carrying sections of fence, lifting validation sample containers into a vehicle, installing remediation equipment, handling equipment (pipes, pumps, power generators, etc.), refuelling reagent. Appropriate aids to lifting and other movements should always be used.

8.2.19 Slips, trips and falls

The nature of remediation work often creates fall hazards. Fall hazards are found where work is carried out at height, for example, loading and unloading a large truck. Falls can also occur at ground level into holes, for example trenches or service pits.

Site conditions should be considered when assessing the hazards and risks associated with outdoor work, including for example any structure or plant being constructed, demolished or dismantled, inspected, tested, repaired or cleaned, fragile surfaces, potentially unstable surfaces, using equipment to work at the elevated level, sloping or slippery surfaces where it is difficult for people to maintain their balance, holes, shafts or pits into which a worker can fall.

A checklist can be useful to identify hazards and risks relating to falls. Fencing, and appropriate safety harnesses should be employed as necessary.

8.2.20 Plant and equipment

Most remediation projects involve the use of plant and equipment. There are significant risks associated with using plant and severe injuries can result from the unsafe use of plant, including limbs amputated by unguarded moving parts of machines, being crushed by mobile plant, sustaining fractures from falls while accessing, operating or maintaining plant, electric shock from plant that is not adequately protected or isolated, burns or scalds due to contact with hot surfaces, or exposure to flames or hot fluids, hearing loss due to noisy plant, or musculoskeletal disorders caused by operating plant that is poorly designed.

Examples of plant and equipment hazards that can be encountered on a remediation site include improper use of equipment, including power tools, pedestrians being struck by vehicles moving around the site, hazards from being close to, on top of, or beneath operating plant or equipment, reversing equipment or plant, air blast from compressed air equipment, etc.

8.2.21 Noise

Many remediation projects can create noisy environments for at least some time, particularly those involving heavy machinery or specialised remediation equipment. Noise from remediation activities can also be a nuisance to members of the public near a site. Noise that is a nuisance can occur at decibels below that which is considered unsafe.

Examples of noise hazards that can be encountered on a remediation site are drilling rigs, heavy machinery, power tools, specialised remediation equipment, such as diesel pumps for groundwater extraction, normal site operations (e.g. if the remediation occurs inside an operational factory).

9 Remediation techniques description

9.1 In situ chemical oxidation (ISCO)

9.1.1 Technique principle

ISCO is an in situ-technique that aims at transforming a contaminant into less mobile and/or less toxic species through chemical oxidation. It relies on the injection of a chemical oxidant (reagent) below ground surface. The oxidation state of the reagent is decreased by accepting an electron to oxidize the target species.

9.1.2 Scope and applicability of the technique (operating window)

ISCO can be used to remediate both unsaturated and saturated zones on a wide range of organic and inorganic compounds even at high concentrations (see [Annex A](#)). Applicability of ISCO depends on the nature of targeted compounds and the oxidant used. Permanganate is effective on alkanes, chlorinated ethanes, dichloroethylene isomers, vinyl chloride, phenols, and some PAHs. Fenton reagent is able to treat sorbed contaminants and DNAPLs. Ozone can also rapidly attack organic contaminants and breaks down their organic carbon-to-carbon bonds. Persulfate is more stable in the subsurface than other oxidants; it can oxidize benzene (in the cases of remediation of fuels spills and benzene, toluene, ethylbenzene, and xylene contaminated groundwater). Hydraulic conductivity greater than 10^{-7} cm/sec is recommended to ensure the effective delivery of the reagents to the zone to be treated by using injection method. The natural oxidant demand (NOD) shall be satisfied first by the injection of a significant amount of oxidant, then the oxidant demand of the contaminant can be satisfied.

9.1.3 Technology description

There are different methods to make the oxidant come into contact with the contaminant (see illustrations in [Annex C](#)):

- a) using injection wells (the oxidant is injected into the soil with the use of pressure which requires vertical injection wells);
- b) using injection via direct push methods;
- c) using recirculation (combining direct injection or infiltration and groundwater abstraction);
- d) infiltrating the oxidant passively through screened vertical wells or drains in trenches;
- e) (deep) soil mixing (e.g. soil is mixed with the oxidant with the use of auger drills);
- f) carrying out ozone-sparging (e.g. the injection of ozone into the saturated zone).

9.1.4 Design considerations and dimensioning

ISCO can be applied both on soil and/or groundwater. In case of soil mixing, the choice of oxidant depends on soil characteristics and characteristics of the contamination source. In case of groundwater, the choice of oxidant depends on the environmental characteristics (geology, hydrogeology, geochemistry) as well as the characteristics of the contamination source and/or contaminant linkage being targeted by the ISCO technique (type of contaminants, distribution). Generally, the most powerful oxidants have the following characteristics:

- a) shorter half-lives and persistence time;
- b) smaller radius of influence;
- c) larger range of oxidable organic compounds.

Sizing and designing an ISCO treatment requires laboratory tests to choose the most efficient oxidant and to optimize the formulation of the oxidant solutions. The number of injections shall be determined precisely. In the same way, in situ pilot tests are strongly recommended to confirm technical choices before full-scale

operation. Hydrodispersive mathematical models can be useful to estimate the position and the dynamic of the in situ oxidative front and to design the injection network (position, number, distance, depth and position of screens, etc.). Tracers tests (mostly bromide, uranine) provide an estimate of the radius of influence of an injection.

9.1.5 Key monitoring parameters

Monitoring is required while ISCO is operated (it is conducted frequently to ensure that the technique is working as intended) but also post-treatment. To determine the effectiveness of ISCO, the following items can be monitored:

- a) groundwater levels;
- b) contaminant, reagent by-products concentrations evolution over time as well as redox conditions;
- c) summary of the volume of soil/groundwater being treated;
- d) summary of the volume of oxidant added;
- e) summary of contaminant concentrations above/below applicable remediation targets (taking into account rebounds effects);
- f) concentration of co-existing substances in soil that can cause groundwater contamination by reaction with oxidant.

9.1.6 Advantages and limitations

ISCO can be relatively fast to achieve its objectives. It can be applied on a wide range of organic and inorganic, compounds (aqueous, sorbed, and non-aqueous) even at high concentrations. ISCO does not generate large amounts of waste. This reduces contaminant exposure, time, and costs because disposal or treatment is minimal.

There are limitations for application at heavily contaminated sites. It is possible to have less oxidant or hydraulic control compared to other remedial technologies. Chemical, physical and biological properties of the soil can be altered using ISCO, which can potentially lead to the introduction of toxic compounds into the ground. For example, ISCO can cause the destruction of natural organic matter on which contaminants (especially organic ones) are adsorbed, or the oxidation of certain metals and metalloids present in a reduced precipitated state. Furthermore, oxidants are not very selective and react with many oxidable species, which leads to a higher consumption of oxidants. The introduction of peroxide and permanganate can lead to the formation of particles (precipitation of manganese or iron) and reduce the permeability of the aquifer ("clogging" effect). There can be a short persistence of some oxidants due to fast reaction rates in the subsurface. In the case of oxidant injection, the heterogeneity of hydraulic conductivity in the subsurface is a limitation factor for ISCO (see [Clause 7](#)).

9.1.7 Specific EHS aspects

For oxidation to occur there shall be a large redox potential which generally requires special safety requirements to handle these oxidants, such as safe handling and storage. Other aspects requiring special safety measures include:

- a) management of hazardous permanganate and persulfate dust;
- b) increase of flammability of many materials due to the presence of ozone;
- c) the generation of ozone, which can involve high-voltage-equipment concerns;
- d) potential risk for uncontrolled exothermic reactions;
- e) potential for preferential migration of oxidants and/or contaminants (liquid or vapor), through underground utilities.

9.1.8 Other techniques or containment approaches that can be combined with the technique

Sometimes, if the oxidation is not complete, the generated products can also be more biodegradable than the initial contaminants, which allows treatment to be combined with bioremediation techniques at contaminant linkage level. Organic matter is sometimes added at the end of the treatment in order to refunctionalize the soil.

9.2 In situ chemical reduction (ISCR)

9.2.1 Technique principle

ISCR is an in situ technique which consists of injecting a reducing agent in soils. It involves the injection of a reductant or reductant-generating material in the subsurface for degrading toxic organic compounds to potentially nontoxic or less toxic compounds, immobilizing metals by adsorption or precipitation, and degrading non-metallic oxyanions such as nitrate.

9.2.2 Scope and applicability of the technique

ISCR is mainly used to remediate chlorinated contaminants that can be present in the saturated zone and unsaturated zone (see [Annex A](#)). It may be applied in some case to inorganics. Like every other remediation technique using injection, homogeneous and permeable soil and aquifer are required for efficient operation.

9.2.3 Technology description

ISCR can be applied both to soil and/or groundwater. The technique relies on using a reducing agent. The most commonly used reductant is zerovalent iron. Other reductants that are used to address metals include ferrous iron, sodium dithionite, sulfide salts (calcium polysulfide), and hydrogen sulfide. The introduction of substrates to microbially produce reducing conditions favourable to microbial reduction of iron and sulfates has also been used to treat dissolved metal contamination. ISCR of metals and metalloids is accomplished by a stabilization mechanism where the target subsurface area geochemistry is manipulated to bring about the direct precipitation, co-precipitation, or indirect adsorption and precipitation (e.g. adsorption to iron hydroxides) of the target chemicals. It leads to a long-term in situ sequestration of the metals.

Remediation of metals using anaerobic biostimulation does not generally involve microbial action with the metals directly, but rather some of the products of their respiration can be used for metal stabilization through direct or co-precipitation. Under strong anaerobic reducing conditions, which can be created using an electron donor and carbon source (e.g. methanol, lactate, molasses) sulfate reduction conditions can be created in an aquifer. An illustration of the technique is provided in [Figure C.3](#) in [Annex C](#).

9.2.4 Design considerations and dimensioning

In case of soil mixing, the choice of reductant depends on soil characteristics and characteristics of the contamination source. In case of groundwater, hydrodispersive numerical modelisation is often required to estimate the position and the dynamic of the in situ reductive front and to design the injection wells network (position, number, interwell distance, depth and position of screens, etc.). Other key parameter to design ISCR remediation are:

- a) injection settings: vertical distribution, flow and pressure of injection, duration, injection type, well size;
- b) extraction settings: well number, well size, flow and pressure rate, location of wells, water treatment unit.

9.2.5 Key monitoring parameters

To determine the effectiveness of ISCR, key monitoring parameters are:

- a) groundwater levels and groundwater flow direction;
- b) the depth of the various structures;
- c) the depth of injection of the reducer;

- d) the quantity of reducer and water being used, injection flow and pressure;
- e) contaminant concentrations and physicochemical parameters (including potential redox) of groundwater upstream, downstream and at the source and by-products concentrations.

9.2.6 Advantages and limitations

ISCR can be effective on a broad spectrum of organic pollutants. It relies on fast reactions. It can be applied to high concentrations of contaminants. The reduction can be complete (total mineralisation). If the reduction is not complete, the degradation by-products generated can sometimes be more biodegradable than the initial pollutants, which allows the treatment to be combined with aerobic/anaerobic bioremediation techniques. In addition, conventional reducers are not very expensive. The process, unlike ISCO, does not destroy soil organic matter.

However, when using ISCR technology, there is a possibility of contaminant transfer and reductants arriving into groundwater. Therefore, a good understanding of the geology and hydrogeology is needed to predict the movement of reductants and to locate recovery wells to allow full recovery of reductants if necessary. The chemical, physical and biological properties of the soil can be temporarily altered but to a much lesser extent than with ISCO. If reduction is not complete, the degradation by-products generated can be more toxic than the original pollutants (e.g. vinyl chloride for perchloroethylene and trichloroethylene). Reducers are not very selective and react with many reducible species. ISCR relies sometimes on wastewater of off-gas treatment.

9.2.7 Specific EHS aspects

Changes in pH and redox can mobilize contaminants other than the targeted ones. Degradation products can be more soluble than the original contaminant. If micro or nano ZVI is used there is a risk for formation of explosive gas.

9.2.8 Other techniques that can be combined with the technique

Combining reductant techniques can often improve the efficiency of the cleanup. After the control of contamination source, ISCR is often used as a diffusion zone remediation.

9.3 Enhanced in situ bioremediation (EISB)

9.3.1 Technique principle

EISB is an in situ engineered technique that introduces physical, chemical and biological changes to the soil to create the conditions necessary for microorganisms to transform contaminants of concern to innocuous by-products. Microbial activity is stimulated or enhanced through:

- bioaugmentation, in which microorganisms are introduced (for example cultures of microbes known to degrade the contaminants of concern or genetically engineered microorganisms); or
- biostimulation, in which the growth of specific microorganisms (or consortia of microorganisms) is stimulated through the introduction of amendments comprising either nutrients or an electron donor.

Biodegradation of organic compounds is based on a redox reaction between an electron donor (contaminants being targeted) and an electron acceptor.

9.3.2 Scope and applicability of the technique (operating window)

EISB can be applied to both organic (e.g. petroleum hydrocarbons) and inorganic compounds (e.g. perchlorate) and in both the unsaturated and saturated zones (see [Annex A](#)). Mineralization occurs for organic compounds when all carbon-to-carbon bonds have been broken. Biotransformation occurs when:

- a) the speciation of inorganic compounds or organic compounds changes through microbiological activity;
- b) organic compounds are transformed into molecules of lower molecular weight (metabolites).