International
Standard

ISO 24212

Remediation techniques applied at contaminated sites

Techniques de dépollution appliquées aux sites pollués

First edition
2024-09

Reference number
ISO 24212:2024(en)

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Published in Switzerland

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 190, *Soil quality*, Subcommittee SC 7, *Impact assessment*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 444, *Environmental characterization of solid matrices,* in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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 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
VBT	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 (VBT)
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 aspectss

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).

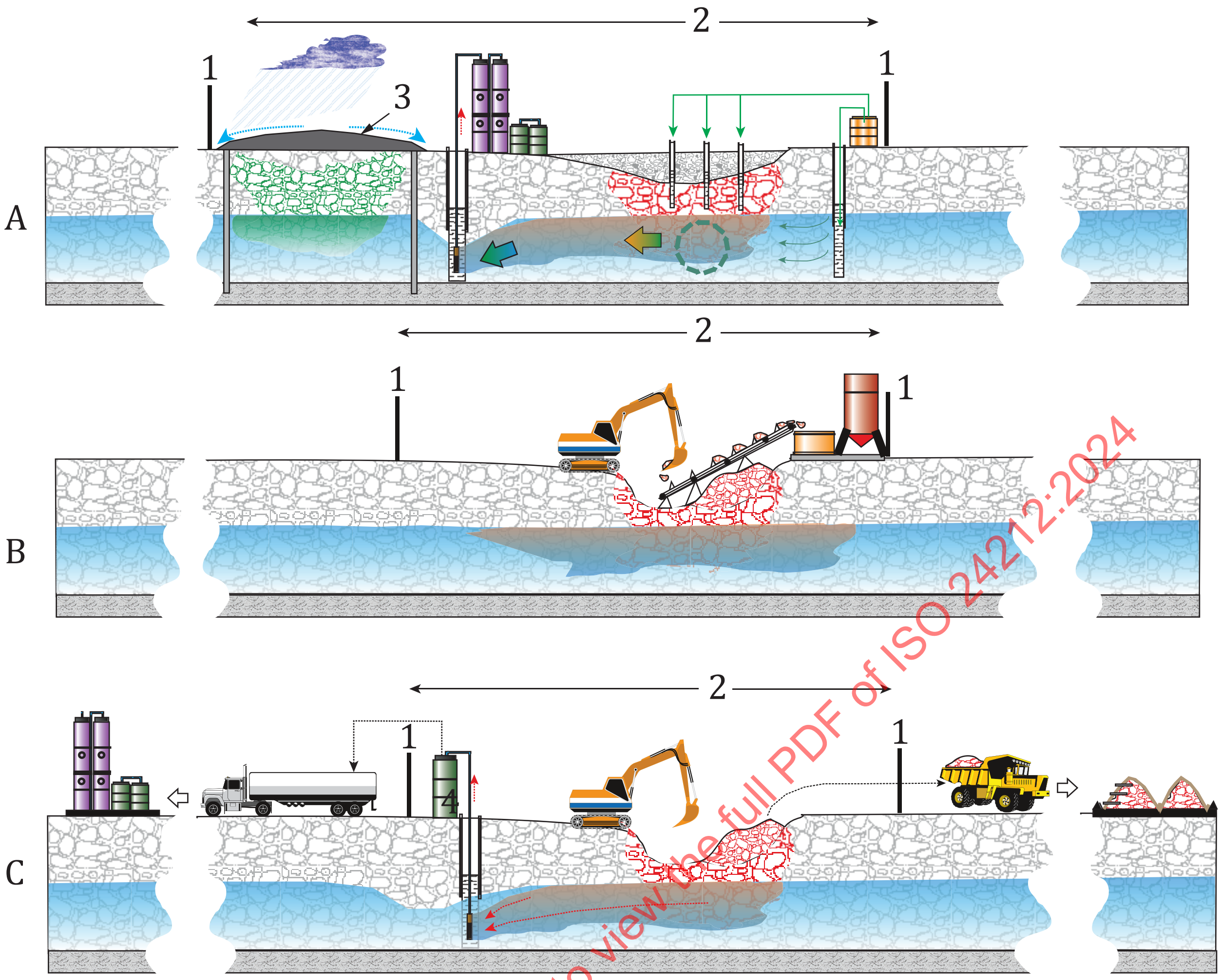
— All in situ treatment techniques that can be applied within the ground and that are physical engineering-based techniques, such as containment or hydraulic control techniques. These techniques treat contaminants directly in or from the ground or remove the contaminant from the environmental medium 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 prerequistes

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 referencials (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		
		Slightly harmful 1	Harmful 2	Extremely harmful 3
Likelihood of harm occurring	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 rebonds 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).

9.3.3 Description of technology

There are several EISB processes, each with specific design requirements, including:

a) loop systems, primarily used to clean up contaminated groundwater [contaminated groundwater from downstream is pumped downgradient from the source with wells to the surface, the abstracted groundwater is mixed with nutrients and an electron donor (commonly oxygen), and the treated water then injected upgradient in the same aquifer];

b) oxygen injection or oxygen release compound (ORC) injection (both aerobic), through an injection gallery for the remediation of organic hydrocarbons in both saturated (e.g. ORC-Barrier) and unsaturated zone;

c) ozone injection (this strong oxidizing agent has potentially a toxic effect on subsurface microbial populations, but ozone can be an efficient means of spreading oxygen throughout a site due to its high solubility);

d) accelerated anaerobic in situ bioremediation (electron donors and acceptors are introduced into a contaminated site in order to increase the population of anaerobic microorganisms thereby increasing the natural ability of microorganisms to degrade the contaminant).

The costs of EISB techniques vary widely depending upon the type and degree of enhancement needed as well other environmental factors. An illustration of the technique is provided in Figure C.4 in Annex C.

9.3.4 Design considerations and dimensioning

The biodegradation of compounds using microorganisms relies on the type and concentration of the targeted contaminants, electron acceptor and time period for which microorganisms are exposed to contamination. The main environmental factors to take into account to assess whether or not biotransformation takes place and to dimension EISB operations are:

a) pH, concentration, temperature and nutrient availability;

b) time and groundwater flow evolution;

c) dispersal of electron acceptors and nutrients for microbial growth;

d) presence or absence of metals such as mercury, lead and cyanide at toxic concentration, and the presence of toxic compounds that can hinder microbial growth during bioremediation.

9.3.5 Key monitoring parameters

The effectiveness of EISB should be continually monitored by analyzing the fate of targeted contaminants and other reactants and products (metabolites) indicative of biodegradation [for example oxygen, Mn^{2+}/Mn^{4+}, Fe^{2+}/Fe^{3+}, SO_4^{2-}, NH_4^+/NO_3^-, Cl, biogases (CO_2, H_2S, CH_4)].

9.3.6 Advantages and limitations

EISB techniques can be applied to treat compounds sorbed to the aquifer materials or trapped in pore spaces. The contaminated zone targeted by the treatment can usually be larger compared to other remedial techniques because the treatment can reach areas otherwise inaccessible. The increase of the microorganism population present in pore spaces reduces the permeability of the soil and the hydraulic conductivity of the aquifer, and therefore reduces the rate of migration of the compounds.

EISB has some limitations, including the degree of cleanup achievable, the time frame necessary to reach remediation goals, in some case the potential production of toxic by-products, the presence of inhibitory substances and/or toxic (too high) concentration of the compound in concern, and the difficulty in utilisation of additives such as nutrients, surfactants and oxygen.

9.3.7 Specific EHS aspects

ORCs have to be handled with care. Biogases (such as methane, carbon dioxide or hydrogen sulfide) shall be monitored to prevent their unacceptable intrusion into ambient air or sensitive locations (e.g. service conduits).

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

A wide range of in situ physical and chemical techniques can be combined with in situ bioremediation techniques e.g. bio-venting, bio-sparging (see 9.8 and 9.9). EISB is often operated on contaminated sites in a second stage, when physico-chemical technologies have reached their technico-economical limits.

9.4 Monitored natural attenuation (MNA)

9.4.1 Technique principle

MNA is a remediation technique performed after source zone remediation is complete. It is an in situ treatment which involves long term sampling and analysis of soil, groundwater and/or ground gas to demonstrate that natural physical, chemical and biological processes are adequately managing risks to specific environmental or groundwater receptors. MNA occurs when mass, concentration, mobility and/or toxicity of pollutant are reduced under natural bio- and/or physical-chemical conditions.

9.4.2 Scope and applicability of the technique (operating window)

MNA is applicable for all (bio) degradable contaminants especially dissolved hydrocarbons and light non-aqueous phase liquids (LNAPL) (see Annex A). When dealing with LNAPL, the technique is referred to as natural source zone depletion (NSZD), albeit the monitoring/assessment approach for NSZD of NAPL is very different from that used for MNA in groundwater. MNA is potentially applicable for dissolved phase halogenated hydrocarbons. Toxicity and/or mobility of some metals can be also reduced under natural conditions.

9.4.3 Description of technology

Natural attenuation occurs via three types of processes:

- physical processes, including dissolution, dispersion and sorption;
- chemical processes, including abiotic oxidation or reduction of contaminants;
- biological processes, including aerobic and anaerobic degradation of oxidizable hydrocarbons and direct or cometabolic degradation (reduction) of halogenated hydrocarbons.

9.4.4 Design considerations and dimensioning

The principle design consideration is the location, depth and response zone construction of the monitoring wells. These need to be downgradient of the primary or secondary source zone and some need to be offset to allow dispersion to be detected. All illustration of possible design considerations is provided in Figure C.5 in Annex C.

Studies have shown that dissolved phase hydrocarbon plumes are typically less than 100 metres in length, but can rarely be much longer. Halogenated hydrocarbon plumes can be longer (typically < 1 km), while more recalcitrant and mobile compounds such as PFAS can form much longer plumes (> 5 km). The length of dissolved phase plumes of conservative inorganic ionic (e.g. bromide) is defined either by the detection limit or a relevant water quality standard (such as a drinking water standard).

9.4.5 Key monitoring parameters

To determine the effectiveness of MNA, the key parameters are upgradient and downgradient concentrations of contaminants, electron donors/acceptors as appropriate, daughter products. If anaerobic degradation occurs, new toxic compounds can be produced that can ruin MNA objectives or pose health hazard. As an exemple, the anaerobic degradation of petroleum products produces hydrogen sulfur (H_2S), a very toxic gas.

9.4.6 Advantages and limitations

MNA is low intensity, exploits natural processes and therefore has, on the short-term, a relatively low cost and low carbon footprint. When the MNA runs for a long time, after several years, a careful life cycle analysis shows that the cumuled carbon footprint can become as high as if the site was remediated.

MNA has some limitations and disadvantages. It requires a robust conceptual site model of hydrogeological, geochemical and microbiological conditions. Detailed site characterization is needed to prove that natural attenuation occurs (reduction of concentration due to mass reduction and not dispersion). It can require protracted time scales. It assumes relatively stable groundwater flow directions, else monitoring wells are needed in new locations. There can be some reserve with the socio-political acceptance (as MNA can be seen as “do nothing”).

9.4.7 Specific EHS aspects

No specific environmental health and safety aspects are entailed beyond those involved in site investigation and sampling and any site-specific issues (e.g. remoteness, lone working, or avoiding operational hazards).

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

MNA can follow on from more intensive techniques such as ISCO (9.1) or enhanced bioremediation (9.3) and it can be the last component of a remediation train.

9.5 Incineration

9.5.1 Technique principle

Inceneration is one of the oldest treatment techniques. It relies on an aerobic combustion in a furnace with high temperatures, which destroys the contaminants or volatilise them. It can be applied on site or off site after the excavation of contaminated soils.

9.5.2 Scope and applicability of the technique

It can be applied to a wide range of contaminants, including mercury and various persistent organic pollutant (POPs). In the case of organic contaminants, the aerobic combustion destroys the contaminants into vapour, carbon dioxide and combustion residues (ash). Metals are not destroyed and are found either in the flue gas or in the solid fraction (ash). Metals in the gas fraction can be oxidised and recovered specifically. Incineration can generally be performed on site (using mobile units) or by an off-site technique.

Implementation is fast and compatible with immediate property development. Treatment times in the desorption unit are only a few minutes to a few tens of minutes. Modern treatment units can treat several tens of tons per hour.

9.5.3 Technology description

The techniques rely on aerobic combustion that destroys organic pollutants into water vapour, carbon dioxide and combustion residues (ash). Metals are not destroyed and are found either in the flue gas or in the solid fraction (ash). Metals in the gas fraction can be oxidised and recovered specifically. As illustrated in Figure C.18, incineration generally consists of two steps:

a) incineration within a first chamber in which organic pollutants are desorbed and volatilised (temperature > 400 °C);

b) incineration within a second combustion chamber in which the organic pollutants are destroyed (temperature > 1 000 °C).

Prior to incineration, the soil is pre-treated (sieving, drying, etc.); only particles a few centimetres in size at most are accepted in the furnace. Gaseous and particulate compounds are carried away by an air stream and are recovered for treatment. Chlorine, nitrogen and sulfur (present as HCl, NOx, and SOx) are removed from the air emissions, usually by neutralisation in alkaline solution.

Heating in the furnace of a desorption unit can be done directly or indirectly. There are different types of ovens, (e.g. rotary ovens, grate furnaces, fluidized bed ovens and infrared ovens).

9.5.4 Design considerations and dimensioning

The dimensioning of incenarition can be done following feasibility tests. The key design parameters to consider are:

- residence time, temperature and turbulence in the treatment unit;
- the target remedial concentrations;
- the heat transfer efficiency of the furnace;
- data required for pre-treatment (grinding, pre-drying, crushing, mixing of lime, gypsum, etc.);
- data required for the treatment of atmospheric emissions (dust levels, volatile compound content, residual content to be obtained in the discharge).

9.5.5 Key monitoring parameters

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

a) concentrations of contaminats, organic matter content, particle size;

b) temperature in the furnace and at the exit, turbulence, residence time, oxygen content, air/fuel ratio;

c) fuel consumption (flow and pressure) or energy;

d) furnace depression and associated air flows;

e) contaminant concentrations in the air emissions;

f) parameters relating to gas treatment (flow rates, vacuum, pressure drop, saturation etc.);

g) contaminant levels at the end of the treatment.

9.5.6 Advantages and limitations

Incineration is a proven technique that has demonstrated high reliability and extremely significant results. It can be quite fast and less expensive than other thermal treatments. It destroys the contaminants. It can treat many contaminants, especially VOCs. it can also be applied on very heavily contaminated soils (the content of organic compounds can be of the order of several percent). It can treat “volatile” metals such as zinc, cadmium, lead, etc. It is effective even for clayey and heterogeneous soils. It makes it possible to achieve very high levels of decontamination.

The technique also has some limitations and disadvantages. The process relies on soil excavation. In addition, particles larger than a few centimetres are not allowed: either segregation or grinding is required, and compacted soils should be crushed. Soils with a moisture content of more than 20 % shall be pre-treated by heating. Also, the heterogeneity and organic matter content of the soils can have a significant impact on the treatment yield.

It is a very energy-intensive technique and requires important treatment of atmospheric emissions. It can therefore be very expensive. Its carbon footprint is high as it releases high CO_2 emissions from the incineration process. On-site treatment requires a large surface area. Very high level of technical expertise is required. It is essential to reach very high temperatures in order not to release some of the contaminants (or their metabolites such as dioxins and furans) into the atmosphere. The process used in off-site treatment requires costly transport. High organic nitrogen content can also require additional treatment of air emissions (due to possible NOx formation). High metal contents lead to problems with air emissions and ash disposal. Soils with high clay and organic matter content are more difficult to treat.

The gases shall most of the time be cooled in order to protect the downstream treatment units. The outlets for very highly contaminated ash shall be considered from the outset of the project as they can pose significant problems.

9.5.7 Specific EHS aspects

Specific areas of potential concern are exposures for on-site workers to hot temperatures when the system is operated. Measures shall be taken to protect on-site workers from incidental contact with exposed hot surfaces.

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

Inceneration relies on excavation (see 9.20). It also relies on off-gas treatment (see 9.21). The treatment of atmospheric emissions is highly variable; the sequence of the various dust removal, oxidation or adsorption and neutralisation units is highly variable.

9.6 In situ thermal remediation (ISTR)

9.6.1 Technique principle

ISTR (also called in situ thermal desorption – ISTD) involves raising the temperature of the subsurface treatment zone, thus increasing the vapour pressure, solubility and diffusion rates of contaminants while decreasing their viscosity, to drive the targeted contaminants to a subsurface location where collection of vapour or soil gas can occur for above-ground treatment. The unsaturated zone or saturated zones can be heated to enhance the release of contaminants. Operating temperatures can range from 80 °C to 800 °C. When temperatures over 600 °C are achieved, organic compounds present in the heated zone can be broken-down via pyrolysis.

9.6.2 Scope and applicability of the technique (operating window)

ISTR is applicable to a wide range of contaminants, which respond well to heating (see Annex A), including: mercury, halogenated volatile organics, energetic nitroaromatic compounds, polychlorobiphenyls (PCBs) and PCBs–Dioxin-like, polychlorodibenzodioxines, polychlorodibenzofurans (PCDD/PCDF), polybrominated dibenzo-p-dioxin, polybrominated dibenzo furan (PBDD/PBDF), pesticides and herbicides. It is particularly useful for extraction of NAPL entrapped in the unsaturated zone and high dissolved concentrations of contaminants in the saturated zone. High-temperature in situ heating is used primarily to treat high-molecular weight compounds (such as halogenated and non-halogenated VOCs, PCBs, diesel and oil-range fuels, and DNAPLs mixtures). ISTR can also used to extract elemental mercury from the unsaturated zone. Removal efficiency can be in excess of 95 % for contaminant mass removal using this technique.

9.6.3 Description of technology

ISTR uses a number of approaches to raise the subsurface temperature, depending upon site setting and the desired temperature range required. Three main heating methods are illustrated in Annex C and are the following.

- Electric heating using a network of electrodes or heaters to heat the soil and groundwater. The heating is achieved by either thermal conductive heating (TCH) where individual heaters are utilised, or electric conduction heating systems (ECH) where current is passed between electrodes, heating occurs through the function of the grounds resistance. ECH is also effective at temperatures between 100 °C and 400 °C in hot spots, depending on the nature of the pollutants. The main obstacle to obtaining the effectiveness of such a device relies in its capacity and time required to cross the 100 °C barrier, e.g. to succeed in extracting all the water from the soil to reach the target temperatures. TCH needs a low soil moisture and can reach 750 °C (high temperature systems) where contaminant desorption occurs (in situ thermal desorption –

ISTD). ECH requires a permeable soil with elevated soil moisture for the current to pass and reach a 100 °C objective (low temperature systems). TCH and ECH both require a dense grid of thermal wells.

- Ignition wells powered through the injection of a combustible gas and air mixture. They are used to heat the soil and start an in situ flameless combustion [in situ combustion (ISC) or smoldering] where the contaminants become the source of energy. It generally requires a medium grid of injection wells to create high temperatures.
- Injection of hot air or hot water or steam. There are a variety of techniques using an injected fluid or combinations to heat the subsurface generally up to a maximum of 100 °C (low temperature). These injections are not effective for low-permeability materials (hydraulic conductivity $< 10^{-4}$ cm/sec). Shallow contaminated areas can result in prohibitively high heat loss to the atmosphere without insulation measures on the surface.

NOTE High temperature can be reached with TCH and in situ combustion technology: locally higher than 800 °C to 1 000 °C with an average temperature within the zone to remediate of 600 °C. Low temperature around 100 °C can be reached by ECH, in situ steam flooding and other heat injection systems.

ISTR techniques are generally combined with a vapour collection and treatment system within the subsurface and above-ground treatment of recovered separated gaseous and liquid phases.

9.6.4 Design consideration and dimensioning

A detailed site assessment is necessary to determine, in the targeted contamination zone, the expected outcome of heating and to define geological properties (soil type, etc.), hydrologic properties (groundwater flow, degree of saturation, etc.). Key parameters are the moisture content, organic matter content within the unsaturated zone, the number and characteristics of the (heat) injection and extraction (gas or vapour) wells network, and the spacing between the wells. The position and the design of these wells depend on the geometry of the targeted zone and their radius of influence (RoI) and/or radius of capture (RoC). Groundwater and vapour recovery and treatment systems shall be designed appropriately for the recovery of elevated temperature fluids (see 9.21). The evaluation and selection of treatment design alternatives for a particular thermal remediation system is based on technical feasibility and the costs (capital and operational) of achieving remediation goals.

9.6.5 Key monitoring parameters

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

a) actual vs target subsurface temperature distribution, (using temperature monitoring wells);

b) mass of organic compounds in the recovered;

c) energy consumption rate and cumulative;

d) pollutant mass reduction in the groundwater.

9.6.6 Advantages and limits

ISTR is a reliable, fast (time frame up to 3 months - 6 months) and proven technique where in situ soil is heavily contaminated, clayey, or the contamination is entrapped and inaccessible for other in situ-treatment. ISTR can solve remediation problems, especially in low permeability soils contaminated with a whole chemical cocktail or when excavation would be too hazardous. ISTR is a very aggressive treatment technology compared to bioremediation technology (e.g. in a clayey context, the soil can become “cooked”). The energy consumption of all thermal installations is high (20 l to 50 l of fuel per tonne of soil). Soil properties, including geotechnical properties, can be changed by the treatment impacting on potential post-treatment site use. Appropriate testing should be carried out as necessary.

9.6.7 Specific EHS aspects

Specific areas of potential concern are exposures to high voltages, hot vapours or steam and hot temperatures when ISTR is operated. Measures shall be taken to protect on-site workers from incidental contact with power lines or exposed hot surfaces. In the case of ISTR targeting hydrocarbons contamination (like gasoline) or low flame point VOCs, security devices and protocols shall be taken into account for the monitoring and proper size design of the treatment units due to the risks of fire an explosion.

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

ISTR are also often designed as part of a remediation treatment train to optimize contaminant recovery. As an example, a low-temperature TCH can be used to optimise a viscous PAH or DNAPL multi-phase extraction systems (see 9.10) or pump-and-treat (see 9.12). The electric methods ECH and SAI (steam) can be applied to the unsaturated or saturated zone while being combined with an MPE technique. ISTR can also be used to enhance the efficiency of all soil vapour extraction (SVE) systems within the unsaturated zone, increasing the extraction rates of vapour and gaseous contaminants within a “hot-SVE” compared to “cold-SVE” (see 9.8).

9.7 On-site thermal desorption

9.7.1 Technique principle

On-site thermal desorption relies on the application of heat to remove volatile contaminants from excavated soil by volatilization or pyrolysis (decomposition by heating) processes (see Annex A). Extracted contaminants are transported within the gas phase and are treated in a gas treatment system. It can be applied on site or off site.

9.7.2 Scope and applicability of the technique (operating window)

Contaminated soil with organic compounds including high concentrations of VOCs [e.g. 10 000 mg/kg (1 % mass fraction) order of magnitude] can be treated using this technique. Soil with high moisture contents (> 40 %) are not recommended due to the high-energy costs for the evaporation of water. Efficiency is reported in excess of 97 %.

9.7.3 Technology description

By heating the excavated contaminated soil to a temperature between 90 °C to 560 °C, mainly in the processing unit (e.g. rotating barrel dryer/desorber), contaminants are volatilised or pyrolysed (see Figure C.8 in Annex C). The released contaminants are then transported in the gas phase and are processed in a separate gas treatment system. The smoke particles are first collected in filters, wet dust collectors and/or electrostatic precipitators; then, the organic compounds are removed by destruction (burning, catalytic oxidation) or fixation (activated carbon, condenser). Thermal desorption units that treat chlorinated solvents shall be equipped with a treatment unit for the neutralization of hydrochloric acid. To cool the soil and to prevent dust-forming, the soil is re-moisturised with water after the thermal desorption phase.

9.7.4 Design considerations and dimensioning

An on-site thermal desorption system is composed of a pre-treatment unit (grinding, mixing); dryer/thermal desorber to remove water and target compounds (e.g. rotary kiln, screw or belt fed unit) heated internally or externally; and powerful gas treatment units (e.g. heat exchanger, dust collectors, post combustion burner or oxidizer, condenser, activated carbon filters). Key parameters to consider when designing an ex situ thermal desorption system are:

a) nature and concentration of contaminants, as these determine the working temperatures of the desorber unit (e.g. for mineral oil: 200 °C to 600 °C; for desorption of total mercury, PAHs, PCB, halogenated VOCs: 150 °C to 600 °C or above) and also the temperatures of the gas treatment unit;

b) the soil moisture, the organic matter, the sulfurous compounds contained in the contaminated soil;

c) the remedial targets and the capacity of treatment needed (commonly 5 t/h to 40 t/h).

9.7.5 Key monitoring parameters

To determine the effectiveness of on-site thermal desorption, key monitoring parameters are:

a) organic matter and moisture, contaminant concentrations within the soil to be treated;

b) temperature, turbulence, residence time in the desorption unit;

c) contaminant concentrations in the treated gas emissions.

The treatment unit's operating parameters (flow rates, depression, head losses, saturation rates of filter, etc.) shall also be monitored.

9.7.6 Advantages and limits

On-site thermal desorption is a reliable, fast and proven technique where the soil is heavily contaminated or too clayey for other treatment. Some contaminants such as halogenated VOCs can be a burden for the whole desorption unit as there is a continuous process of renewing corroded parts within the installation (on average up to 20 % operational costs). The need for thorough treatment of desorbed volatiles, an essential part of the process, can result in desorption being a costly form of treatment as it is usually used for heavily contaminated soils. The energy use in thermal installations is high (20 l to 50 l of fuel per tonne of soil) thus the carbon footprint is high.

A potential concern is hot temperature exposure for nearby workers from the burner surfaces and various pipes. The off-gases treatment units shall be specially designed to avoid fire and blast hazards. The treated gas emissions shall be continuously monitored and corrective action made instantaneously, for example when a malfunctioning burner releases dioxin-like compounds.

The physical and other properties of the treated soil can be radically changed because water of hydration can be lost from many minerals including gypsum and at least some clay minerals, and organic matter and all organisms can be destroyed. These changes, and possibly a dark coloured aspect, can hinder its recycling as a soil-like material or within construction. Appropriate testing, including possibly plant growth and toxicity tests, can be required.

9.7.7 Specific EHS aspects

Specific areas of potential concern are exposures for on-site workers to high voltages, hot vapours and hot temperatures when the system is operated. Measures shall be taken to protect on-site workers from incidental contact with power lines or exposed hot surfaces. In the case of the system targeting hydrocarbon contamination (like petroleum) or low flame point VOCs, security devices and protocols shall be taken into account for the monitoring and proper size design of the treatment units due to the risks of fire and explosion.

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

Desorption relies first on the excavation of contaminated soil (see 9.20). New generations of processor units can be used to more effectively vaporize or burn the contaminants (e.g. rotating kiln, Archimedean screw, conveyor) in combination with innovative pre-treatments (e.g. pre-drying, additives, segregation, homogenization, pellets).

9.8 Soil vapour extraction (SVE)

9.8.1 Technique principle

SVE or vacuum extraction or venting is an accepted and proven technique for in situ soil remediation. It is used for the removal of volatile compounds from the unsaturated zone. SVE establishes a vacuum in the subsurface to create a pressure/concentration gradient that facilitates the mass transfer of applicable contaminants from NAPL and adsorbed contaminants, and transfer of constituents dissolved in soil moisture to the vapour phase. The vapour is then removed from the subsurface through extraction wells and can then treated aboveground to recover or destroy the contaminants.

9.8.2 Scope and applicability of the technique (operating window)

SVE can treat light TPH such as gasoline, BTEX, VOCs and SVOCs, generally with a vapour pressure of greater than 133 Pa at 20 °C (see Annex A). SVE relies upon air flow, thus it only works in gas permeable materials (sandy-silty to gravelly soils, with a permeability greater than 10^{-5} m/s). The vacuum induced in the soil through SVE induces fresh atmospheric airflow though the unsaturated zone. SVE can also be used to protect indoor spaces from soil gas intrusions, commonly termed SSD (sub slab depressurisation) where very low flow and applied vacuums are utilised.

9.8.3 Technology description

The extraction network is typically constructed of vertical wells and/or horizontal drains connected with suitable piping (underground or lying on the surface) to a vacuum extraction unit to induce desired vacuum (typically an applied vacuum of up 30 kPa). A number of vacuum technologies are available dependent upon flow rates and vacuum applied to the system. These include centrifugal fans, claw blowers and lobe blowers.

Gas treatment units may use activated carbon filtration, biofiltration or catalytic oxidation. Control systems for safe operation including explosive atmosphere controls are key to safe effective operation. An illustration of the technology is provided in Annex C, Figures C.9 and C.10.

9.8.4 Design and dimensioning considerations

The key parameters for dimensioning SVE are:

a) air-permeability of contaminated zone;

b) soil-vapor mass transfer coefficient;

c) extent of the contaminated area and thickness of the unsaturated zone;

d) the magnitude and distribution of the air flow.

These parameters impact on the return on investment (ROI), the return on capital (ROC) of each well, and the remediation effectiveness and end of an SVE operation. The dimensioning includes:

- the number, spacing and characteristics of the injection wells;
- the ROI and ROC of the extraction wells;
- the number, spacing and characteristics of the extraction wells (depth, diameter, trenches, wells, etc.);
- the type and power of the extraction unit;
- the dimensions of the treatment unit.

The targeted contaminated area shall be fully covered by the ROC of SVE extraction network. Mathematical models may be used for dimensioning and predicting performances of SVE. Soil air-permeability may be measured in the fields by extraction tests or by experimental lab-scale approaches.

If the groundwater level is shallow, the groundwater level can rise due to SVE and groundwater enter the SVE well, so it is necessary to prevent the groundwater level from rising by groundwater pumping.

9.8.5 Key monitoring parameters

To determine the effectiveness of an SVE technology, the key parameters are:

a) well head vacuum and the network head depression;

b) extracted flow;

c) soil-gas concentrations of the contaminants being targeted;

d) concentrations and/or flow (m^3/h) and/or mass fluxes (g/h, kg/day) in atmospheric releases.

If SVE is operated on a source of contamination to reduce a contaminant linkage, groundwater quality upgradient and downgradient of the source shall be monitored before, during and after the closing of the remediation operation.

9.8.6 Advantages and limits

SVE is easy to operate and relatively inexpensive. This technique is proven and has demonstrated great reliability. SVE can continue to be used while the site remains in operation or even begins to be redeveloped. High-permeability heterogeneities limit its efficiency. The most limiting factor for the use of this process is vapor pressure. A compound with a vapor pressure below 67 Pa (at 20 °C) is not remobilizable under normal venting conditions. In addition, the limiting Henry's law constant for significant volatilization is 0,01 Pa·m^3/mol (at 20 °C).[12] SVE is operated on unsaturated zones with thickness of more of 1,5 m to 3 m depending on the context. In the case of low permeability moisty soils, geomechanical properties of the soil can be disturbed by SVE due to the extraction of soil natural moisture causing soil retraction. Because of the saturation of pore spaces, SVE is of limited effectiveness on soils with high grade of moisture.

9.8.7 Specific EHS aspects

The extraction of volatile hydrocarbons requires consideration of the potential to form explosive atmospheres within the process. The equipment should be designed in conformity with local standards. Typically, vapours are controlled in the region of 15 % to 25 % of the lower explosive limit in the extraction units and pipes to reduce the risk of explosion. This concentration also limits heat buildup in activated carbon adsorber units, minimising the potential for combustion within the beds.

Dilution of extracted gases with fresh air is often used as a control, especially at start up of the SVE project.

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

Possible supporting techniques in combination of SVE are bioventing, thermal enhancement SVE. The introduction in the soil of fresh air during SVE operation stimulates aerobic biological activity. Biodegradation of organic compounds can be enhanced by the injection of nutrients within “bioventing”. Bioventing is applicable to all biodegradable contaminants, but has been applied most frequently and reportedly most successfully to sites with petroleum hydrocarbon contamination. The efficiency of SVE can be improved by thermal enhancement SVE, to increase the in situ volatilization rates of contaminants (see 9.6). Venting can also be combined with air-sparging to remove the same compound dissolved in the aquifer (see 9.9).

NOTE Dynamic and pneumatic containment is another use of SVE. SVE is very versatile and as pumping for groundwater can be used as a dynamic and pneumatic containment. SVE can be used as a constructive measure to mitigate subsurface contaminant vapor intrusion into building (sub slab depressurization system).

9.9 Air-sparging

9.9.1 Technique principle

Air-sparging is an in situ technique based on the mass transfer (volatilization) of dissolved volatile compounds from the water of the saturated zone to soil gas of unsaturated zone via air bubbles generated by injection of air within the aquifer. Air bubbles (with gaseous compounds) generally move upward toward the unsaturated zone, where an SVE system may be employed to capture the contaminated air. The injection of fresh oxygen in the aquifer can also stimulate aerobic biodegradation.

9.9.2 Scope and applicability of the technique (operating window)

Air-sparging is used to address a wide range of dissolved VOCs (see Annex A). Hydrogeological settings with homogenous hydraulic conductivity in the saturated zone (> 10^{-5} m/s), and permeability to air in the unsaturated zone provide optimal performance when operating air-sparging.

9.9.3 Technology description

Air-sparging technologies typically combine an air injection well network and an SVE wells network. Air is injected in vertical wells, screened below the targeted contaminated zone, using an air-compressor or blower at a pressure determined by the depth of the screened portion of the wells, the air flow required and the lithology. Usually, the air injections are discontinuous (“runs”) whereas associated SVE runs continuously. On site, off-gases treatment unit is often required before discharging the air to the atmosphere. An illustration of the technique is provided in Figure C.11 in Annex C.

9.9.4 Design considerations and dimensioning

Key parameter to design an air-sparging system are:

a) ROI of in situ air-stripping and the ROC of SVE;

b) depending on the size of targeted contamination and ROC, ROI of each well, the number, characteristics (depth, diameter, etc.) of the extraction and injection networks and spacing of the wells.

9.9.5 Key monitoring parameters

The air-sparging technique requires a strict control of soil gas migration to avoid uncontrolled gas migration. To determine its effectiveness, key monitoring parameters are:

a) groundwater level;

b) concentration of contaminant in water and gas;

c) indicators of biodegradation.

The monitoring of treatment units operating parameters (flow rates, depression, head losses, saturation rates of activated granular carbon filter, etc.) is also required.

9.9.6 Advantages and limits

This technique can be a cost-effective method for reaching remedial objectives within reasonable time frames (few months to several years depending on the context) and can be more effective than pump-and-treat methods. The advantage of air-sparging is that it can remediate soil contamination in the capillary zone, which is difficult to remediate by SVE or groundwater pumping. Air-sparging can cause mounding of groundwater, thus in shallow groundwater conditions breakthough to surface can occur. The presence of LNAPL both in free-phase and within the geology can produce a free-phase layer where none was previously present, and high off-gas concentrations. Complex/heterogeneous geological settings can limit ROI.

9.9.7 Specific EHS aspects

When air-sparging aims light hydrocarbons, extraction and off-gases treatment units shall be specially designed to avoid fire and blast hazards. High injection pressures can induce liquefaction of soils.

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

Oxygen added to the contaminated groundwater can stimulate aerobic biodegradation of contaminants below and above the water table. This biodegradation may be enhanced by the injection in the targeted zone of nutrients and/or bacterias (combined bioventing and biosparging technologies – see 9.8 and 9.3).

9.10 Multi-phase extraction (MPE)

9.10.1 Technique principle

MPE (also called slurping) is an in situ technology that utilises vacuum-assisted free product and/or groundwater recovery with bioventing and SVE to simultaneously recover free product (if present) and remediate the vadose and capillary/smear zones and shallow saturated zone.

Groundwater, LNAPL, and soil gas typically are recovered simultaneously from wells placed throughout the treatment area. One or more high-vacuum pumps/blowers are used to generate the required vacuum. “Slurping” involves use of a drop tube (stinger) that is placed near the oil-water interface (or bottom of the LNAPL saturated thickness) in each extraction well to focus recovery at the capillary/smear zone fringe and shallow saturated zone. Drop tubes use high velocity airflow to entrain LNAPL/water droplets at the liquid interface for removal. The extracted vapors, liquid-phase organics and the contaminated groundwater are then separated and treated using different technologies. Where large volumes of LNAPL are present, this technique can produce explosive atmospheres within the extraction system when using stingers. An alternative approach in this instance, or when the ground is highly productive is the use of a pump within the wells to abstract liquids, minimising the deliberate volatilisation of VOCs.

9.10.2 Scope and applicability of the technique (operating window)

This technique can be utilised for a range of contaminants within contaminated soil and groundwater, i.e. the unsaturated zone and the saturated zone (see Annex A). MPE is suitable for application in low permeability aquifers and in heterogeneous conditions. However, this process can only be applied to shallow depths due to difficulties with entrainment when overcoming atmospheric conditions.

9.10.3 Technology description

The MPE system typicall comprises a series of vertical extraction wells. These are linked by a pipework extraction network to the process plant. This typically comprises a liquid/vapour separator, vacuum pumps and specific treatment systes for recovered LNAPL, contaminated groundwater and gas. Dependent upon the design of the system, the field network can be unitary for entrained fluid flow within extracted gas phase, or it can include separate lines for each extracted phase (liquid/gaseous). A network of monitoring wells is used to monitor flows and quality of groundwater in and around the treatment area. An illustration of the technique is provided in Figure C.12 in Annex C.

9.10.4 Design considerations and dimensioning

The hydrogeological characteristics (porosity, permeability, heterogeneity, water table fluctuations, etc.) as well as the LNAPL characteristics (thickness, transmissivity, viscosity, interfacial tension, density, distribution/concentrations in the different phases) shall be carefully characterized. The definition of remediation objectives within the LNAPL source zone (reduction of the mass) and in the gaseous phase as well as in the aqueous phase are the main elements which condition the treatment system to be implemented. Pilot tests are recommended to determine the RoC of the extraction wells and the recovery time. These RoCs depend on flow rates/pressures, fluid viscosities, relative permeabilities, environmental heterogeneities etc. Mathematical models for predicting free-product recovery can be useful too.

9.10.5 Key monitoring parameters

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

a) LNAPL removal rates and cumulative LNAPL volume;

b) (time and space) evolution of apparent LNAPL thickness in extraction wells;

c) groundwater levels;

d) well head vacuum and the network head depression;

e) extracted flow;

f) soil-gas concentrations for compounds in concern;

g) soil-water concentrations for compounds in concern;

h) concentrations and/or flow (m^3/h) and/or mass fluxes (kg/d) in gas and water outflow;

i) energy consumption of the entire installation, including ex situ water/oil treatment unit;

j) parameters related to water and gas treatment units (head loss, consumption of supplies, etc.).

9.10.6 Advantages and limitations

MPE technique is mature, easy to operate. The extraction of all contamination phases (free product, dissolved and gaseous) is very effective and drastically limit the risks of unexpected rebound effects when extraction units are shut down. MPE wells can act as hydraulic control, trapping the contamination. MPE can improve free-product recovery efficiency without extracting large quantities of ground water. The system is designed to minimize environmental discharge of ground water and soil gas.

MPE systems are appropriate for low permeability and/or heterogeneous formations. Dual phase vacuum extraction is more effective than SVE for heterogeneous clays and fine sands. However, it is not recommended for lower permeability formations due to the potential to leave isolated lenses of undissolved product in the formation. Where ground conditions are highly permeable, it is likely to be more efficient to consider DPLE or DPE.

The vacuum technologies for groundwater remediation are operated when water table doesn’t exceed 9 m. Energy consumption can be high due to the effort applied.

9.10.7 Specific EHS aspects

MPE systems can create significant hazard by the production of large volumes of hazardous vapours. With regard to how the equipment is designed, operated and maintained, local requirements can apply. The post extraction treatment process can also have concentration constraints which need consideration and control for dilution.

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

When free-product removal activities are completed, the system is easily converted to a conventional bioventing system to complete the remediation. MPE for liquid/vapor treatment is generally combined with bioremediation, air-sparging, or bioventing when the target contaminants include long-chained hydrocarbons. Combination with complementary technologies (e.g. pump-and-treat in 9.12) can be required to recover groundwater from high yielding aquifers.

9.11 Dual pump liquid extraction (DPLE)

9.11.1 Technique principle

DPLE or oil pumping recovery is an in situ technique which consists of LNAPL-mass recovery via physical removal by hydraulic recovery (e.g. pumping and skimming). Skimming consists of the selective removal of only fluid (LNAPL) using a pump or similar continuous mechanical device. Both LNAPL and water are removed. Less intensive LNAPL recovery techniques such as the use of adsorbent socks, manual bailing, passive skimmers, or vacuum trucks are not being considered here.

9.11.2 Scope and applicability of the technique (operating window)

DPLE is the most widely used technique to recover mobile LNAPL (diesel, fuel, gasoline, solvents, etc.) floating on groundwater table, where the apparent thickness (in the wells) is generally over 1 cm. Groundwater extraction can also provide hydraulic containment of potentially migrating LNAPL.

9.11.3 Technology description

In DPLE, the drawdown of LNAPL and groundwater through water pumping (in wells) induces an LNAPL gradient toward the recovery well. Groundwater drawdown can expose submerged LNAPL thereby increasing LNAPL mobility and recovery rate. Skimmers are placed at the oil-water interface. The most commonly used systems for skimming are hydrophobic filters, floating skimmers and oleophilic bands. LNAPL recovery can be undertaken in vertical wells or horizontal trenches (for shallow aquifers). The performance of each well is characterized in terms of its RoC. Ex situ treatment unit are required to separate (oil-water separator) LNAPL from water and to remove dissolved contaminant present in pumped groundwater before discharge. An illustration of the technique is provided in Figure C.13 in Annex C.

9.11.4 Design considerations and dimensioning

Site-specific data for technology evaluation shall be collected with a special attention to the measurements of site-specific hydrogeological (porosity, permeability, etc.) or LNAPL (composition, density, viscosity, removal rates, LNAPL transmissivity values, etc.) characteristics. The definition of remediation objectives within the LNAPL source zone (reduction of the mass, stabilization of the mobile LNAPL, containment of the source) and downstream of the source (restoration of the aquifer, interception of the plume, protection a drinking water well, etc.) are the main elements which condition the treatment system to be implemented. Bench-scale testing and/or pilot testing can be important steps toward evaluating feasibility of the technique. Conducting, in an on-site structure, pumping and LNAPL monitoring tests allows assessing their mobilization capacity. Mathematical models for predicting free-product recovery can be useful too.

9.11.5 Key monitoring parameters

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

a) LNAPL removal rates and cumulative LNAPL volume;

b) (time and space) evolution of apparent LNAPL thickness in wells or trenches;

c) groundwater levels;

d) energy consumption of the entire installation, including ex situ water/oil treatment unit.

9.11.6 Advantages and limitations

The advantages of this technique are that:

a) it is relatively simple and quick to set up;

b) it produces little soil disturbance and it is possible to treat under buildings;

c) LNAPL removal is associated with hydraulic containment;

d) it contributes to reduce sources of dissolved (saturated zone) and gaseous (unsaturated zone) contamination.

However, it is not effective for small thicknesses of LNPAL (less than 1 cm) and if it is necessary to remove LNAPL residual contamination.

9.11.7 Specific EHS aspects

The design of LNAPL extraction unit shall consider the risks of fire and/or explosion when targeted LNAPL is made of volatile flammable compounds (gasoline, cyclohexane, etc.). Recovered LNAPL often has to be disposed ex situ and off-site as a waste.

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

To improve the performance of the treatment, it is possible to increase LNAPL extraction rate using surfactant-enhanced subsurface remediation (SESR) (surfactant is injected to decrease interfacial tension and increase solubility) or cosolvent flushing (a solvent is injected to increase LNAPL solubility and mobility). In both cases LNAPL and water are recovered hydraulically.

9.12 Hydraulic techniques for groundwater remediation

9.12.1 Technique principle

Hydraulic techniques are the most established in situ groundwater treatement techniques and/or contaminated groundwater containment. Hydraulic techniques involve the retrieval of groundwater and/or NAPL from a contaminated aquifer using one or more extraction wells, trenches or galleries, and treating the water in an above-ground treatment system prior to discharge. Pumps can be submerged or aboveground. Depending on the contaminants being considered and their concentration, the pumping rates and the discharge quality requirements, the treatment of extracted groundwater/NAPL often includes multiple technologies used in a treatment train.

9.12.2 Scope and applicability of the technique (operating window)

Hydraulic techniques can be applied for a wide range of dissolved organic contaminants (e.g. light petroleum hydrocarbons, BTEX, chlorinated compounds) and inorganic contaminants [e.g. metal, metalloids, nitrate, cyanid, (per)chlorate] present in groundwater (see Annex A).

Hydraulic techniques can be applied to meet four different objectives (see illustrations of the techniques in Figure C.14 in Annex C):

- to extract mass of dissolved contaminants within or near source contamination to remove mass and to clean-up the groundwater (groundwater quality restoration) [usually called pump-and-treat (P&T)];
- to create a hydraulic dynamic containment of the contaminant plume in the groundwater as a pathway management technique [pumping is operated between the source of contamination and sensitive groundwater receptors (e.g. drinking water supply)];
- to reduce the water table to enhance LNAPL recovery (e.g. LNAPL dual pumping recovery – see 9.11);
- to reduce the water table to increase the thickness of the unsaturated zone targeted by other soil remediation techniques [e.g. “cold” or thermally enhanced SVE (see 9.8), multiphase extraction (see 9.10), soil excavation (see 9.20)].

9.12.3 Technology description

Pumping is operated from one or more vertical wells, horizontal drains, galleries or trenches, screened at suitable hydrogeological interval, and connected with a pipe network. Groundwater extraction is achieved using surface-mounted pumps (for water table at a depth up to 9 m below ground level) or electrical or pneumatic submersible pumps. Extraction wells are always associated with special designed monitoring wells networks. Also, water treatment unit is necessary (see 9.21).

9.12.4 Design considerations and dimensioning

The choice of relevant technique and associated design and dimensioning depends on the remediation objectives and hydrogeological conditions (e.g permeability, water table, aquitard configuration). For P&T and hydraulic containment techniques, the entire plume shall be included in the capture zone, the width of which depends on the aquifer hydraulic properties, groundwater flow, and pumping rate(s). The number of wells necessary to intercept the plume and well design (depth, position of screened section, diameter, etc.) depends on the whole width of the plume and performances (pumping rates) of each well. Targeted withdrawal depends on the hydraulic properties of the aquifer, the technical characteristics of the wells/drains, and for LNAPL recovery, optimal in well oil renewal. Pumping rates are limited by the aquifer hydraulic properties but also by the on-site ex situ treatment capacities and discharge regulation. Casings and screens of wells or drains shall be made of materials resistant to the contaminants involved, like stainless steel, HDPE or PVC. Hydraulic flow models are built to simulate the flow field in the vicinity of wells. Predictive modeling is also completed to approximate groundwater cleanup times. Modelling is based on specific conceptual model of the contaminated area requiring a comprehensive characterization.

9.12.5 Key monitoring parameters

Performance and effectiveness are monitored by measuring hydraulic heads and gradients, pumping rates, inlet versus outlet (discharge) of on-site ex situ treatment units, mass extraction (dissolved, LNAPL). Groundwater flow directions, dissolved contaminant distributions/evolution in groundwater are monitored using a monitoring specially designed wells network.

9.12.6 Advantages and limitations

These techniques:

a) are relatively simple, competitive in terms of cost, and proven;

b) may be applied on a wide range of organic as inorganic contaminants.

They produce little soil disturbance, they are applicable to treat under buildings and they may be combined with a wide range of in situ remediation techniques. The effectiveness of a hydraulic technique is reduced in low-permeability and/or heterogeneous aquifers. The operation cost drastically increases when mass extraction/concentrations decrease with time. Overall time frame of these techniques can be prohibitive (weeks to decades) and shall be carefully checked.

9.12.7 Specific EHS aspects

They vary significantly from site to site depending on the contaminant present. Special attention shall be given when LNAPL (composed of volatile flammable compounds) and electrical devices (pump, etc.) are present in wells to prevent the risk of explosion.

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

Hydraulic techniques may be combined with a wide range of in situ remediation techniques. To improve the system performance, it is possible to combine these techniques with chemical processes (washing), biological or physical processes (hydraulic fracturing). They can be associated with a treatment of the unsaturated zone (washing, ventilation, etc.). The reinjection upstream of the water pumped and eventually treated makes it possible to concentrate flows into the hydraulic trap ("hydraulic loop"). By moving dynamically the extracting wells along the plume spine, a dynamic groundwater re-circulation is achieved by increasing the actual groundwater flow rate through the plume, and injecting water at the edges of the plume to create a very effective contaminant pumping system. Extracted contaminated groundwater may be treated ex situ after its extraction (see 9.21 for treatement techniques applied on water).

9.13 Soil washing

9.13.1 Technique principle

Soil washing aims to remove contaminants in soils by washing excavated contaminated soils with a liquid (water, solvent, specific reagent). It can be applied on-site or off-site. Ex situ soil washing systems assume that most contaminants of concern bind to the finer soil fraction, consisting of clays, silts, and fine organic matter as opposed to the larger sand and gravel fraction.

9.13.2 Scope and applicability of the technique (operating window)

Soil washing can be applied to remove various organic and inorganic contaminants. It is mainly applied on heterogeneous soils to concentrate the finer fractions, generally the most contaminated (see Annex A). It is particularly useful for the separation of low-degradable compounds that recalcitrant to other remediation techniques (e.g. PAHs, PCBs, dioxins and furans, pesticides) and to metals/metalloids. It can be used to treat large quantities of oil spill-contaminated beach sand. The separated contaminants are concentrated and reduced in weight for disposal, incineration (on-site or off-site) or possibly stabilization and solidification.

9.13.3 Technology description

As illustrated in Figure C.15 in Annex C, soil washing processes consist of several steps:

a) particle size separation (gravels, coarse, and fine particles) to isolate the fraction bearing the contaminant;

b) washing of the fine fraction with water, water with additives or solvent;

c) treatment of washed water;

d) management of residual waste.

The process uses equipment and machinery typically used in quarrying and mining (e.g. trommels, sieves, cyclones) with a strong water treatment unit (e.g. hydro-cyclones, up-flow tanks, flotation units, belt presses).

9.13.4 Design and dimensioning considerations

In the cleaning treatment phase, a treatability test shall be performed to determine the treatment conditions after fully understanding the properties of the contaminated soil and separated fractions, concentrates, wastewater, etc. The soil cleaning method is a combination of several quarrying processes. Since the selection and combination of the purification process involves cleaning with water or other solvents, the best classification process or combination of processes (e.g. sieving separation, specific gravity separation, magnetic separations, and flotation separation process) shall be determined with treatability tests. The efficiency of a washing system is in the 50 % range if poorly designed and can reach up to 90 % if the correct contaminated fraction is targeted. Contaminants usually tend to accumulate in the fine particles, but depending on the history of contamination, the concentration can be high even in/on the coarse particles and if these are not washed by a conventional soil washing system, the system shall be redesigned.

9.13.5 Key monitoring parameters

To determine the effectiveness of a soil washing technology, the key parameters are:

a) organic matter and moisture, contaminant concentrations within the soil to be treated;

b) flow rates in the washing tank, water or solvent consumption, soil residence time;

c) washed water quantity and quality after treatment, removal effectiveness of specific contaminants in treated soils, exhaust dust or VOCs emission if any.

9.13.6 Advantages and limitations

If the contamination is concentrated in the fine fraction of the contaminated soil the efficiency is very high, the volume of soil to be landfilled and the costs associated is reduced by approximately 90 %. The large volume of soil that is not contaminated after washing can be reused as backfill at the site but it is only coarse soil. A soil-washing unit can easily handle a large volume/mass of contaminated soils (25 t/h or 50 t/h).

Efficiency decreases if the soil is very silty or clayey (the technique is generally ineffective for soils with over 30 % silt, clay, or organic matter). Treatment of the wash water can be tricky if chemical additives are used because these shall also be treated. VOCs can generate air emission that require a specific air treatment unit. Treated soil is usually coarse and can cause geotechnical issues for reuse of the site.

9.13.7 Specific EHS aspects

Potential concerns are mechanical parts and chemical handling for nearby workers. As a quarry system, noise and vibration caused by the plant shall be controlled. Odours when sieving contaminated soil shall be controlled as well as VOCs emission. In town, a mobile washing unit may be placed in tent with an air treatment unit.

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

Soil shall be excavated first (see 9.20). Contaminated fine particles separated by hydro-cyclone or other methods can be subjected to other techniques including new sieves, swirl effect cyclone etc. to increase the effectiveness of remediation. When residual organic contamination within the sludge cakes is high, the soil washing process can be followed by an incineration process applied to the sludge cakes (see 9.5). But, if the residual contaminants are less concentrated, the sludge cake can be disposed of on-site with an appropriate cover system if it does not pose any risks to human health and the environment (see 9.17).

9.14 Biopiling

9.14.1 Technique principle

Biopiling consists of placing contaminated soils in a heap and undertaking a biological treatment. It can take place on site or off site. The contaminated extracted soils are generally amended and the conditions in the biopiling shall be controlled (e.g. aeration, addition of nutrients). Biopiling is almost exclusively aerobic.

9.14.2 Scope and applicability of the technique (operating window)

Biopiling can treat contaminated soils that are retrieved from the unsaturated zone or saturated zone with petroleum products such as BTEX. Other organic compounds such as VOCs, pesticides, PAHs, can also be treated under certain conditions, but with lower efficiencies.

Biopiling treatments are preferably applied to soils with contaminant concentration that are below 15 g/kg to 20 g/kg of hydrocarbons for “classic” oil products. Such biological technique is based on complex biodegradation mechanisms that are generally very long. The treatment time can therefore be high and highly variable depending on the remediation objectives. It can vary from a few weeks to several months, or even years (18 months to 24 months).

9.14.3 Technology description

Once extracted, the contaminated soil matrix is mixed with an amendment (structuring agent) before being placed in the treatment zone. The treatment zone comprises at least a leachate collection system and aeration units (extraction or air blowing) to optimise oxygen transfer and stimulation of biodegradation. Biological degradation is mostly achieved by biostimulation. The biodegradation shall be controlled (temperature, moisture content, nutrients, oxygen, pH).

As illustred in Figure C.16, biopiles are usually covered by an impermeable geomembrane to limit rainwater infiltration, contaminatant volatilization and temperature maintenance/increase. The heaps are generally not higher than 3 m (to avoid compaction). The collected leachate is partly recycled and partly treated on site before being discharged. Atmospheric emissions are treated if necessary (e.g. if VOCs are present).

9.14.4 Design considerations and dimensioning

Data needed for designing biopiling treatment are mainly collected during biodegradability tests (oxygenation of the in situ medium, humidity, concentration of nutrients, temperature, density of the adapted microbial population in place, degradation time). These tests, combined with intrinsic parameters of the environment (water permeability, air permeability, percolation speed, etc.) help defining the optimal operating conditions and the sizing of the treatment unit.

Key parameter to design a biopiling treatment are:

a) geometry;

b) the characteristics of the ventilation network (oxygenation rate);

c) the characteristics of the sprinkler system (nutrient addition and leachate recirculation);

d) type of nutrients;

e) possibly, the size of the treatment units (for the wastewater and off-gas treatement).

9.14.5 Advantages and limitations

Biopiling is a reliable and well proven technique for organic biodegradable compounds. It can reach very high degradation rates. It relies on a destructive process and can be applied to many contaminants. It is widely used in the case of heterogeneous and easily biodegradable soils. It is a technique that allows excellent microbial control (oxygenation of the environment, humidity, concentration of nutrients, temperature, density of the microbial population in place, etc.). Therefore, controlling biopiling parameters (i.e. biodegradation process) is easier than controlling the key parameters in in situ biological treatments. It can be competitive in terms of cost and performance. It can improve physical qualities of the treated soil (particularly the organic matter content).

There are also some limitations to the technique. High concentrations of metals/metalloids are not compatible with this process and high concentrations of contaminants can be toxic for microorganisms (TPH above 50 000 mg/kg and up to 100 000 mg/kg). Biopiling requires excavation and somes sorting of the excavated materials (granulometries larger than 60 mm are often excluded from the process.), and the fate of excavated soils shall be carefully examined. On the other hand, the percentage of fine particles is also a limiting factor as soils containing clay and a high organic matter content lead to a high adsorption of contaminant on the solid matrix, (which decreases the treatment yield). Low temperatures considerably reduce the efficiency of the treatment. In addition, soil heterogeneity can interfere with the homogeneity of the airflow distribution and thus the effectiveness of the treatment. Static biopiles can lead to less homogeneous results than those obtained with turning or mixing. Atmospheric emissions sometimes require air treatment, which lead to additional costs. The height of the heap is generally between 1 m and 3 m maximum, which sometimes implies a consequent ground surface. The addition of structuring agents sometimes increases the volume of material to be treated.

9.14.6 Key monitoring parameters

To determine the effectiveness of a biopiling technology, the key parameters are:

- vacuum at the extraction wells;
- parameters relating to the bacteria development (pH, temperature, conductivity, redox potential, humidity, C/N/P/K ratio);
- content of possible additives;
- contaminant concentrations in the soil and soil gases (e.g. monitoring of CO_2 emission).

In some cases, contaminant concentrations in the atmospheric emissions and parameters relating to gas treatment (flow rates, depression, pressure drop, saturation of activated carbon, etc.) can be considered. In addition, contaminant concentrations in wastewater and parameters relating to water treatment can also be considered (see 9.21).

9.14.7 Specific EHS aspect

As with any biological degradation technique, it is important to monitor the gaseous emissions, which can present a strong odour nuisance and an H_2S risk in the case of anaerobic reactions.

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

The process relies first on excavation to be carried out (see 9.20). It also relies on treatments techniques for the wastewater and off-gas (see 9.21). In some cases, biopiling can be heated (between 25 °C and 45 °C) to promote biodegradation (injection of heated air, circulation of hot water in a closed circuit, etc.).

9.15 Landfarming

9.15.1 Technique principle

The process is simple and consists of spreading a low thickness of contaminated soils on an impermeable surface and then promoting aerobic biodegradation through conventional farming techniques. The technique can be applied on site or off site.

NOTE The process as described here is a development from the practice of sludge farming (sometimes also referred to as landfarming) used for many years to dispose of oil refinery sludges. The oily waste was spread on the surface of the soil and then, with the addition of nutrients to stimulate microbiological activity, ploughed in. This process clearly has a potential for adverse environmental impacts if not properly designed and managed.[13]

9.15.2 Scope and applicability of the technique (operating window)

This traditional technique has various application in different countries. Other techniques are often preferred, such as treatments by biopiling and by composting, which require less space and allow better control of environmental conditions. Nevertheless, landfarming is effective in treating soils contaminated by organic compounds including BTEX, phenols, PAHs, and petroleum hydrocarbons with some positive experiences for pentachlorophenols, heavy hydrocarbons, and pesticides (see Annex A). However, high concentrations of contaminants can be toxic to microorganisms and high concentrations of metal(loid)s are incompatible with this process. In addition, volatile organic compounds (such as BTEX) can simply be dispersed to atmosphere rather than degraded.

9.15.3 Technology description

Landfarming consists of spreading a small thickness (usually < 50 cm) of contaminated soil (on-site or off-site) over large areas (tens to hundreds of square metres). This practice allows interaction between the contaminated soil and the atmosphere (see Figure C.17 in Annex C). The aim of the technology is to promote ventilation and therefore aerobic degradation. Ploughing the soil allows regular aeration. Biological integration is also favoured by the addition of nutritional supplements (minerals and fertilizers). Once mixed with structuring agents such as straw to aid air and moisture ingress, and various amendments, soils are usually turned regularly to improve ventilation.

The contaminated soil shall be spread out on an impermeable support (asphalt, geomembrane, more rarely concrete) to avoid any contamination of soil and underground water. The leachate is collected and either treated before discharge into the environment or recirculated to promote humidification and bacterial renewal. If necessary or if it is possible, the operations can be carried out under a tent or a hangar to limit the spread of airborne dust and the dissemination into the atmosphere of volatile compounds.

9.15.4 Design considerations and dimensioning

The data required for dimensioning a landfarming operation are mainly collected during biodegradability and compost compatibility tests. These tests associated with identification of the intrinsic parameters of the environment allow the definition of the optimal operating conditions and the sizing of the processing unit, including:

a) the surface required for treatment;

b) the type of compost and structuring agent and required input ratio;

c) the frequency of ploughing;

d) if necessary, the characteristics of the sprinkler network and the dimensions of the liquid treatment units.

Landfarming processing consists of the following:

— pretreatment (homogenization, screening, addition of nutrients and amendment of organic or structural matter);

- fixed treatment platform on impermeable support (clay, concrete, HDPE or equivalent) including means to collect and recycle the leachate;
- agricultural equipment for ploughing;
- equipment for monitoring the conditions of the treated soils (oxygenation, humidity, nutrient concentration, temperature, current microbial population density) and environmental impacts (groundwater, superficial, and air);
- storage of solid and liquid wastes resulting from treatment.

9.15.5 Key monitoring parameters

Like any biological treatment, to determine the effectiveness, the essential parameters to be controlled are humidity, nutrients, pH, and temperature. In addition, other key monitoring parameters are:

a) the proper development of bacteria (pH 6 to 8, temperature 10 °C to 25 °C, humidity with 40 % to 85 %, and C-N-P-K ratio);

b) development of the contaminants in soils including the metabolites which can be produced.

9.15.6 Advantages and limitations

Landfarming is a simple technique to design and implement. It is competitive in terms of cost and performance. It is a proven technique used for heterogeneous and easily biodegradable contaminants. It relies on a destructive process which allows better control than biological treatments in situ, and improvement of the physical qualities of soils.

However, the technique has some disadvantages and limiting factors. It relies on soil excavation, substantial pre-treatment, and large areas of impermeable support. It produces dust during ploughing. It leads to the evaporation of volatile contaminants directly into the atmosphere. Its biodegradation is less efficient than biopiling and composting. Its effectiveness is controlled by the soil characteristics (particle size, organic matter content) and operating temperatures.

9.15.7 Specific EHS aspects

Volatile compounds should be specifically collected and treated to limit atmospheric transfers.

If landfarming operations are carried out in a tent or similar, those working within the covered area shall have independent air supplies, ploughing equipment etc. should be intrinsically safe, and exhausted ventilation air should be treated to remove volatile contaminants as necessary.

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

Landfarming relies on excavation (see 9.20) Additional techniques for the separation of soil grain sizes or treating gases can be implemented (see 9.21).

9.16 Vertical barrier technologies (VBT)

9.16.1 Technique principle

Vertical containment relies on physical passive containment. They are not treatment techniques but engineered-based techniques aiming at containing in situ contamination. They aim to prevent groundwater flow out of the contaminated area through installation of a vertical barrier between the source of contamination and groundwater and/or surface water to be protected. Barriers can be placed around the periphery of the contaminated site or installed downstream or upstream of the contamination source.

NOTE There are two types of physical passive containment: vertical barrier technology and surface containment (see 9.17).

9.16.2 Scope and applicability of the technique

Vertical containment is an in situ technique and can be applied to almost all types of contaminant (VOCs, PCBs, PAHs, metals/metalloids) (see Annex A). However, some contaminants are not compatible with the usual containment materials.

The implementation of these different types of vertical containment can requires very specialised and expensive construction equipment which can usually only be justified for a minimum volume of contaminated soil, below which excavation is more appropriate.

9.16.3 Technology description

Table 4 shows the main techniques of vertical containement and their frequency of use (see Figure C.19 in Annex C).

Table 4 — Main techniques of vertical barrier (ADEME)

Principle	Technique	Principal material(s)	Frequency of use
Excavation of soil and placement of watertight material	Slurry wall	Slurry bentonite/cement Plastic concrete	+++++
	Composite slurry wall	Slurry bentonite/cement with geomembrane or sheet peeling	++++
Soil displacement and placement of watertight material	Thin wall	Slurry bentonite/cement	+++
	Sheet piling	Steel	+
Reduction on site of permeability	Injected sheet	Injection grout	++
	Soil mixing	Cement or slurry bentonite/cement	++
	Jet grouting	Cement	++

9.16.4 Design considerations and dimensioning

Dimensioning requires consideration of:

a) geotechnical soil characteristics (type of soils, stability, etc.);

b) hydrogeological context (groundwater depth, permability of the saturated zone, etc.);

c) specific objectives, design life, area, remediation limits, end uses etc. of the VBT project;

d) site characteristics (topography, actual uses, access, water balance model, etc.).

It is necessary to verify the compatibility of the contaminants with the containment materials before selecting the technique. In general, the barrier should be anchored in an impermeable formation.

9.16.5 Key monitoring parameters

Vertical containments require very long-term monitoring to track their effectiveness. Monitoring shall allow the functioning of the containment to be understood and permit the evolution of its efficiency to be determined. Most often, the monitoring consists of taking and analysing samples from groundwater or surface water in order to verify its quality and how this evolves over time. Regular checks should be performed to ensure that containment measures are still in place and functional.

9.16.6 Advantages and limitations

Table 5 shows the advantages and the limitations of vertical containment systems.

Table 5 — Advantages and limitations

Advantages	Limitations
— Large range of contaminants — Adapted for large volumes of inorganic and mixed contamination — Reliability	— Contamination stays in place — Specific and onerous construction equipment — Only permits limitation of horizontal transfers — Very long-term monitoring and servicing — Need to keep track of the contamination and implementation of use restrictions — Can require other treatment techniques

9.16.7 Specific EHS aspects

In the case of slurry walls, soils shall be excavated using slurries supporting the side of the excavated trench. Surplus slurry can be contaminated and shall be disposed as waste.

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

Vertical containments can be combined with the other remediation techniques [e.g. cover systems (see 9.17), pump-and-treat (see 9.12), permeable reactive barrier (see 9.18)].

9.17 Cover systems

9.17.1 Technique principle

Cover systems rely on physical passive containment. They are not treatment techniques but engineering-based techniques aiming at containing in situ contamination. They enable:

a) physical isolation of the contaminated ground from the outside environment;

b) control of liquid and gas flows;

c) improvement of mechanical stability;

d) support for buildings and vegetation.

Although covers can consist of a single layer of suitable material preventing site users from coming into contact with contamination and dispersal of contaminants by wind and precipitation, they are often multi-functional and comprise a number of layers intended to perform specific functions. For example, limit or prevent infiltration of water, provide drainage for water and/or gas, prevent upward migration of gas, prevent upward migration of contaminated groundwater, support vegetation, limit rooting depth, support buildings and other structures, contain electrical and other services to buildings, etc. Each cover system shall be designed on a site-specific basis.

NOTE 1 There are two types of physical passive containment: vertical barrier technology (see 9.16) and surface containment.

NOTE 2 The term “capping” is sometimes used but this is best restricted to instances where the primary function is to prevent water ingress, e.g. on old landfills.

9.17.2 Scope and applicability of the technique

A cover system is a suitable option for heterogeneous contamination not susceptible to other remediation techniques. Containment can be temporary or final.

Cover systems shall be designed to provide the required functions for the specific conditions of each site, including:

a) the nature and extent of the contamination;

b) the geological, hydrogeological and hydrological characteristics of the site;

c) the intended use of the land.

Most covering systems are intended to be permanent. However, sometimes they are temporary, and intended to function for only a short time. They can, for example, be part of an emergency response intended to prevent contact between contaminants and those who can enter the site, and to prevent the spread of contamination by wind action or movement of precipitation on the site. They can also be intended to improve the trafficability of the site and/or provide a working platform for installation and operation of some other remediation technique.

9.17.3 Technology description

Multi-layered covers use layers of differing materials to perform different functions. The materials used can be natural (e.g. top soil, gravels, clay, sand), synthetics (e.g. HDPE geomembrane or other geosynthetic material, clay liner, concrete, bitumen) or a combination. Depending on the functions to be performed, the thickness of the cover system can vary from as little as 0,3 m (e.g. for a temporary separation layer) to well over 1 m. The thickness depends on the materials used and the functions required. It is recommended to avoid overly complex designs because of the difficulties in measuring the quality of the installation. Illustrations of cover system(s) are provided in Figure C.20 in Annex C.

A typical multi-layer system can include, together with other elements, from top to bottom:

a) a surface layer to support vegetation;

b) a protection layer to prevent physical intrusion (if composed of a low-permeability material it can also serve to limit infiltration);

c) a water/gas drainage layer;

d) a low-permeability layer to prevent water infiltration;

e) a foundation layer.

An important component in many cases can be a capillary break layer usually composed of a free-draining granular material (it can sometimes also serve as a gas/water drainage layer). The potential capillary rise depends on the fineness of the material and sometimes can be several metres above the water table.

Covers can be difficult to apply on sloping or domed sites without first carrying out engineering works (e.g. benching) to shape the material to be covered to limit the possibility of erosion and slope failure etc.

9.17.4 Design considerations and dimensioning

A conceptual site model (CSM) (see ISO 21365 for guidance on CSMs) for the remediated site shall identify all the functions that the covering system is required to perform and how the cover can develop over a prolonged period of time. It is essential to identify forseeable events such as changes in land use, flooding or rising groundwater levels, settlement, cultivation and development of vegetation with time, and colonisation by deep-rooting trees and burying animals. It is crucial to know whether covering the site ends action on the site or whether there is an intention to develop the site immediately or in the near term. It is also recommended to consider wether practical and enforceable controls are required, depending on how the site is used in the future. It is also important to identify any constraints that can influence the design of the covering system. For example, it can be unacceptable to raise site levels by 15 m because this can impact adjacent sites and possibly induce settlements that can promote dispersal of contaminated groundwater and ground gas. Among the parameters that should be considered are:

a) geotechnical soil characteristics (type of soils, stability, etc.);

b) hydrogeological context (groundwater depth, permability of the saturated zone, etc.);

c) specific objectives, design life, area, remediation limits, intended end uses etc. of the land;

d) site characteristics (topography, actual uses, access, water balance model, etc.).

The choice of materials is based on their costs, their availability and their characteristics with respect to the previously defined functions (protection, sealing, drainage, filtration, reinforcement, resistance to erosion, design life, type of contaminant).

When the provision of the cover system is a prelude to development of the site with buildings or other structures, it is essential to take account of any engineering works required to enable planned construction works to be carried out. Consideration shall be given, for example, to required engineering bearing pressures, the location and form of services to be provided, and the need to ensure that subsequent construction works do not compromise the functioning of the cover system.

9.17.5 Key monitoring parameters

Cover systems usually lead to the imposition of use restriction measures and requirements to keep a permanent record of their presence and design, and to specify the operating and the maintenance methods. Appropriate environmental monitoring shall be set up to verify the absence of impact on the environment when it has been decided to contain the contamination.

A distinction shall therefore be made between:

a) measures carried out immediately after work to confirm proper installation (permeability testing, defect detection methods, confirmation of layer depths, etc.);

b) long-term monitoring measures [groundwater and surface water quality analyses, monitoring of air emissions, absence of erosion, confirmation of integrity (e.g. absence of works that can have undermined effectiveness)] and maintenance measures.

9.17.6 Avantages and limitations

Table 6 shows the advantages and the limitations of cover systems.

Table 6 — Advantages and limitations

Advantages	Limitations
— Large range of contaminant types — Adaptable for large volumes of inorganic and mixed contamination — Reliability — Turnaround times and costs	— Contamination stays in place — Very long-term monitoring and maintenance — Need to keep track of the contamination and implementation of use restrictions — Can require other treatment techniques to be used in conjunction — Difficult to apply on sloping or domed sites without first carrying out engineering works to shape the material to be covered to limit the possibility of erosion and slope failure.

9.17.7 Specific EHS aspects

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

Cover systems can be combined with the other remediation techniques, including, for example, vertical containments, pumping and treatment, permeable reactive barriers, ground gas control systems.

9.18 Permeable reactive barrier (PRB) systems

9.18.1 Technique principle

A PRB enables the remediation of contaminated groundwater. PRB consist of a vertical permeable zone made of reactive materials [(also called reactive zone (RZ)]. It is placed perpendicular to the groundwater flow direction in order to intercept a plume of dissolved contaminants in the saturated zone. Targeted contaminants can be either immobilized (absorbed) or chemically and/or biologically degraded, detoxified, mineralized or converted into less innocuous forms as they migrate passively through the reactive zone under the control of natural hydraulic gradient.

9.18.2 Scope and applicability of the technique (operating window)

PRB systems can treat a wide range of pollutants whether organic or inorganic that are present in an aqueous form in groundwater (see Annex A).

9.18.3 Technology description

Two geometric configurations are most frequently used for PRB systems (see Figure C.21):

a) continuous PRB, which is a single reactive permeable "wall" installed across the plume;

b) funnel-and-gate (FAG); which comprises a permeable gate also called reactor (RZ), and that is placed at the convergence of two impermeable walls that redirect the plume towards and through the reactive zone.

Zerovalent Iron (ZVI) is commonly used as reactive material for the RZ for the remediation of chlorinated solvents, redox-sensitive metals and metalloids (e.g. Cr, As). A wide range of other reactive materials is also available: GAC, zeolite, sawdust for immobilization, ORC or HRC (aerobic or anaerobic). Biowalls are PRBs that promote biological treatment of groundwater.

9.18.4 Design considerations and dimensioning

The quality of installation of a PRB system is critical for its successful performance and includes geotechnical and civil design considerations, e.g. various trenching technologies, direct injection, large-diameter borehole-filled completions are possible. The PRB design relies on the most suitable barrier location and configuration. It should consider an appropriate reactive matrix type with relevant hydraulic conductivity and specify the length/width of the barrier. The performance and the design of PRB are highly dependent on several parameter such as treatment objectives, local hydrogeological settings, type of contaminant(s), concentration and mass transfer of contaminant(s) (i.e. 3D plume geometry) in groundwater, and the nature, permeability and thickness of reactive barrier. Two main variables shall be considered for the proper design of PRB:

a) the capture zone (the width of the barrier necessary to intercept the entire plume);

b) the residence time (the time required for contaminated groundwater to flow through the reactive matrix to achieve the treatment goals).

9.18.5 Key monitoring parameters

A dense monitoring well network is required downgradient and upgradient of the plume to monitor and control groundwater levels, the numbers of wells reflecting the geometry of the system (larger numbers of wells upgradient and fewer, downgradient for funnel-and-gate geometry than for continuous barriers). Site-specific long-term performance monitoring plans based on a hydrogeological conceptual model should be developed to detect processes that can jeopardize a PRB's performance such as:

a) loss of reactivity;

b) decrease in hydraulic conductivity of RZ;

c) decrease in contaminant residence time in RZ;

d) short-circuiting or leakage in the funnel (for FAG).

9.18.6 Advantages and limits

PRBs appear to be sustainable in situ techniques as they are passive, long lasting, cost-effective alternatives compared to traditional active pump-and-treat which has low operational and maintenance costs but higher installation costs. To limit the risk of failing to identify bypassing preferential contaminant pathways, an exhaustive site characterization is essential for the success of PRB systems. Undesirable processes such as clogging and biofouling can occur in the RZ hindering the PRB's performance. Conventional PRBs require some excavation, which limits them to fairly shallow depths of about 20 m. The existence of above-ground structures and/or buried rocks or networks of pipes can limit the feasibility of a PRB's construction. Waste (soil material, sludges) requiring disposal can be generated during trenching. There is also a need to anchor the PBR within the (preferably low-permeability) bedrock beneath the aquifer to a minimum depth of 2 m (otherwise groundwater bypasses the barrier).

9.18.7 Specific EHS aspects

This technique induces the management of waste produced when trenching within polluted soils and saturated GAC (for RZ intended to immobilize contaminants).

9.18.8 Possible combination with other techniques and technique variations

A wide range of innovative reactive materials can be used as the reactive matrix. Some additional groundwater treatment such as sparging (see 9.9) or additives injections (redox regulation, complexing agent, skimmers) can be placed upgradient of the PRB to optimize its operation.

9.19 Immobilisation techniques for soil and solid materials

9.19.1 Technique principle

Stabilization and solidification processes can be applied alone or in combination, in the latter case usually being characterized as stabilization/solidification (S/S) processes. Stabilization processes are those in which the chemical form of a substance of interest is converted to a form that is less mobile. Solidification processes convert contaminated soils and other materials (e.g. dredged silts) into a consolidated mass or otherwise improve the physical characteristics of the treated material. S/S processes are often applied ex situ to excavated contaminated soils and/or materials before disposal by landfilling or use beneficially in earthworks. Although ex situ S/S can be carried out in a single operation, better results are often obtained if stabilization is carried out as a separate operation before solidification. S/S can also be applied in situ.

NOTE The underlying principles for in situ immobilisation techniques are the same as those for ex situ processes. The major differences concern the methods of application and how to verify that treatment has been effective and continues to be so.

9.19.2 Scope and applicability of the technique (operating window)

Immobilisation techniques are best suited for soils contaminated with metals, radionuclides, other inorganic compounds, and non-volatile organic compounds. Volatile contaminants are typically not good candidates for solidification, as the contaminants can evaporate into the atmosphere during the mixing process. S/S processes may be applied to a wide range of fine-grained to coarse-grained materials.

Issues affecting the applicability of in situ processes include how the contaminants are distributed in the ground (e.g. relatively homogeneous or very heterogeneous across the plan area to be treated and/or with depth), the nature of the ground [e.g. mineralogy, particle size distributions, presence of putrescible materials, location and size of the contaminated ground and bearing capacity (relevant to whether heavy machines can be used)], and the hydrological regime (e.g. position of the water table).

9.19.3 Technology description

The same mix combinations can in general be used for in situ and ex situ treatment. An illustration of the in situ and ex situ technique is provided in Figures C.22 and C.23 in Annex C.

Stabilizing agents are often added only as a small proportion of the overall mix. Stabilizing agents that have been used include organophilic clays, activated carbon, biochar, reducing agents (e.g. ferrous sulfate to convert chromium VI to chromium III), and precipitation agents to convert soluble salts to insoluble salts (e.g. sulfates to sulfides). Binding agents include cementitious materials [e.g. Portland cement, pozzolan, hydraulic slag (e.g. ground granulated blastfurnace slag), and lime], polymers, silicates, and thermoplastic materials. Other possible reactive amendments are different types of zerovalent iron (ZVI): microsized ZVI, nanosize ZVI, sulfidated ZVI. When S/S is applied ex situ, a degree of homogenization of the input materials is sometimes carried out before the various treatment agents are added to the mix.

There are numerous examples of material treated ex situ being used beneficially in earthworks, e.g. filling a disused dock to form a construction platform; reclaiming land from the sea; as sub-base beneath roads and construction slabs. A variety of mixing equipment can be used for ex situ treatments.

Depending on the depth at which treatment is required, in situ treatment can be applied using:

— conventional agricultural techniques to add amendment materials (e.g. fertilizers, lime, organic matter) to cultivated land and during land reclamation;

— conventional engineering techniques to add amendment materials such as lime and hydraulic slags to natural ground or imported materials such as gravels and crushed rock to form a sub-base beneath roads and areas of hard-standing;

— deep mixing using augers to form overlapping columns of treated materials (applicable to many metres depth);

— in situ immobilisation using amendment injection.

9.19.4 Design and dimensioning considerations

The choice of binding agents and the design of mixes are highly specific to the contaminated material to be treated and thus treatability studies are always required. Some potential contaminants (e.g. lead, zinc, phosphates, phenols) can interfere with the setting and strength development of the cementitious mix. Treatability tests are essential and can be used not only to optimize technical performance but also as ways of controlling costs. The leaching test and other tests should be carried out by a laboratory experienced in the use of the tests to be employed. All trials should be carried out using the materials that would be used in the full-scale application if it goes ahead. This is necessary because Portland cement and other binding agents can vary greatly in their composition and properties, and this can affect the treatment results. Treatment agents should comply with quality and environment requirements and be fully described and characterized in terms of physical and chemical properties.

The effectiveness of S/S processes is critically dependent on the efficacy of mixing of the contaminated materials with stabilizing reagents and binder. The contaminants to be treated can at best exhibit limited solubility, be present at only very low concentrations (for example less than 0,1 %) and be unevenly distributed through the soil. Stabilizing agents are often added only as a small proportion of the overall mix, a few percent at most, so bringing them into contact, especially in situ, with the target contaminants is always problematic, especially if they are solids. Hence, in many cases of S/S, it is solidification that dominates effectiveness. In addition, some proposed stabilization agents are not necessarily stable in the alkaline cement matrix.

The mineralogy of the material to be treated can sometimes be critical due to potential volume instability. For example, Portland cement can react with glass and certain siliceous materials (alkali-silicate reaction) and sulfates, and sulfides (e.g. pyrites) can react to form sulfates which then react with the cement. These expansive reactions can take many years to become manifest so expert testing is required. Cement can also react with any aluminium metal present in the soil to form hydrogen. As for any cement-based material, the solidified material can be subject to external attack/modification by carbon dioxide, sulfates, acid waters, and sea water. Some binder combinations are generally more resistant to such attack. Inherent in these sorts of problems is the fact that cement-based materials can continue to develop their properties, including possibly leachability, over many years. In contrast, treatability studies extend at most for a few months.

9.19.5 Key monitoring parameters

Key monitoring parameters are similar for ex situ and in situ immobilization techniques. The following parameters shall be determined/monitored during an immobilisation operation:

a) quantities of soil to be treated and the initial concentrations of contaminants;

b) water consumption, mixing ratio of soil and stabilisation and/or binding reagents;

c) leachability of treated materials (not only for substances of initial concern but also those whose mobility can be increased by the treatment, e.g. due to changes in pH);

d) permeability and compressive strength of solidified material;

e) quality of mixing.

Verification of the quality of mixing and other performance parameters is clearly easier for ex situ processes and for in situ processes when the treatment depths are shallow. Established procedures for verifying performance in engineering applications can be adapted when similar treatment processes are used. When treatment is applied at depth verification investigations are expensive and difficult because of the need to take cores at depth.

It should be noted that in the typically alkaline environment in the setting mix, substances other than those detected in preliminary leachability tests on the material to be treated can be solubilized, e.g. metallic aluminium dissolves reacting to evolve hydrogen, or aluminium from clay minerals is solubilized. Appropriate analytical tests and other tests are required during treatability studies which extend beyond the substances that were the trigger for deciding that remediation was required.

9.19.6 Advantages and limitations

Ex situ S/S technologies have many advantages. Firstly, they can be applied to different types of soils.

They can reduce the accessibility of contaminants to the environment and stabilization also reduces availability. They improve the handling of many materials, in particular sludges and high-water content materials. They also allow synergies with ground preparation for geotechnical purposes.

NOTE They are also established technologies for dealing with hazardous wastes.

However, they have some limitations and disavandages. They lead to mass and volume increase (increasing the masses to be landfilled and the costs associated). They are ineffective for organic compounds. They need long-term performance monitoring. They can lead to potential adverse impact on the surrounding environment (e.g. impact on pH, ORP, water contents) when treated materials are placed on or in the ground. When treated materials are placed on, or in, the ground, a covering system, and possibly vertical containment barriers, can be required, e.g to limit water ingress or to enable reuse of the land.

In situ S/S technologies generally have similar advantages and disadvantages to ex situ treatments. However, they have some particular disadvantages.

a) The longevity of a stabilization process applied at shallow depths, e.g. liming to reduce availability of phytotoxic metals to plants, can be limited and repeat applications can be required indefinitely in the future.

b) The uncertain longevity of the in situ S/S applied at depths, because of, for example, change of environmental or hydrological conditions such as infiltration of acid rain or cyclic wet-dry actions, can lead to the degradation of solidified materials and/or destabilization of the contaminants.

9.19.7 Specific EHS aspects

Specific health protection equipment is required for the staff when handling hazardous materials including treatment agents such as Portland cement (highly alkaline and caustic and sometimes containing chromium VI which can cause or promote dermatitis). Heat generated during cement setting and hardening can cause volatilization of volatile substances. Reaction of cement with waste metals especially aluminium can cause development of hydrogen thus creating a hazardous atmosphere in and around mixing equipment.

In some circumstances, it can be necessary to provide a cover to treated materials, although in some instances this can be provided by the subsequent engineered cover, e.g. a road. In the case of agricultural and similar soils (e.g. parkland), residual risks to sites users, farm animals and the wider environment should be assessed before the treatment method is selected for application.

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

Solidified contaminated soil can be buried on the surface or underground, but containment in the form of barrier walls can be required to provide absolute protection against leaching and in the form of a cover system to prevent exposure of the treated material, to protect the material from weathering and to enable reuse of the land. In some cases, long-term restriction on land-uses can be required, e.g. no conversion to residential use without further remediation.

9.20 Excavation

9.20.1 Technique principle

Excavation of contaminated soil is the simplest and fastest method to remove soil contamination. The excavated contaminated soil is treated or disposed of on-site (e.g. in a repository requiring containment measures) or off-site. The excavation, i.e. the created void, is backfilled with either treated soil or uncontaminated material moved from elsewhere on the site or imported from off-site.

9.20.2 Scope and applicability of the technique (operating window)

All types of contaminated soils can be excavated, regardless of grain size and contaminant content (see Annex A). Only contaminated soil above the groundwater level can be subject to excavation unless dewatering is first carried out. Dewatering requires groundwater extraction and measures to control the water level while the works proceed (e.g. groundwater monitoring, hydraulic containment). If the groundwater is contaminated with light non-aqueous phase liquids (LNAPL), excavation only takes place once the floating layer has been removed (see 9.10). The feasibility of excavation is partly governed by the geotechnical properties of the ground as they affect the stability of the excavation itself (created void, pit) and the stability of nearby walls and buildings.

9.20.3 Description of technology

Excavation is carried out using various combinations of mechanical equipment such as excavators and dump trucks depending on the scale of the excavation and the accessibility of the site for vehicles (see Figure C.24). Excavations should at all times be properly sloped or provided with appropriate continuous temporary support. During the excavation, in the presence of dusts, VOC or odours, specific measures are required (e.g. real time monitoring, mitigation measures, excavating in several phases). The excavated soil can be stored in a (temporary) installation on site or can be immediately transported off-site to a final disposal or treatment installation.

9.20.4 Design considerations and dimensioning

The design of a soil removal operation involves several steps:

a) calculation of the tonnage and volume of contaminated soil to be excavated and the actual volumes to be moved allowing for “bulking” (correction made using an expansion factor);

b) geotechnical study for assessing slope stabilities etc. and, if necessary, design of temporary supporting walls and groundwater extraction systems;

c) excavation relying on prior identification of needed equipment, access ramps, and excavation phases;

d) sampling to check that removal of contaminated soil has been carried out as planned (usually the walls and bottom are sampled and analysed on an agreed pattern).

NOTE 1 If the site is large and accessible for vehicles, an access ramp can be built to permit entry of large trucks directly into the excavation pit. If such access is not possible, equipment such as dumpers and excavators descend into the pit as they work. Excavated soil is then hauled up to a temporary surface storage area prior to being picked up by trucks. On small sites, excavated soil can be lifted by a long arm backhoe and directly put on a truck or a surface platform.

NOTE 2 Excavation is possible near, in or under buildings, by employing specific civil engineering measures and using special smaller equipment.

9.20.5 Key monitoring parameters

The monitoring parameters to consider or measure the effectiveness of the technique implementation are excavation and surrounding buildings stability, air quality (dusts, VOCs emission), concentration of contaminant remaining in soils in the bottom and sides of the excavation, water table and groundwater quality.

9.20.6 Advantages and limitations

Excavation is a reliable, fast and proven technique where the terrain is well accessible and the contaminant is located at shallow depths (ideally maximum 6 m to 7 m below ground level). When the situation becomes too complex (e.g. presence of groundwater, too many nearby buildings, presence of volatile compounds, treatment or disposal sites being too far away), project costs can grow exponentially to become prohibitive and CO_2 emissions increase dramatically. Costs and environmental impacts similarly rise if fill material has to be imported over a long distance.

9.20.7 Specific EHS aspects

Major potential concerns include slope stability and the release of emissions of VOCs and contaminated dust into the atmosphere while excavating, posing important risks to on-site work activities or the surroundings. In old landfill sites where putrescible material is present, carbon dioxide and oxygen deficient air can accumulate at the base of excavations. Poorly covered loads can give rise to significant release of dust. However, movement of large numbers of large noisy trucks (lorries) through local streets can often be the major hazard to people in the locality. Potential carryover of contamination to public roads and highways is an issue where excavation plant is operating on a site. Care shall be taken to ensure that potentially contaminated material is not inadvertently transported off-site on vehicle wheels, etc.

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

Excavation techniques often have to be combined with other(s) treatment techniques for the remediation to be successful. In addition, water sprinklers can be used to limit the emission of dust during the excavation. Modified foam or soil washing additives may be used for the limitation of VOC or dust emissions during the excavation of soils. If necessary, excavation can take place in a tent. This enables emissions to be contained and treated via an emission-reducing technique (see air treatment 9.21).

9.21 Off-gas treatment technologies and wastewater treatment technologies

9.21.1 General

Extracted groundwater or extracted gas (also called off-gas) can require treatment depending on its composition and national regulation requirements. Treatment can be necessary for wastewater and gas emissions from on site processes but also from in situ approaches such as SVE (see 9.8) or air-sparging (see 9.9). Other sources of contaminated water resulting from remediation works can also require treatment. This can be the case for example as a result of dewatering of excavations or sludges. There is a large variety of possible processes than can be suitable for treating different groups of contaminants depending on chemical and physical properties of the compounds of concern (see Annex A and Annex B). Specific separate processes are selected if they can treat the contaminants extracted from a particular remediation system and within a treatment train (e.g. prefiltration process of pumped groundwater contaminated with VOCs, followed by mass transfer into air by air-stripping process, and absorption of the gaseous compounds from off-gases from a stripping process onto granular activated carbon filter). Pretreatment can also be required to remove solids (particles, etc.).

9.21.2 Carbon adsorption

Granular activated carbon filtering (GACF) is a treatment technique that can be applied to both off-gas tratement and wastewater treatement [with contaminants in a dissolved form for wastewater (see Figure C.25)]. GACF is suited for a wide range of organic (e.g. hydrocarbons, VOCs) and inorganic (e.g. metals) compounds. Compounds present in water or in air flowing through a permeable medium made of granular activated carbon (GAC) are adsorbed on activated carbon while purified water or air are released. The activated carbon adsorbs the organic material. It also protects other water treatment units such as reverse osmosis membranes and ion exchange resins from possible damage due to oxidation or organic fouling.

Most activated carbons are made from raw materials such as nutshells, wood, coal and petroleum. Functionalized GAC is used for certain compounds (e.g. mercury with sulfur or sulfuric polymers doped GAC). Different raw materials produce different types of activated carbon varying in hardness, density, pore and particle sizes, surface areas, extractables, ash and pH. These differences in properties make certain carbons preferable over others in different applications.

Activated carbon is a proven technology for the removal of organics. The removal efficiency reaches up to 99 %. The efficiency is lower with low input concentrations.

Designing an activated carbon filtration system shall take into account the differences in the water to be treated, the type of activated carbon used, and the wastewater quality and operating parameters of the wastewater.

9.21.3 Off-gas treatment technologies

9.21.3.1 Catalytic oxidation (electric/gas-fired thermal catalytic oxidation)

A thermal catalytic oxidizer (CATOX) relies on an electric thermal oxidation system where a catalyst is added to the process to transform the exhaust (VOCs such as volatiles hydrocarbons, BTEX, VOCs, and PAHs) into CO_2, water and excess heat which can then be safely released into the atmosphere. Processing heat is approximately 450 °C to 500 °C. The catalyst allows the non-halogenated VOCs and PAHs to be processed at a lower temperature which can be economically efficient as no additional energy is needed. When halogenated COVs are oxidized, the oxidizer shall be heated with continuous electricity consumption. Furthermore, HCl is produced in off-gases which is cooled producing a condensate that can be neutralized before release. Treatment capacities of 500 m^3/h and 1 500 m^3/h are currently available. Usually, CATOX are technically and economically efficient compared to granular activated carbon filtration for VOCs concentration over 50 mg/m^3 (but it depends on the air flow, the volume to treat and the duration of the treatment).

9.21.3.2 Biofilters

The biofilter treatement relies on using peat, compost or soil as an air-permeable matrix to support the biodegradation of VOCs and for odour being vented through. The targeted compounds are non-halogenated and biodegradable VOCs. It is a simple and low-cost process with a low-input approach resulting in the destruction of the contaminants that are targeted. Like every biological technology, this process is vulnerable to poisoning and requires lots of space. The efficiency of biofilter decreases as fungal growth occur in the matrix. This technology is suitable for relatively low flow rates and low concentrations of contaminants.

9.21.4 Wastewater treatment technologies

9.21.4.1 Free product recovery

The pure products essentially recovered during pumping/skimming operations are very poorly miscible with water (LNAPL of the fuel, gasoline type; DNAPL, etc.). The principle of the free product recovery treatment relies on separating groundwater from pure product (free product). It is based on the low miscible nature of these products as well as on the difference in density between NAPL and water. It is a well established and simple technology.

9.21.4.2 Coagulation/flotation

Particulates and flocs present in water may be removed using flocculation/coagulation treatment. In these processes small air bubbles are injected into the wastewater in a separating tank. The bubbles attach to the suspended flocs, which in turn carry them to the surface where they are removed by a surface-skimming device. Flotation is often used in ex situ treatment for groundwater contaminated with dissolved metals. A coagulation step is operated prior to flotation to produce metallic flocs by the binding of metal with anionic polymers of hight molecular weight. Sand filtering and a pH adjustment are sometime required before coagulation. The choice of the coagulation agents depends on the metal targeted, the chemical composition of the water to be treated and the aimed metal concentration in the water out (removal efficiency). Flocculation/coagulation is a well-established treatment technology.

9.21.4.3 Chemical-precipitation

Chemical-precipitation treatment relies on the transformation of dissolved contaminants into insoluble compounds using chemical reactions such as pH changes (acid-base reactions). Targeted contaminants are metals, inorganics, hydroxides, sulfides and carbonates. The technology is simple, relatively low cost and large volumes of contaminated water can be processed at once. The main difficulty is to maintain optimum pH conditions for all metals in complexe mixtures.

9.21.4.4 Neutralisation (pH)

This treatment is simple, relatively low cost and large volumes of contaminated water can be processed at once. It is based on the injection of a strong acid (generally HCl) to decrease the pH or of a strong-base (generally NaOH) to increase the pH, for pH control. Acids and alkalis are the targeted compounds of this technology. Neutralisation may be used as a pretreatment operation prior to other physico-chemical processes where a stable near-neutral pH is required (e.g. coagulation/flocculation, ion exchange). Strong acids and strong bases are corrosive solutions which should be handled with care.

9.21.4.5 Air-stripping

Air-stripping can treat wastewater contaminated with dissolved organic volatile compounds. It consists of transferring the mass of dissolved compounds from water to air. Air-stripping is usually operated in pack columns or in aeration tanks. Atmospheric air is blown in these columns or tanks. The process has a removal efficiency up to 90 % depending on the compounds that are targeted. Stripping units connected in series are often necessary to reach the targeted residual concentrations when high concentration is observed in the wastewater.

With air-stripping, extracted contaminants are not destroyed. Air-stripping leads to oxygenation of treated water and thus stimulates aerobic biological activity. So the treatment may be followed by granular activated filtration of the air used before release in the atmosphere. The mixing of water with air produces oxidative condition in water causing:

a) the shift in the calco-carbonic equilibrium and $CaCO_3$ precipitation within the stripping units;

b) Fe, Mn oxidation and precipitation with fouling/clogging within the stripping units;

c) stimulation of aerobic bacterial growth and biofouling.

Packed stripping towers may be periodically emptied to remove old clogged packing (to be disposed as a waste) and be filled with a new packing. Operation costs are mainly due to electrical consumption (blower) and the maintenance and waste disposal in relation with the fouling withing stripping units. Air-stripping is a well established and simple technology.

9.21.4.6 Water filters

Filtering is a mechanical separation that relies on the particle size of the permeable filter medium that is being used. Suspended particles are separated by forcing the fluid through a porous material such as gravel, sand, diatomaceous earth. The suspended particles are trapped on the surface and/or within the porous spaces. This technique is suited for contaminants attached to a particular particle size. Filter can also support biodegradation of some organic compounds (by the development within the porous media of biofilms). Filtration units are usually equipped with automated back-flush systems to collect and remove fines. This technique is simple and well understood and is often used as pretreatment step to protect water treatment units that are sensitive to the presence of suspended particle (e.g. ion exchange resin). One of the main limitations is the need to dispose of the contaminant residue.

9.21.4.7 Chemical oxidation

Chemical oxidation relies on using ozone, hydrogen peroxide, permanganate, persulfate, ultraviolet light, or other elements to degrade the target contaminants (inorganics, and VOCs). The limitations include possibility of incomplete oxidation and the formation of intermediate contaminants, fouling and interference by high suspended particles in case of UV irradiation.

9.21.4.8 Ion exchange

The principle of this technique is to remove contaminant ions in water by exchanging them with ions brought by the exchange resin (H^+, Na^+, K^+, Mg^{2+}). Ion exchange is usually used to process water contaminated with metals and other inorganics like nitrate, ammonia, perchlorate and chlorate, silicates. The main advantage of the technique is the availibility of specific resins for specific contaminants (selective resins). The disadvantage is that contaminants aren't destroyed in ion exchange (mass transfer from water into the resins) and used resins shall be regenerated (with the production of wastewater to be disposed or destroyed) or disposed of. Other limitations are the high operation costs of the technique and the risks of fouling within ion exchange resins.

9.21.4.9 Reverse osmosis - ultrafiltration techniques

Reverse osmosis-ultrafiltration is based on the separation of a solvent from a solution by application of an external pressure across a semi-permeable membrane to reverse the normal osmotic flow. It results in water flowing from the side of high solute concentration to the side of low solute concentration, thereby increasing the concentration of the solute on one side of the membrane. Reverse osmosis is applied to inorganics dissolved in water at low concentrations. The main advantage of the technique is its high removal efficiency, but it requires stringent pH control and it doesn't destroy the contaminants. The concentrate process residue shall be destroyed or disposed of. Furthermore, there is a risk of fouling of the membrane and required high energy consumption.

9.21.4.10 Biodegradation: rotating biocontactors

After the removals of solid particles present in the water, wastewater is brought into contact with a microbial biofilm and with atmospheric air. Contactors are rotated to ensure the membrane is oxidated while in contact with waste stream. Targeted compounds are biodegradable organics and inorganics such as alcohols, phenols, phtalates, cyanides, ammonia. The main limitation of this process is the limited range of treatable contaminants and its vulnerability to poisoning, for example by a spike in contaminant locally.

9.21.4.11 Biodegradation: polishing in sand and gravel filters

This technique is based on the colonisation by indigenous microorganisms of sand/gravel filters to promote biodegradation of some organic compounds as well as reductions in BOD/COD (biochemical oxygen demand/

chemical oxygen demand). This technique is applied on various organics present dissolved in water. It’s a simple low-tech process with a low-input approach resulting in the destruction of the contaminants of concern. Like every biological technology, this process is vulnerable to poisoning.

9.21.4.12 Evaporation

Evaporation treatment is used to separate a clean condensate from a contaminated concentrate using processes such as pervaporation (evaporation accross an organophilic membrane). This technique is mainly applied to wastewater contaminated with solvents. Its advantage is to be able to reduce the volume of the waste treatement to be treated. Its limitations are high costs and poor availibility.

Annex A
(informative)

Remediation techniques, characteristics and conditions of implementation

Table A.1 presents the remediation techniques described in this document, with some characteristics and conditions of implementation.

Table A.1 — Remediation techniques, characteristics and conditions of implementation

Subclause	Technique	Mechanism	Treatable contaminants	Concentrations treated	Time	Conditions: saturated zone (SZ) / unsaturated zone (UZ)	Applications frequency
9.1	**In situ chemical oxidation (ISCO)**	Oxydizers are injected in the soil or the soil malaxed with such additives. Chemical reactions or free radicals destroy contaminants on contact.	Wide range of contaminants	Moderate to high	Weeks to months	SZ and UZ	Multiple applications required
9.2	**In situ chemical reduction (ISCR)**	Reductors as zerovalent iron or other metals or alloy are injected in the soil or the soil malaxed with such additives. Contaminants are chemically reduced or precipitated.	Specific chlorinated contaminanys (PCE, TCE, DCE and VC)	Moderate to low	Weeks to months	SZ and UZ	Multiple applications required. Single application common
9.3	**Enhanced in situ bioremediation (EISB)**	Microorganisms transform contaminants of concern to innocuous by-products under aerobic condition.	Petroleum hydrocarbons and other compounds including MTBE	Moderate to low	Months to a year	SZ	Every 6 months-12 months, as needed. Single application common
9.3	**Accelerated anaerobic in situ bioremediation**	Microorganisms transform contaminants of concern to innocuous by-products under anoxic conditions (accelerated anaerobic in situ bioremediation).	Chlorinated VOCs	Moderate to low	Years	SZ	Multiple applications required
9.4	**Monitored natural attenuation (MNA)**	Contaminants are degradated or depleted under natural bio- and/or physical-chemical conditions.	All (bio)degradable contaminants especially dissolved hydrocarbons. Treats light non-aqueous phase liquids (LNAPL) if natural source zone depletion (NSZD)	High to low	Months to a decade	SZ and UZ	Requires monitoring every 6 months-12 months, as needed
9.5	**Incineration**	Very high temperature removes contaminants from excavated soil by pyrolysis processes. This is done in controlled conditions.	Wide range of contaminants including mercury and various POPs	Moderate to very high	Weeks to months	UZ	Single application
9.6	**In situ thermal remediation (ISTR)**	Low temperature (100°) is delivered to subsurface to drive the contaminant to the collecting wells (venting or multi phase extraction).	Volatile and semivolatiles compounds	Moderate to high	Years	SZ and UZ	Single application
9.6	**In situ thermal desorption**	High temperature (600°) is delivered to subsurface to transform the contaminant into soil gas or vapour and collect it through wells.	Wide range of contaminants including COVs, mercury and various POPs	Moderate to very high	Months to a year	UZ	Single application
9.6	**In situ combustion**	Ignition temperature (600°) and air are delivered to subsurface to initiate in situ flameless combustion. The contaminants become the source of energy.	Petroleum hydrocarbons and other compounds including MTBE	Moderate to high	Months to a year	SZ and UZ	Single application

Sourced from References [7] and [8]. Reproduced with the permission of the authors.

Table A.1 *(continued)*

Subclause	Technique	Mechanism	Treatable contaminants	Concentrations treated	Time	Conditions: saturated zone (SZ) / unsaturated zone (UZ)	Applications frequency
9.7	**On site thermal desorption**	High temperature (600°) removes volatile contaminants from excavated soil by volatilization or pyrolysis processes. This is done in controlled conditions.	Wide range of contaminants including mercury and various POPs	Moderate to high	Weeks to months	UZ	Single application
9.8	**Soil vapor extraction (SVE)**	Soil gas is extracted from the soil in the unsaturated zone.	Volatile compounds	Moderate to low	Months to years	UZ	Single application
9.9	**Air-sparging**	Air is injected under pressure into the groundwater. Volatile contaminants are transferred to the compressed air and pumped by a soil vapour extraction.	Volatile compounds	Moderate to high	Months to years	SZ	Single application
9.10	**Multi-phase extraction (MPE)**	Contaminants are removed by three phases (LNAPL/DNAPL, dissolved and soil vapor) by a high-vacuum extraction system.	Light non-aqueous phase liquids (LNAPL) or dense non-aqueous phase liquids (DNAPL) liquids as petroleum hydrocarbons and halogenated volatiles	Moderate to high	Months to years	SZ and UZ	Single application
9.11	**Dual pump/liquid extraction**	Contaminants are removed by two phases (LNAPL /DNAPL and dissolved) by pumping wells.	Light non-aqueous phase liquids (LNAPL) or dense non-aqueous phase liquids (DNAPL) liquids as petroleum hydrocarbons and halogenated volatiles	Moderate to high	Years	SZ and UZ	Single application
9.12	**Hydraulic techniques for groundwater remediation**	Groundwater is pumped to collect and treat the contaminants in the dissolved phase.	Wide range of dissolved contaminants	High to low	Years to decades	SZ	Single application
9.12	**Hydraulic techniques for groundwater remediation**	Creation of a hydraulic dynamic containment of the contaminant plume in the groundwater or withdraw the water table.	All dissolved contaminants	High to low	Years to decades	SZ	Requires monitoring
9.13	**Soil washing**	Soils are excavated and washed with a liquid (water or solvent).	Wide variety of organic and inorganic contaminants	Moderate to high	Weeks to months	UZ	Single application
9.14	**Biopiling**	Soils are excavated and spreaded on waterproof support and then aerobic biodegradation is promoted through compost, structuring agent and growing agent additives.	Petroleum hydrocarbons and other compounds including BTEX	Moderate to low	Weeks to years	UZ	Single application
9.15	**Landfarming**	Soils are excavated and spread on field through conventional aerobic biodegradation farming technique.	Petroleum hydrocarbons and other compounds including BTEX	Moderate to low	Months to years	UZ	Single application

Sourced from References [7] and [8]. Reproduced with the permission of the authors.

Table A.1 *(continued)*

Subclause	Technique	Mechanism	Treatable contaminants	Concentrations treated	Time	Conditions: saturated zone (SZ) / unsaturated zone (UZ)	Applications frequency
9.16 and 9.17	**Physical passive containments**	Horizontal containments prevent contacts with the contaminants and infiltration of rain or evaporation of the contaminants. Vertical sealing prevents the contaminants to be spread out.	Wide range of non-volatile contaminants can be enclosed especially heavy metals, cyanides, dioxin, explosives, POPS	Very high to low	Weeks	SZ and UZ	Requires monitoring every 3 months to 6 months, as needed
9.18	**Permeable reactive barriers (PRB) systems**	A vertical permeable zone made of reactive materials treats contaminants in the groundwater.	Various dissolved contaminants as chlorinated solvents and redox sensitives heavy metal(oïds)	Moderate to low	Years to decades	SZ	Single application
9.19	**Immobilisation techniques for soil and solid materials**	Contaminants are promoted in a stable structure by a chemical reaction, complexation or capture in a polymer.	Various metal(oïds) contaminents as Cr6+ and some organics as dioxins or phosphorus products	All concentrations	Weeks to months	UZ	Single application
9.20	**Excavation**	Physical removal of contaminants	All contaminants	All concentrations	Days to week	SZ and UZ	Single application
9.21	**Off-gas treatment technologies and wastewater treatment technologies**	Combined physical, chemical, biological process on extracted gas or water	Various contaminants	High to low	-	SZ and UZ	Single or multiple depending on site conditions and treatment goals
Sourced from References [7] and [8]. Reproduced with the permission of the authors.							

Annex B
(informative)

Remediation techniques suitability for contaminants

Tables B.1 to B.4 present the suitability of remediation techniques to treat contaminants.

Table B.1 — Remediation techniques suitability for organic contaminants

						Organic compounds									
						Volatiles			Non volatiles						
Objectives and approach for remediation strategy	**Where remediation takes place**	**Targeted media/ matrix**	**Principle of treatment technique**	**Remediation technique**	**Reference subclause in this document**	**Halogenated volatile organic compounds**	**Non-halogenated volatile hydrocarbons (as BTEX)**	**MTBE/TBA**	**Petroleum hydrocarbons**	**Polyaromatic hydrocarbons**	**Energetic nitroaromatic compounds**	**PCB and PCB – Dioxin-like**	**PCDD, PCDF/PBDD PBDF**	**Pesticides and herbicides**	**Emerging pollutant as PFOS/PFAS**
Protection measures and cut-off of contaminants migration pathways	In situ without excavation	Soil/unsaturated zone	Physical	Horizontal passive containment – capping	9.17	•	•	•	•	•••	•••	•••	•••	•••	?
	In situ without excavation	Soil/unsaturated zone		Vertical passive containment	9.16	•	•	•	•	•	•••	•••	•••	•••	?
	In situ	Groundwater/ saturated zone		Dynamic and hydraulic containment (Pump-and-treat)	9.12	•••	•••	•••	•••	•••	•	•	☒	☒	•••
	In situ	Soil gas/unsaturated zone		Dynamic and pneumatic containment (soil vapor extraction, SVE)	9.8	•••	•••	•••	•	☒	☒	☒	☒	☒	☒
	In situ	Solid matrix (saturated, unsaturated zone)	Physical and chemical (for stabilization)	In situ immobilization via stabilization/ solidification	9.19	☒	☒	☒	☒	•	?	•	•	•	☒

••• applicable, suited

• applicable subject to specific feasability studies

☒ unsuitable

? not studied

Table B.1 *(continued)*

						Organic compounds									
						Volatiles			Non volatiles						
Objectives and approach for remediation strategy	**Where remediation takes place**	**Targeted media/ matrix**	**Principle of treatment technique**	**Remediation technique**	**Reference subclause in this document**	**Halogenated volatile organic compounds**	**Non-halogenated volatile hydrocarbons (as BTEX)**	**MTBE/TBA**	**Petroleum hydrocarbons**	**Polyaromatic hydrocarbons**	**Energetic nitroaromatic compounds**	**PCB and PCB – Dioxin-like**	**PCDD, PCDF/PBDD PBDF**	**Pesticides and herbicides**	**Emerging pollutant as PFOS/PFAS**
Removal or destruction or transformation of targeted pollutant within the source of pollution (remediation measure)	In situ	Groundwater/ saturated zone	Biological	Natural attenuation	9.4	•	•••	•	•••	•	☒	☒	☒	☒	?
	On site/off site	Soil		Biopiling	9.14	•	•••	☒	•••	•	•	☒	☒	☒	?
	In situ	Soil		Bioventing	9.7	☒	•••	•	•••	☒	☒	☒	☒	☒	?
	In situ	Groundwater and soil		Enhanced aerobic biodegradation	9.3	•••	•	•	•	•	•	☒	☒	☒	?
	In situ	Groundwater		Enhanced anaerobic biodegradation	9.3	•••	☒	☒	☒	☒	λ	☒	☒	?	?
	In situ	Groundwater and soil		Biosparging	9.8	•••	•	•	•	☒	☒	☒	☒	☒	?
	On site	Soil		Landfarming/ composting	9.15	☒	•••	•••	•••	•	•••	☒	☒	☒	?
	In situ	Groundwater	Chemical	In situ chemical oxidation (ISCO)	9.1	•••	•••	•••	•••	•••	•	☒	☒	☒	?
	In situ	Groundwater		Chemical reduction (ISCR)	9.2	•••	☒	☒	☒	☒	?	☒	☒	☒	?
	On site (after excavation)	Soil		Soil-washing	9.13	•••	•••	•••	•••	•••	•	•	•	•	☒

••• applicable, suited

• applicable subject to specific feasability studies

☒ unsuitable

? not studied

Table B.1 *(continued)*

						Organic compounds									
						Volatiles			Non volatiles						
Objectives and approach for remediation strategy	**Where remediation takes place**	**Targeted media/ matrix**	**Principle of treatment technique**	**Remediation technique**	**Reference subclause in this document**	**Halogenated volatile organic compounds**	**Non-halogenated volatile hydrocarbons (as BTEX)**	**MTBE/TBA**	**Petroleum hydrocarbons**	**Polyaromatic hydrocarbons**	**Energetic nitroaromatic compounds**	**PCB and PCB – Dioxin-like**	**PCDD, PCDF/PBDD PBDF**	**Pesticides and herbicides**	**Emerging pollutant as PFOS/PFAS**
Removal or destruction or transformation of targeted pollutant within the source of pollution (remediation measure)	In situ	Groundwater	Physical	Pump-and-treat	9.12	•••	•••	•••	•••	•	•	☒	☒	☒	•
	In situ	Groundwater		Multi phase extraction (MPE)	9.10	•••	•••	•••	•••	☒	☒	☒	☒	☒	☒
		Groundwater		Dual pump liquid extraction (DPLE)	9.11	☒	•••	•	•••	☒	☒	☒	☒	☒	☒
	In situ	Groundwater		Air-sparging	9.9	•••	•••	•••	☒	☒	☒	☒	☒	☒	•
	In situ	Groundwater		Venting, soil vapor extraction (SVE)	9.8	•••	•••	•••	•••	☒	☒	☒	☒	☒	?
	On site/off site after excavation	Soil/solid matrix		Incineration	9.5	•••	•	•••	•••	•••	•••	•••	•••	•••	?
	In situ	Soil		In situ thermal desorption (high T°C)	9.6	•••	•••	•	•••	•••	☒	•••	•••	•••	?
	In situ	Soil		In situ combustion (high T°C)	9.6	•	•••	•••	•••	•••	☒	☒	☒	☒	☒
	In situ	Soil		In situ thermal remediation (low T°C)	9.6	•	•	•	•••	•••	☒	•	•	•	?
	In situ	Groundwater	Special design for in situ treatment	Permeable barrier (biological, physical)	9.18	•••	•••	•••	•••	•••	•	☒	☒	•	?

••• applicable, suited

• applicable subject to specific feasability studies

☒ unsuitable

? not studied

Table B.2 — Remediation techniques suitability for elements and inorganic contaminants

Objectives and approach for remediation strategy	Where remediation takes place	Targeted media/matrix	Principle of treatment technique	Remediation technique	Reference	Elements and inorganic compounds					
						Asbestos	Metals (Pb, Cr, Cu, Cd, Ni, Zn, etc.) and metalloids (As, Sb, Te,...)	Elemental mercury (Hg°) and mercury inorganic compounds	Cyanid and cyano-compounds (isocyanate, etc.)	Chlorate and perchlorate	Nitrate and ammonium
Protection measures and cut-off of contaminants migration pathways	In situ without excavation	Soil/unsaturated zone	Physical	Horizontal passive containment – capping	9.17	•••	•••	•••	•••	•••	•••
	In situ without excavation	Soil/unsaturated zone		Vertical passive containment	9.16	•	•••	•••	•••	•••	•••
	In situ	Groundwater/saturated zone		Dynamic and hydraulic containment (Pump-and-treat)	9.12	☒	•••	•••	•••	•••	•••
	In situ	Soil gas/unsaturated zone		Dynamic and pneumatic containment (Soil vapor extraction, SVE)	9.8	☒	☒	•	☒	☒	☒
	In situ	Solid matrix (saturated, unsaturated zone)	Physical and chemical (for stabilization)	In situ immobilization via stabilization/solidification	9.19	•••	•••	•	•	?	?
Removal or destruction or transformation of targeted pollutant within the source of pollution (remediation measure)	In situ	Groundwater/saturated zone	Biological	Natural attenuation	9.4	☒	•	•	☒	•	•••
	On site/off site	Soil		Biopiling	9.14	☒	☒	☒	☒	•	•••
	In situ	Soil		Bioventing	9.7	☒	☒	☒	☒	☒	☒
	In situ	Groundwater and soil		Enhanced aerobic biodegradation	9.3	☒	☒	☒	☒	☒	•
	In situ	Groundwater		Enhanced anaerobic biodegradation	9.3	☒	☒	☒	☒	•••	•••
	In situ	Groundwater and soil		Biosparging	9.8	☒	☒	☒	☒	☒	☒
	On site	Soil		Landfarming/composting	9.15	☒	☒	☒	☒	☒	•
	In situ	Groundwater	Chemical	In situ chemical oxidation (ISCO)	9.1	☒	•••	☒	☒	☒	☒
	In situ	Groundwater		Chemical reduction (ISCR)	9.2	☒	•••	?	☒	?	?
	On site (after excavation)	Soil		Soil washing	9.13	☒	•••	•	•	•••	•••

••• applicable, suited

• applicable subject to specific feasability studies

☒ unsuitable

? not studied

Table B.2 *(continued)*

Objectives and approach for remediation strategy	Where remediation takes place	Targeted media/matrix	Principle of treatment technique	Remediation technique	Reference	Elements and inorganic compounds					
						Asbestos	**Metals (Pb, Cr, Cu, Cd, Ni, Zn, etc.) and metalloids (As, Sb, Te,...)**	**Elemental mercury (Hg°) and mercury inorganic compounds**	**Cyanid and cyano-compounds (isocyanate, etc.)**	**Chlorate and perchlorate**	**Nitrate and ammonium**
Removal or destruction or transformation of targeted pollutant within the source of pollution (remediation measure)	In situ	Groundwater	Physical	Pump-and-treat	9.12	☒	•••	•	•	•••	•••
	In situ	Groundwater		Multi phase extraction (MPE)	9.10	☒	☒	☒	☒	☒	☒
		Groundwater		Dual pump liquid extraction (DPLE)	9.11	☒	☒	☒	☒	☒	☒
	In situ	Groundwater		Air-sparging	9.9	☒	☒	☒	☒	☒	☒
	In situ	Groundwater		Venting, soil vapor extraction (SVE)	9.8	☒	☒	☒	☒	☒	☒
	On site/off site after excavation	Soil/solid matrix		Incineration	9.5	☒	☒	☒	•	☒	☒
	In situ	Soil		In situ thermal desorption (high T°C)	9.6	☒	☒	•••	☒	☒	☒
	In situ	Soil		In situ combustion (high T°C)	9.6	☒	☒	☒	☒	☒	☒
	In situ	Soil		In situ thermal remediation (low T°C)	9.6	☒	☒	☒	☒	☒	☒
	In situ	Groundwater	Special design for in situ treatment	Permeable barrier (biological, physical)	9.18	☒	•	•	•	•	•

••• applicable, suited

• applicable subject to specific feasability studies

☒ unsuitable

? not studied

Table B.3 — Groundwater treatment techniques and off-gases treatment techniques suitability for organic contaminants

			Organic compounds									
			Volatiles			Non volatiles						
	Principle of treatment technique	**Remediation technique**	**Halogenated volatile organic compounds**	**Non-halogenated volatile hydrocarbons (as BTEX)**	**MTBE/TBA**	**Petroleum hydrocarbons**	**Polyaromatic ydrocarbons**	**Energetic nitroaromatic compounds**	**PCB and PCB – Dioxin-like**	**PCDD, PCDF/ PBDD PBDF**	**Pesticides and herbicides**	**Emerging pollutant as PFOS/PFAS**
Groundwater treatment technique (on site)	Physical	Ion exchange resins	☒	☒	☒	☒	☒	☒	☒	☒	☒	?
		Granular activated carbon filtering	•••	•••	•••	•••	•••	•••	•	☒	•••	?
		Air-stripping	•••	•••	☒	☒	☒	☒	☒	☒	☒	?
		Inverse osmosis and membrane filtration technique	☒	☒	☒	☒	☒	☒	☒	☒	☒	?
	Chemical	Oxidation (O_3)	•	•	•	•	••	?	•	?	•	?
		Flocculation/precipitation/ filtration	☒	☒	☒	☒	☒	☒	☒	☒	☒	?
	Biological	Bioreactor	•	•••	•••	•••	☒	•	☒	☒	☒	?
		Rhizofiltration	•	•	?	•••	☒	☒	☒	☒	☒	?
Off-gases treatment techniques (on site)	Physical	Granular activated carbon filtering	•••	•••	•••	•••	☒	☒	☒	☒	☒	?
		Catalytic oxidation (CATOX)	•••	•••	•••	•••	☒	☒	☒	☒	☒	?
		Condensation	•••	•••	☒	•••	☒	☒	☒	☒	☒	?
	Thermal	Open - burning (flare)/internal combustion	•••	•••	•	•••	☒	☒	☒	☒	☒	?
	Biological	Biofiltration	•••	•••	•	•••	☒	☒	☒	☒	☒	?

••• applicable, suited

• applicable subject to specific feasability studies

☒ unsuitable

? not studied

Table B.4 — Groundwater treatment techniques and off-gases treatment techniques suitability for elements and inorganic contaminants

			Elements and inorganic compounds					
	Principle of treatment technique	**Remediation technique**	**Asbestos**	**Heavy metals (Pb, Cr, Cu, Cd, Ni, Zn, etc.) and metalloids (As, Sb, Te, etc.)**	**Elemental mercury (Hg°) and mercury inorganic compounds**	**Cyanid and cyano-compounds (isocyanate, etc.)**	**Chlorate and perchlorate**	**Nitrate and ammonium**
Groundwater treatment technique (on site)	Physical	Ion exchange resins	☒	•	•	•	•••	•••
		Granular activated carbon filtering	☒	•	•	•	☒	☒
		Air-stripping	☒	☒	☒	☒	☒	☒
		Inverse osmosis and membrane filtration technique	☒	•	•	•••	•••	•••
	Chemical	Oxidation (O_3)	☒	☒	☒	☒	☒	•
		Flocculation/precipitation/filtration	☒	•••	•••	•	☒	☒
	Biological	Bioreactor	☒	•	☒	•	•••	•••
		Rhizofiltration	☒	☒	☒	☒	☒	☒
Off-gases treatment techniques (on site)	Physical	Granular activated carbon filtering	☒	☒	•••	☒	☒	☒
		Catalytic oxidation (CATOX)	☒	☒	☒	☒	☒	☒
		Condensation	☒	☒	•	☒	☒	☒
	Thermal	Open - burning (flare)/internal combustion	☒	☒	☒	☒	☒	☒
	Biological	Biofiltration	☒	☒	☒	☒	☒	☒

••• applicable, suited

• applicable subject to specific feasability studies

☒ unsuitable

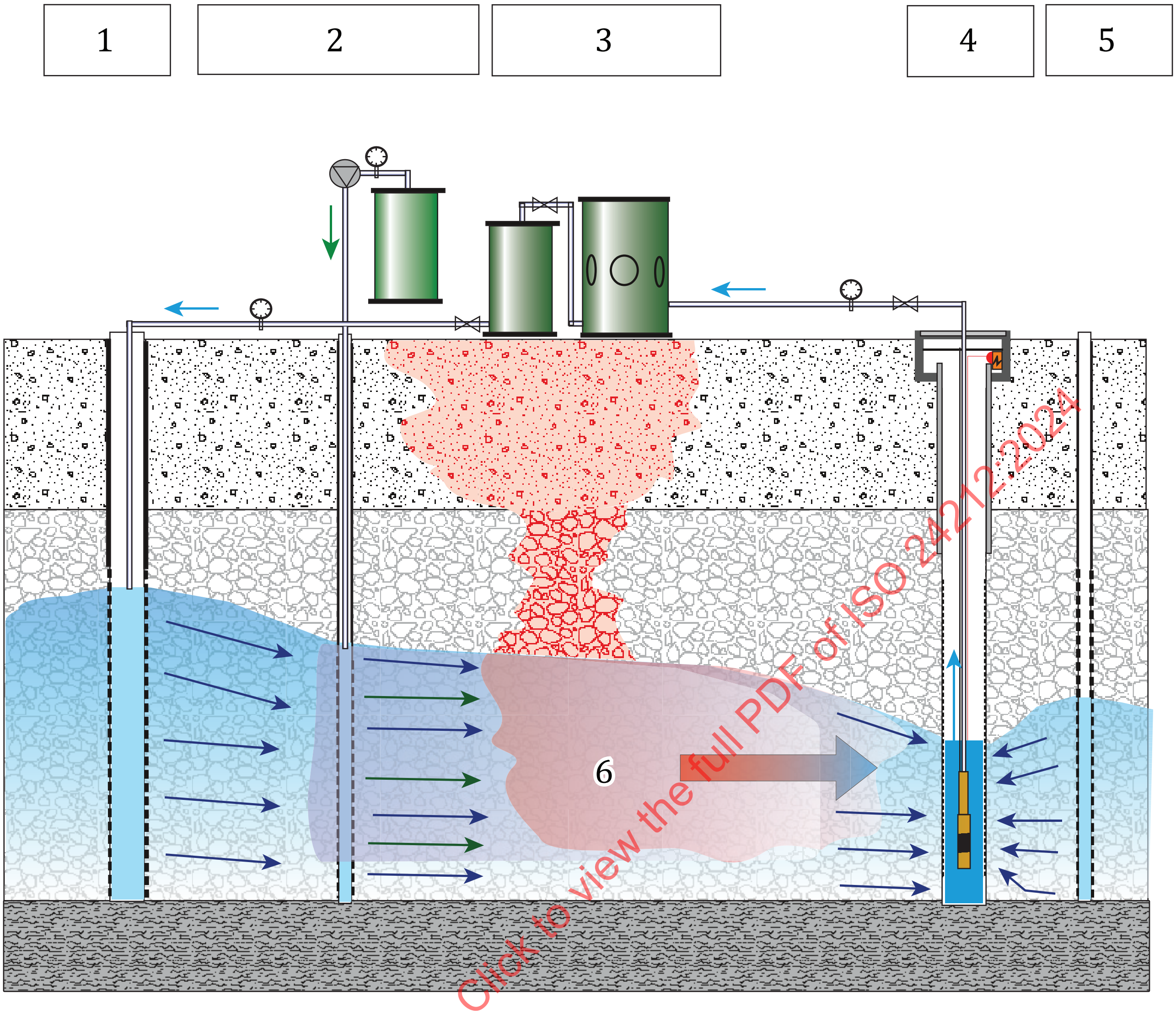
? not studied

Annex C
(informative)

Examples of illustrative diagrams of remediation techniques

Figures C.1 to C.25 below illustrate the remediation techniques described in this document.

WARNING — All the figures presented are only examples. For most of the techniques, there can be variations that are not illustrated.



Key

1 reinjection well

2 chemical oxidant mixing tank and injection well

3 water treatment (optional)

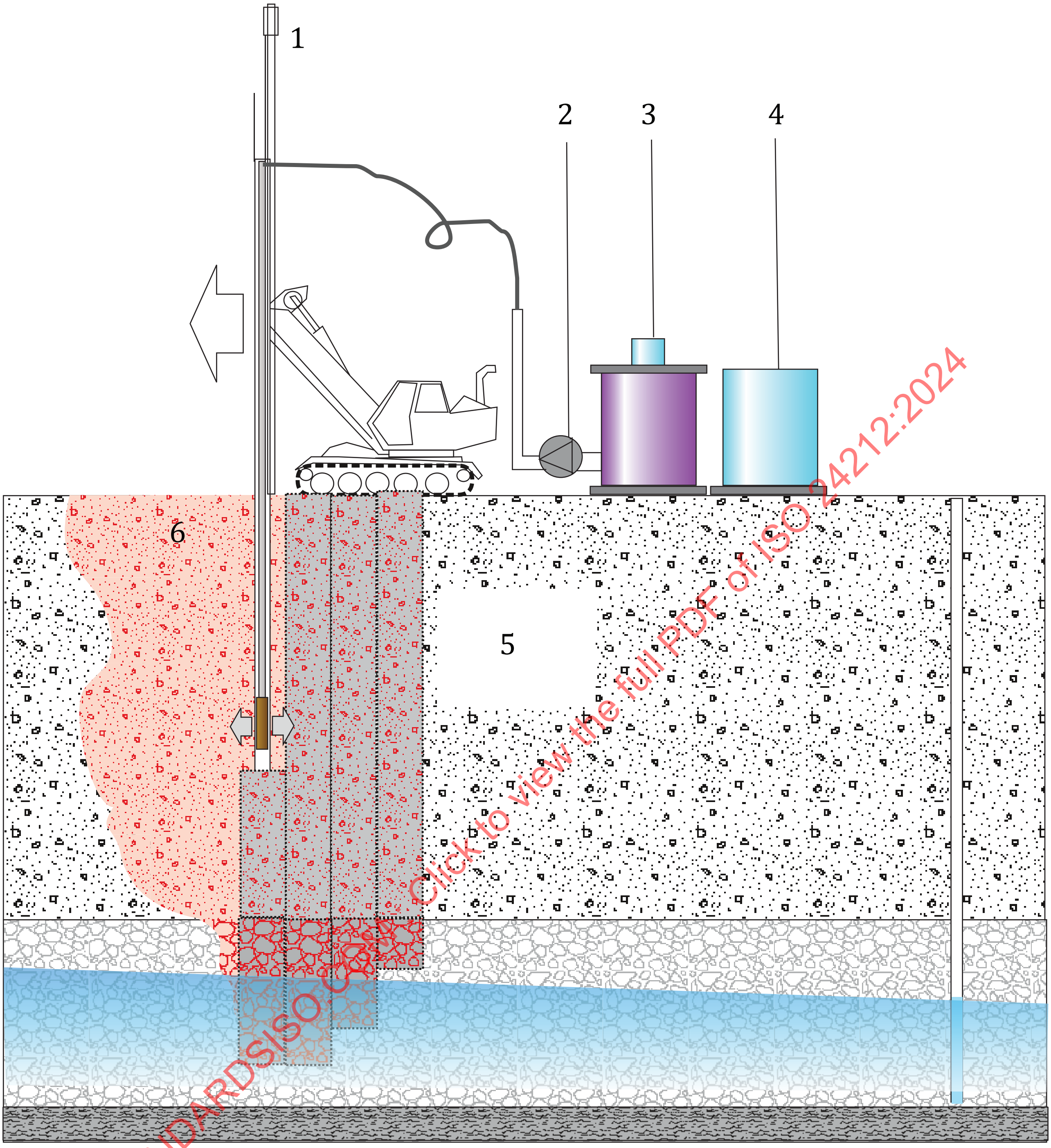
4 pumping well

5 monitoring well

6 oxidation

Source: Reference [12], reproduced with the permission of the authors.

Figure C.1 — In situ chemical oxidation (ISCO) applied to contamination present in the saturated zone, with the oxidant being injected into the soil with the use of pressure through vertical injection wells

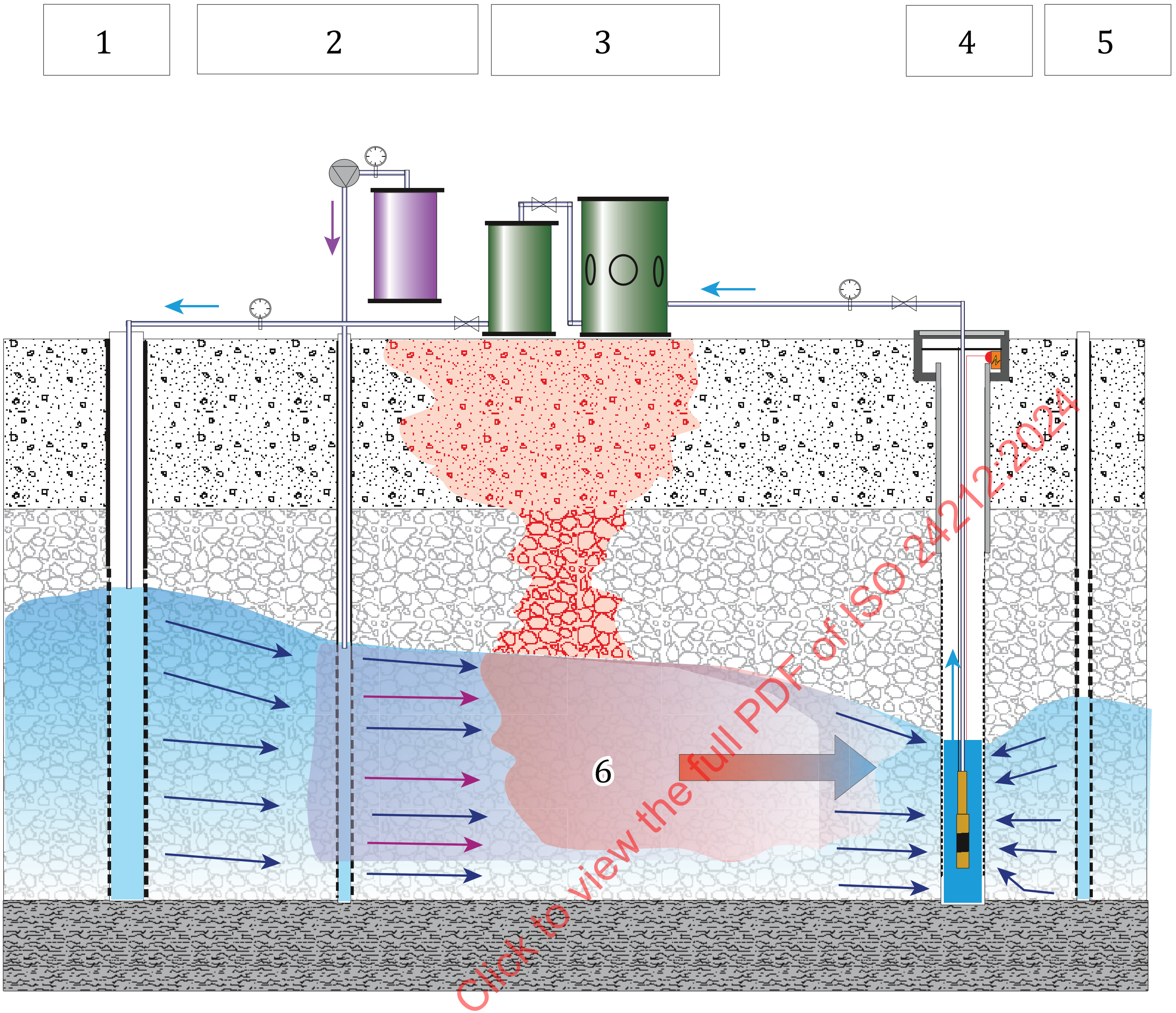


Key

1 drilling and injection of oxydising solution (soil mixing unit)
2 pump
3 mixing tank for preparing oxidising solution
4 water tank
5 soil mixed up with the oxydising solution
6 contaminated soil

Source: Reference [12], reproduced with the permission of the authors.

Figure C.2 — In situ chemical oxidation (ISCO) applied to contamination present in the unsaturated zone, with the oxidant coming into contact with the contaminant by (deep) soil mixing (with the use of auger drills)

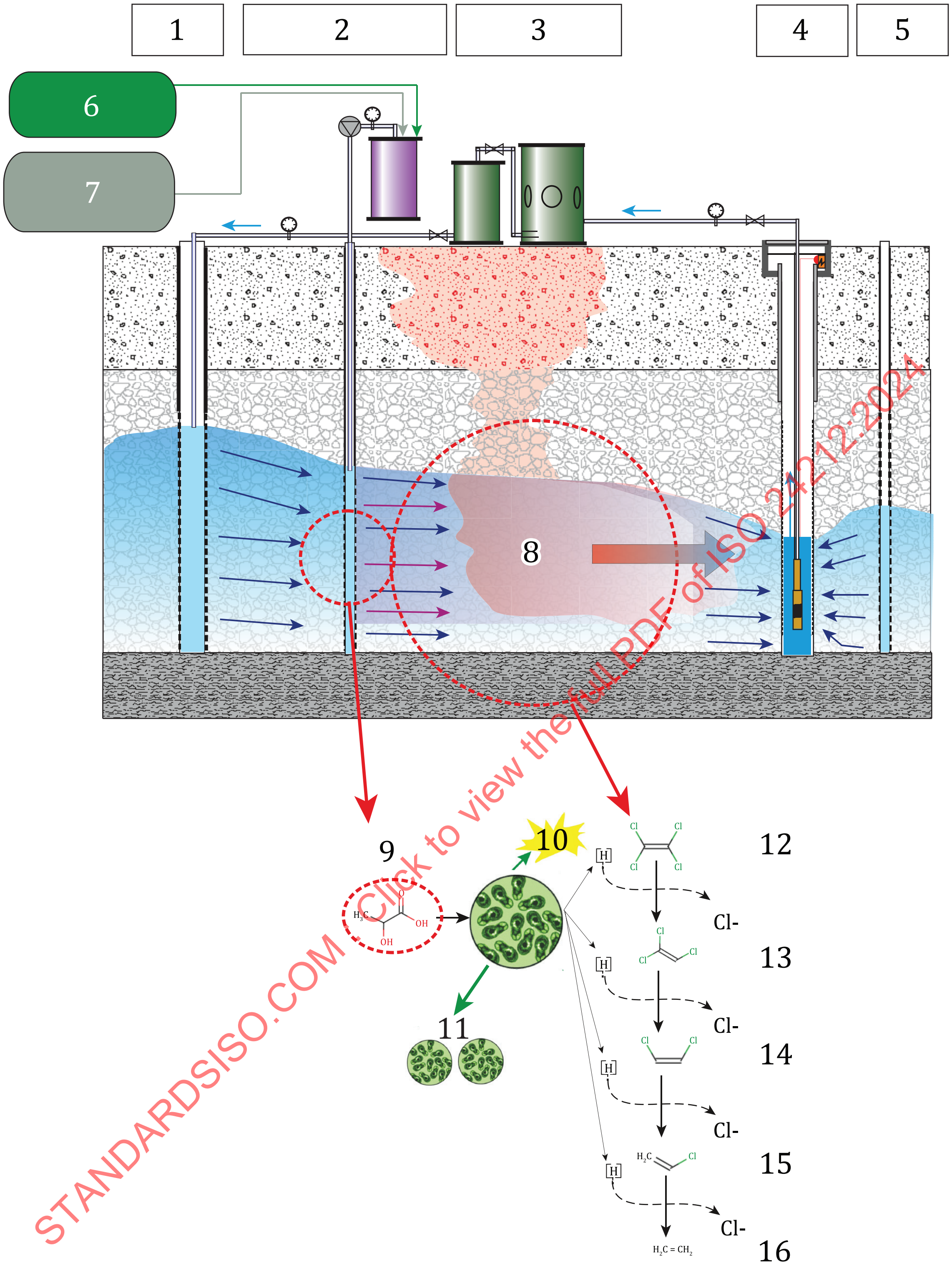


Key

1	reinjection well
2	reducing chemical agent mixing tank and injection well
3	water treatment (optional)
4	pumping well
5	monitoring well
6	reduction

Source: Reference [12], reproduced with the permission of the authors.

Figure C.3 — In situ chemical reduction (ISCR) principle



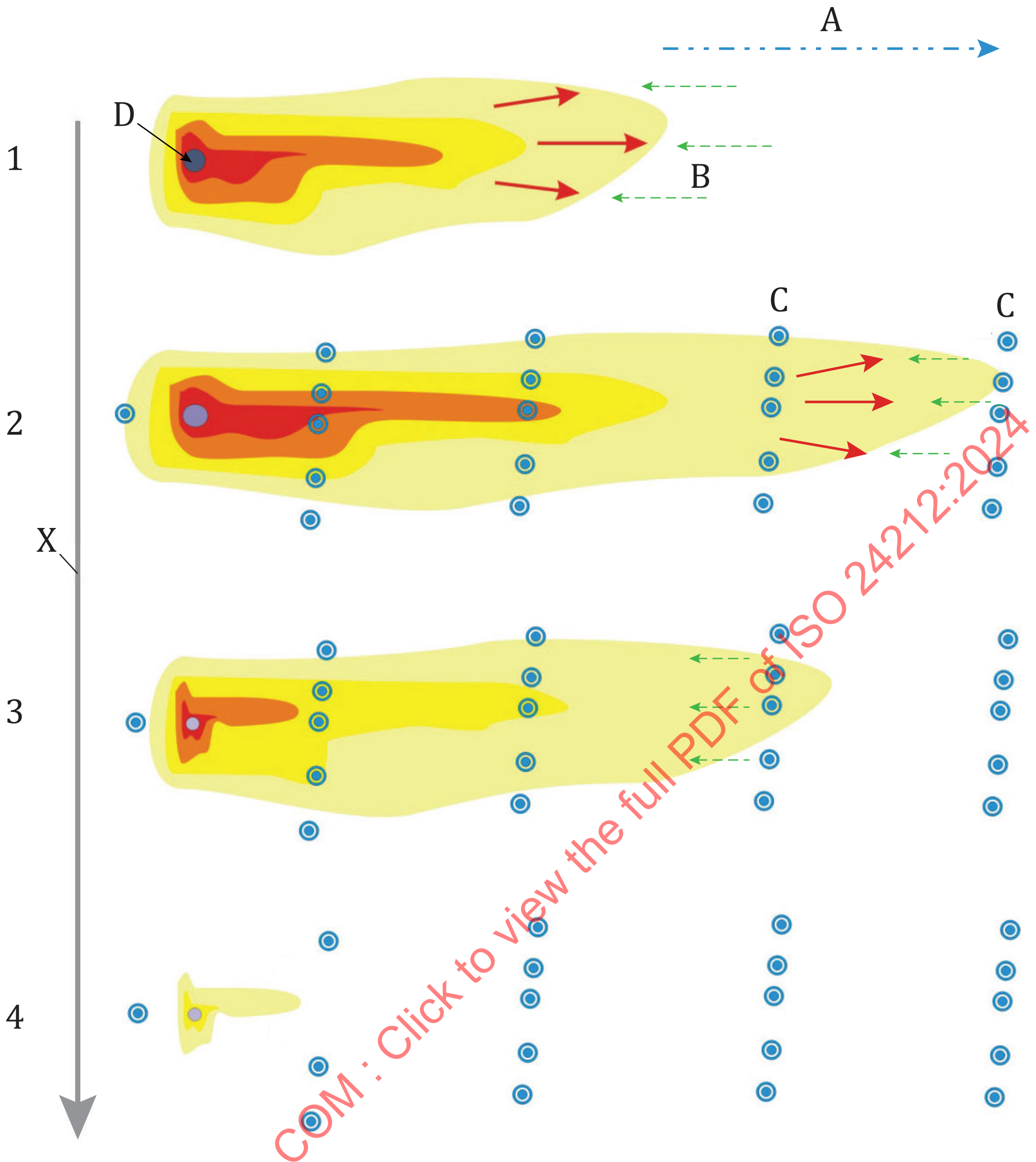
Key

1	reinjection well
2	mixing tank and injection well
3	water treatment (optional)
4	pumping well
5	monitoring well
6	injection of base nutrients N/P: biostimulation

7 injection of adapted and well selected bacteria: bioaugmentation
8 reduction dechloration
9 organic substrate: acetates, sugars (molasses), etc
10 energy heat
11 biomass
12 tetrachlorethene
13 trichlorethene
14 cis 1,2-Dichlorethene
15 vinyle chlorid
16 ethene

Source: Reference [12], reproduced with the permission of the authors.

Figure C.4 — Enhanced in situ bioremediation (EISB)

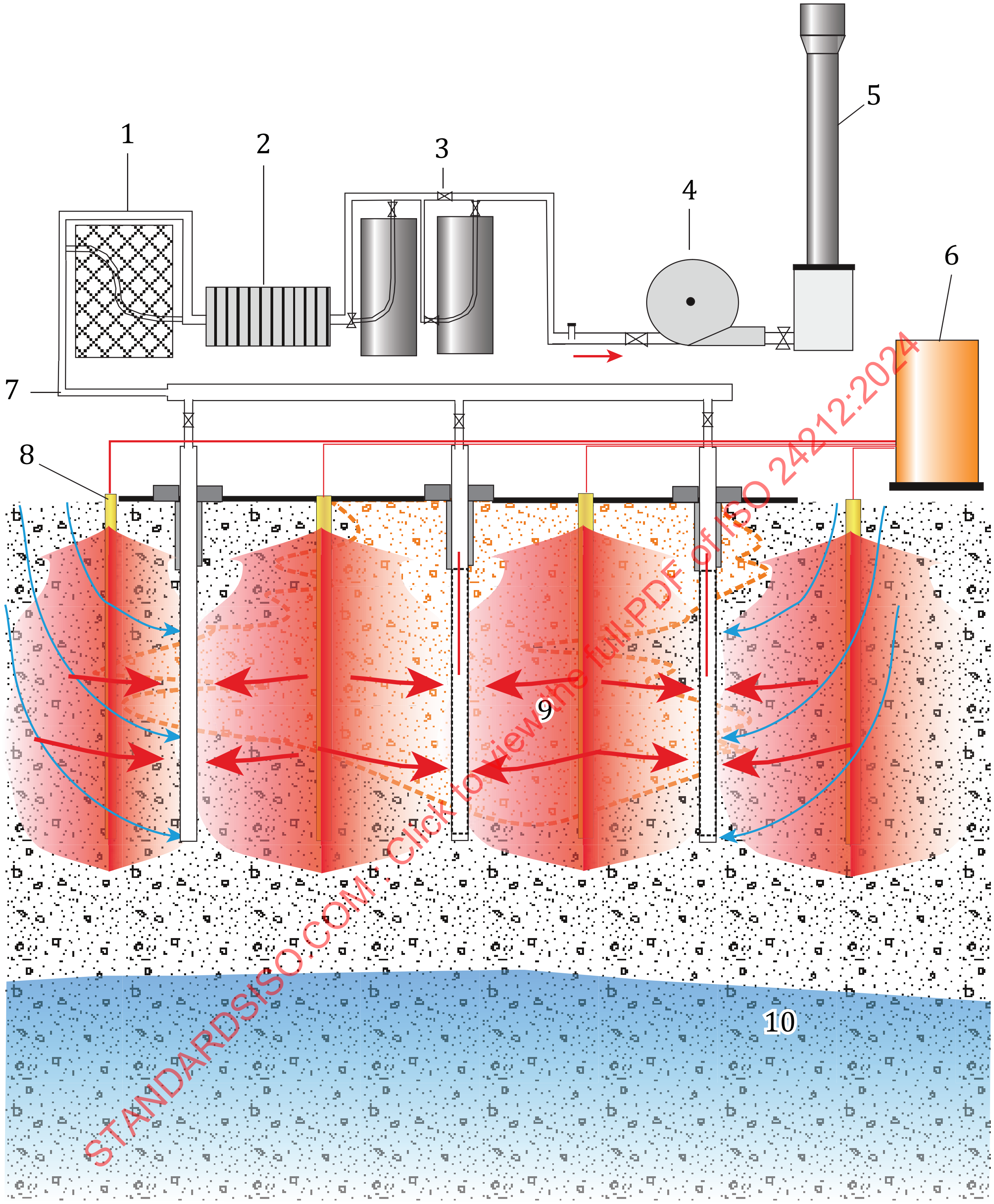


Key

A	groundwater flow direction
B	leading eadge
C	lines of monitoring wells
D	residual point source of contamination after active cleaning up operations
X	time
1	phase 1: plume development
2	phase 2: stabilization
3	phase 3: resorption
4	phase 4: disparition
→	migration by convection
⇠	degradation/dispersion/dilution

Source: Reference [12], reproduced with the permission of the authors.

Figure C.5 — Monitored natural attenuation (MNA) principle scheme over time



Key

1	oxydizer	6	voltage control system
2	heat recovery unit	7	extraction well network with collecting device
3	stage 1 Gas-treatment	8	heater electrode