ANTARCTIC CLEAN-UP MANUAL

1. *Introduction*

a) Background

In 1975 the Antarctic Treaty Parties adopted Recommendation VIII-11, which contained the first agreed guidance for the appropriate management and disposal of waste generated by expeditions and stations, with a view to minimising impacts on the Antarctic environment. As awareness of the potential environmental impacts of the disposal of waste in the Antarctic region increased, in parallel with improvements in logistics and technology, the Parties identified a need for improved on-site treatment of wastes and for the removal of some wastes from the Antarctic Treaty area.

Through Recommendation XV-3 (1989) the Parties adopted more stringent waste disposal and management practices, based on recommendations from a SCAR Panel of Experts on Waste Disposal in the Antarctic, with the aim of minimising impact on the Antarctic environment and minimising interference with scientific research or other legitimate uses of the Antarctic. These practices not only addressed requirements for the management of wastes associated with present and future activities, but also called for programmes to clean up existing waste disposal sites and abandoned work sites, and for an inventory of locations of past activities.

Many elements of Recommendation XV-3 are closely reflected in the current provisions for waste disposal and management, contained in Annex III to the Environment Protocol, on Waste Disposal and Waste Management. The Environment Protocol as a whole sets the context in which the provisions of Annex III should be implemented.

Among other requirements Annex III provides, in Article 1.5, that:

> 'Past and present waste disposal sites on land and abandoned work sites of Antarctic activities shall be cleaned up by the generator of such wastes and the user of such sites. This obligation shall not be interpreted as requiring:
>
> a) the removal of any structure designated as a historic site or monument; or
>
> b) the removal of any structure or waste material in circumstances where the removal by any practical option would result in greater adverse environmental impact than leaving the structure or waste material in its existing location.'

Prior to these instruments, waste management at Antarctic facilities often involved the open burning and disposal of waste in tips. Similarly, it was commonplace to abandon disused facilities and leave them to deteriorate. Many past waste disposal sites and abandoned work sites require ongoing management today. Such sites are frequently characterised by a mix of physical debris (*eg*, building materials, machinery, vehicles, general rubbish) plus chemical contaminants, some of which may be in containers (which are subject to deterioration) and some of which may have been released into the environment. In some instances waste disposal sites extend into the near shore marine environment. Seepage and runoff from abandoned sites, and from more recent spill sites, can result in contamination spreading to other parts of the environment. In general such contaminants degrade very slowly in Antarctic conditions.

Based on extrapolation from a few well documented sites, it has been estimated that the volume of abandoned, unconfined tip materials in Antarctica may be greater than 1 million m^3 and that the volume of petroleum-contaminated sediment may be similar (Snape and others, 2001). Although this is a relatively small volume compared to the situation in other parts of the world, the significance of the associated environmental impacts is magnified due to the fact that many Antarctic contaminated sites are located in the relatively rare coastal ice-free areas that provide habitat for most of the terrestrial flora and fauna.

b) Overall Clean-Up objective

The overall objective for Parties' actions to address environmental risks posed by past waste disposal sites on land, abandoned works sites of Antarctic activities, and sites contaminated by spills of fuel or other hazardous substances is:

> To minimise adverse impact on the Antarctic environment, and to minimise interference with the natural values of Antarctica, with scientific research and with other uses of Antarctica which are consistent with the Antarctic Treaty, by cleaning up past waste disposal sites on land, abandoned work sites of Antarctic activities, and sites contaminated by spills of fuel or other hazardous substances. Such clean-up actions shall not require the removal of any: structure designated as a historic site or monument: pre-1958 historic artefacts / sites subject to the interim protection provided by the provisions of Resolution 5 (2001); or structure or waste material in circumstances where the removal by any practical option would result in greater adverse environmental impact than leaving the structure or waste material in its existing location.[1]

This objective reflects requirements outlined in Annex III (Waste Disposal and Waste Management) to the Protocol on Environmental Protection to the Antarctic Treaty (the Environment Protocol) and later Resolutions relevant to sites and objects/artefacts of potential historic or heritage value.

c) Purpose of the Clean-Up Manual

The purpose of this manual is to provide guidance to Antarctic Treaty Parties in order to meet the objective above. The manual includes key guiding principles and links to practical guidelines and resources that operators can apply and use, as appropriate, to assist with addressing the requirements of the Environment Protocol, in particular Annex III. The practical guidelines are recommendatory and not all guidelines will be appropriate to all operations, or to all sites. The manual is intended to be updated and added to as new work, research and best practice emerge.

The guidance provided here is focussed on the repair and remediation of past waste disposal sites on land, abandoned work sites of Antarctic activities, and sites contaminated by spills of fuel or other hazardous substances. Practical guidance for preventing, monitoring and responding to the introduction of non-native species is presented in the Committee for Environmental Protection (CEP) Non-Native Species Manual.

The Council of Managers of National Antarctic Programs (COMNAP) has developed a Fuel Manual, which outlines important measures for spill prevention and containment. This Clean-Up Manual complements the COMNAP Fuel Manual by providing guidance on appropriate clean-up and restoration actions, which the COMNAP Fuel Manual indicates should be addressed as part of the Operational Plans to be prepared for individual facilities or relevant geographic areas.

In practice, it will not be practicable to clean up all past waste disposal sites on land, abandoned work sites of Antarctic activities and contaminated sites immediately or concurrently, so the manual also aims to provide guidance on identifying priorities for clean-up activities, and on remediating or removing contaminated materials to a level where ongoing environmental risks are mitigated.

Reasons to undertake timely clean-up action, in accordance with the provisions of the Environment Protocol, include:

- many abandoned waste disposal sites and abandoned work sites contain potential contaminants in containers (*eg*, drums filled with fuel, oil, chemicals), and there is a limited time before they deteriorate, causing contamination and making clean-up much more difficult;

[1] Resolution 2 (2018) *Guidelines for the assessment and management of Heritage in Antarctica* includes guidance and support in the process of assessing and determining whether a site/object should be managed as heritage, including whether it merits Historic Site and Monument (HSM) listing, in the context of obligations under both Annex V and Annex III to the Protocol on Environmental Protection to the Antarctic Treaty (Environment Protocol).

- as noted by the 2010 Antarctic Treaty Meeting of Experts on Climate Change and Implications for Antarctic Management and Governance, climate changes could accelerate localised release of contamination from past waste disposal sites and abandoned work sites through increased melting;
- the harmful effects of chemical contaminants on the environment and ecosystem can increase with increasing exposure time, and increase the chance of cumulative impacts from exposure to other environmental stressors;
- dispersion processes (*eg*, entrainment with melt water) can cause the total area contaminated to increase with time, in some cases resulting in contamination of the marine environment;
- some sites may otherwise be lost to the ocean or covered by ice/snow where they may continue to have detrimental impacts but will be much more difficult and costly to manage; and
- possible risks to human health (*eg*, hazardous chemicals or other substances, such as asbestos).

2. Key Guiding Principles

Information management

Record keeping is important throughout the clean-up process and should commence well before any clean-up activities occur on site.

1) Record keeping should be designed so that information on individual sites is easily accessible and so that information on actions and events at each site can be added over time.
2) The record of information should be kept up to date and should include the precise location and status of contaminated sites, planned and actual timelines for clean-up actions, the clean-up actions that have occurred, the reasons why key decisions were made and the lessons learned.
3) The type of information to be recorded should reflect its intended use, including:
    - site assessment and prioritisation;
    - supporting operational decisions;
    - ensuring compliance to environmental impact assessment / permit conditions;
    - monitoring and evaluating the effectiveness of a clean-up process; and
    - facilitating the exchange of information between Parties and with other stakeholders.
4) Record keeping should be designed so that it can also be used as the foundation for the Antarctic-wide inventory of locations of past activity, in accordance with Article 8.3 of Annex III.

Site assessment / characterisation

An assessment of the features of the site that will influence how contaminants behave, and the environmental values that may be impacted, should be undertaken before considering how best to clean up a site.

5) The site assessment should consider:
    - the nature and extent of physical debris and/or chemical contamination, and the landscape (*eg*, geology, geomorphology, hydrology, glaciology) of the site and surrounding area, with particular emphasis on slope, aspect and water flows;
    - potential challenges for clean-up actions presented by the location, landscape, and surrounding area (*eg*, accessibility and susceptibility to damage from machinery or recovery equipment);
    - the environmental values of the site and surrounding area, including the range of values protected under the Environment Protocol; and
    - likely changes at the site including deterioration of containers (such as rusting fuel drums), changes in chemical compositions (*eg*, through natural weathering processes) and transport of the contaminants (*eg*, from wind or water flow).

6) All available information should be used to assess the current impact and potential future threat to the environment from the contamination.

Environmental risk assessment

Environmental risk assessment is the process of determining the inherent risks posed by the site to the environmental values.

7) The environmental risk assessment should use the information gained during site assessment, including uncertainties, and should inform the decisions taken throughout the clean-up process.
8) The environmental risk assessment should assist to prioritise which site(s) should be cleaned up first, to decide among the various clean-up options (see below) and to set realistic targets for clean-up (see below).
9) The environmental risk assessment should be regularly reviewed and confirmed or modified during the clean-up process.

Environmental quality targets for clean-up

In some cases, the complete removal of all traces of contamination would be impractical, or would result in greater adverse environmental impact. Environmental quality targets for clean-up are the concentration of contaminant that may remain within the environment without creating unacceptable impacts on the environmental values of the site.

10) Environmental quality targets for clean-up should be determined on a site specific basis taking into account the characteristics of the site and the environmental values present.
11) From the viewpoint of biodiversity conservation, environmental quality targets should be based on the sensitivity of relevant species to the specific contaminants (such as from ecotoxicology studies).
12) Environmental quality targets are just one factor when considering the options for clean-up (see below).

Consideration of clean-up options

At the highest level the range of possible clean-up options for sites contaminated by fuel and other hazardous substances may include: do nothing (which may result in natural attenuation); containment on site to reduce dispersion; *in situ* remediation to enhance attenuation processes; removal from the site with treatment in Antarctica (clean-up *ex situ*); and removal from the Antarctic Treaty area. Within each of these options there are further choices of possible clean-up actions (see below).

13) A risk assessment should be undertaken for all clean-up options being considered, with a focus on ensuring that greater adverse environmental impact does not occur as a result of the clean-up process.
14) Options analysis should consider the environmental quality targets and risk of additional adverse impacts arising from the clean-up activity. Given the practical realities of operating in Antarctica, other relevant considerations are likely to include feasibility, available technology, practicality, safety of personnel, cost-effectiveness, and opportunities for international cooperation.

Clean-up actions

Clean-up actions are the operational activities that happen at the site and / or elsewhere on material that has been removed from the site.

15) Wherever appropriate, plans and environmental impact assessments for new activities in Antarctica should consider the nature and scale of any clean-up activity which will be

subsequently required. Actions to clean up sites of past activities should also be subject to environmental impact assessment in accordance with the provisions of the Protocol[2].

16) Clean-up techniques developed for contaminated sites in other regions of the world may have some value in Antarctica but are likely to require modification to make them suitable for local conditions.

17) All clean-up options, including the 'do nothing' option, may require some commitment of resources, such as monitoring (see below) to confirm the environmental risk assessment.

18) In some cases containment on site to reduce dispersion will be identified as the best means of protecting environmental values. Techniques for containment should be designed for:
    - the types of contaminants present (the principal distinction being organic (*eg*, fuel) or inorganic (*eg*, metals from waste dumps); and
    - the characteristics of the environment (*eg*, freeze/thaw process, seasonal presence of free water, physical characteristics of the site such as slope and substrate).

19) *In situ* remediation to enhance attenuation processes (*eg*, enhanced biodegradation by the adding of nutrients, increasing temperature and aerating soil) can be cost-effective and is likely to be less disturbing to the environment than options requiring extraction, but techniques must be appropriate for the types of contaminants and the characteristics of the environment (as above).

20) Removal from the site with treatment in Antarctica may create more disturbance at the site than *in situ* remediation but has the potential advantage of relocation to a site that is more easily managed such as close to a station. The receiving site should be controlled to ensure the safety of personnel and to prevent further environmental impact (*eg*, clearly identifiable and known to station personnel, contained to prevent dispersal of contaminants).

21) In some cases the removal of contaminated materials from the Antarctic Treaty area may be the most appropriate option for addressing the requirements of the Environment Protocol. As above, this may create more disturbance than *in situ* remediation and, in the case of ice-free sites, also has the disadvantage of removing rare soil from Antarctica. This option is also likely to be the most costly, is dependent on the availability and capacity of shipping, and may raise biosecurity or contaminated material concerns for the receiving country.

22) Monitoring and evaluation (see below) should be designed as an integral part of the clean-up process.

23) Clean-up should be considered complete only once the environmental quality targets have been met.

Monitoring and evaluation

Monitoring and evaluation are both used to characterise and record the quality of the environment but have specific and distinct roles before, during and/or after clean-up.

24) Monitoring should be undertaken to identify and provide early warning of any adverse effects of the clean-up activity that may require modifications of procedures, and to assess and verify predictions identified in the environmental impact assessment.

25) Evaluation refers to determining whether the clean-up activity has achieved the desired environmental quality targets.

26) Both monitoring and evaluation should focus on the vulnerable environmental values of the site and take into account the final use of the data.

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[2] The *Guidelines for Environmental Impact Assessment in Antarctica (*Resolution 1 (2016)) provide advice on the process for and elements that require consideration in an environmental impact assessment.

3. *Guidelines and resources to support clean-up*

As the manual is developed, this section will be expanded to contain voluntary guidelines and resources to assist Parties to address their clean-up obligations under Annex III to the Protocol. Examples of desirable materials include:

- a standard approach and/or form for record keeping and reporting on clean-up activities;
- checklists and/or matrices for environmental risk assessment;
- guidance for detailed site assessment
- scientific information to inform the setting of appropriate environmental quality targets;
- techniques for preventing mobilisation of contaminants such as melt water diversion and containment barriers;
- techniques for *in situ* and *ex situ* remediation of sites contaminated by fuel spills or other hazardous substances;
- techniques for the clean-up of buildings or other structures at abandoned work sites;
- techniques for separation and recovery of fuel spilled on ice or snow;
- guidance for planning and undertaking monitoring and evaluation; and
- guidance for the identification and detection of sites requiring clean-up (including for example abandoned worksites, waste disposal sites, spill sites covered by ice/snow)

Resources

Checklist for Preliminary Site Assessment: See Annex 1

Guidance for Construction and Management of Biopiles for the Bioremediation of Petroleum Hydrocarbon Contaminated Soil in the Antarctic: See Annex 2

Guidance for Construction and Management of Permeable Reactive Barriers for the Treatment of Hydrocarbon Contaminated Groundwater in the Antarctic: See Annex 3

References

General

- The Antarctic Environments Portal includes information summaries relevant to clean-up (https://www.environments.aq/)
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CEP papers

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Consideration of clean-up options

CEP papers

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- ATCM XXXVIII IP16 *Bioremediation on the Brazilian Antarctic Station area* (Brazil)
- ATCM XXXVIII BP12 *Remediation of fuel-contaminated soil using biopile technology at Casey Station* (Australia)
- ATCM XXXVIII BP13 *Remediation and reuse of soil from a fuel spill near Lake Dingle, Vestfold Hills* (Australia)
- ATCM XXXIX IP76 *Environmental Remediation in Antarctica* (Brazil)

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- ATCM XXXVIII BP12 *Remediation of fuel-contaminated soil using biopile technology at Casey Station* (Australia)
- ATCM XXXVIII BP13 *Remediation and reuse of soil from a fuel spill near Lake Dingle, Vestfold Hills* (Australia)
- ATCM XL IP74 *Clean-up and removal of Italy installations at Sitry airfield camp along the avio-route MZS-DDU, Antarctica* (Italy)
- ATCM XL IP48 *Clean-up of Scientific Equipment and Infrastructure from Mt. Erebus, Ross Island, Antarctica* (United States)

- ATCM XL IP49 *Report on Clean-up at Metchnikoff Point, Brabant Island* (United Kingdom)
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Annex 1: Checklist for Preliminary Site Assessment

Assessment and Reporting Information			
Title of Report/Assessment			
Date of Report		Prepared by:	Contact details:
Date of Site Visit (if applicable)		Assessor(s):	Contact details:

General characteristics of Site				
Place Name				
Location (coordinates of point)			Status (Antarctic Specially Protected Area (ASPA) / Antarctic Specially Managed Area (ASMA) etc):	
Location (coordinates of bounding polygon)	North:	South:	East:	West:
Nearest Operational Antarctic Station		Distance from Station:	Accessibility:	
General Description of Site				
Landscape Type (seasonally ice-free land, lake, permanent snow/ice, marine)				
Geomorphology (slope, aspect, hydrology, landscape features etc)				
Geology (rock type, rock fracturing etc)				
Regolith (depth and type of soil/sediment if present, depth to permafrost etc)				
Fauna / flora present				

HISTORY OF SITE USE AND CONTAMINATION EVENTS	
History of Site Use and Activities	
Information Sources (Station/Voyage Leader Reports, people interviewed, photographs etc)	
Contamination History (operational activities and events, such as spills and spill responses if applicable)	
Information Sources (Station/Voyage Leader reports, incident reports, people interviewed, photographs etc)	

CONTAMINANT CHARACTERISATION					
Contaminant Type	**Contained Material (*eg*, in drums, containers, fuel storages) estimated quantity (range: min/max)**	**Uncontained/mixed with soil/water etc estimated quantity (range: min/max)**	**Evidence (field observations - sight, smell etc)**	**Coverage (patchy/localised, whole site etc)**	**Samples Taken (Yes/No, number, type)**
1. General waste (including abandoned waste dumps)					
2. Metals (*eg*, batteries, equipment with heavy metals)					
3. Hydrocarbons (including fuel and oil)					

4. Other organic chemicals (*eg*, polychlorinated biphenyls (PCBs), flame retardants etc)					
5. Radionuclides					
6. Sewage, Nutrients					
7. Biological wastes					
8. Asbestos					
9. Other Contaminants					

CONTAMINANT MOBILISATION PROCESSES AND PATHWAYS

Mobilising Processes	**Site Specific Information on Processes**	**Timing (daily /seasonal /multi-year /occasional etc)**
Surface melt streams		
Sub-surface / groundwater		
Tidal inundation		
Wind		
Deterioration of containers		
Sensitivity to climate change processes		
Other processes (such as vehicle movements)		

VALUES/RECEPTORS POTENTIALLY OR ACTUALLY IMPACTED

Values/Receptor	**Site-Specific Information on Values/Receptors and Exposure Pathways (include estimates of distance from contaminants)**	**Actual or Potential Impacts?**
Fauna and flora		
Scientific		
Historic		
Aesthetic		
Wilderness		

Geological and geomorphological		
Other environments (atmospheric, terrestrial [including aquatic, glacial, marine])		
Human health		
Other values/receptors (such as station water supply)		

OTHER FACTORS TO CONSIDER

Issue	Comments
Potential for cumulative impacts from other activities or sites	
Interaction with activities of other Parties	
Critical timing (including logistics and operational factors, access, freeze/thaw, breeding cycles, other sensitive times etc)	
Factors that may influence ability to clean-up without creating greater adverse environmental impacts	
Location of contaminants in relation to ground surface (*eg*, surface only, completely / partially buried)	
Health and Safety (including human exposure pathways, personal protective equipment (PEP), access restrictions etc)	
Incident response plans (including those actually implemented at site and existence of relevant Contingency Plans)	
Interim control measures already in place	

Unusual specialist skills, experience or accreditation required for personnel involved in further investigation, sampling and management of site	

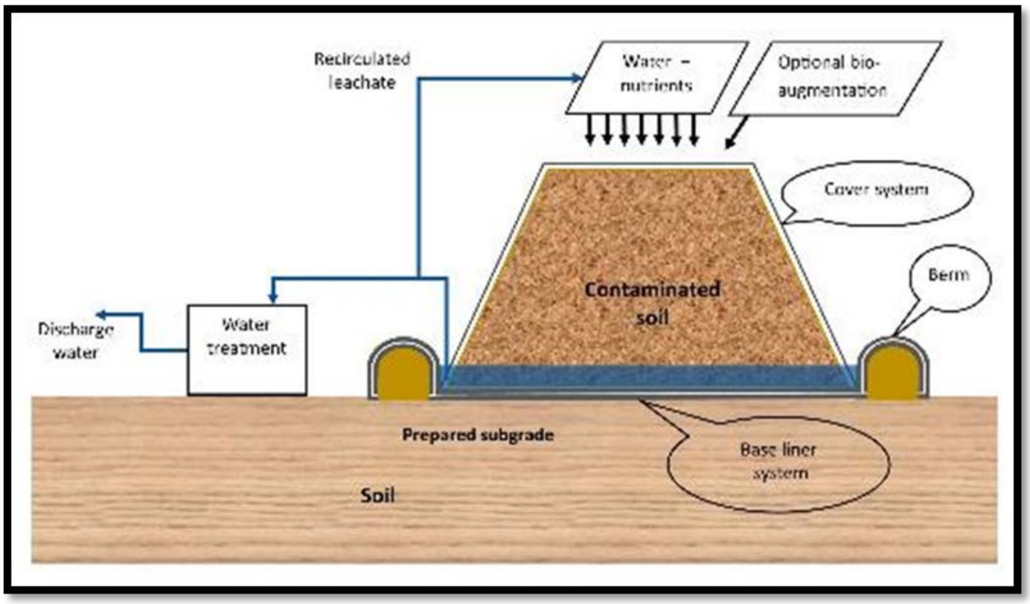
MANAGEMENT RECOMMENDATIONS (MAY BE REVISED IF NEW INFORMATION BECOMES AVAILABLE OR CONDITIONS CHANGE)	
Proposed Action	**Comments**
No Action Proposed ◻	
Further Investigation ◻	
Contain ◻	
Clean-up ◻	
Other ◻	

Annex 2: Guidance for Construction and Management of Biopiles for the Bioremediation of Petroleum Hydrocarbon Contaminated Soil in the Antarctic

Definitions

A *biopile* is a purposefully designed mound of soil used to accelerate the degradation of *petroleum* contaminants. It utilises *bioremediation*, the process of using microbes to degrade contaminants. Biopiles are used in situations where a decision has been made to excavate and treat the contaminated soil above ground. When a composite *liner system* is used, biopiles also have the advantage of isolating the contaminated soil from the environment, thus preventing further environmental impact. Biopiles typically rely on *biostimulation* (the addition of nutrients, and/or oxygen, heat, moisture, organic carbon) to degrade contaminants more rapidly than they otherwise would in the environment. Biopiles may also use *bioaugmentation* (the addition of microbes), although in Antarctica, microbes must be cultivated from the existing native soil microbial population and not imported or introduced[3].

Figure 1: Schematic of a biopile



When to use biopile technology

Biopiles are just one of several techniques that can be used to remediate petroleum contaminated soil in Antarctica (1). The decision to use a biopile occurs once a site assessment has been conducted and an environmental risk assessment process has identified the following:

- The presence of contaminant in soil (*eg*, diesel fuel) in the environment at concentrations which pose an unacceptable environmental risk in that location, and/or through migration;

[3] The Protocol on Environmental Protection to the Antarctic Treaty, Annex II (Conservation of Antarctic Fauna and Flora) prohibits the introduction of living organisms that are not native to Antarctica, except for specified purposes.

- The contaminant in soil is likely to degrade slowly *in situ*, and an in-ground treatment technique (*eg*, soil vapour extraction, chemical oxidation, electro-kinetic oxidation, or in-ground aeration/nutrient addition) is unsuitable.
    - Examples of factors that affect the suitability of these techniques may include: ground conditions, the distribution of contaminant, limitations or uncertainty of ensuring the remediation treatment reaches the contamination, and/or the environmental risk of applying amendments in an uncontained manner.
- The contaminated soil can be practically excavated.
    - Practicality is site specific but could include: site accessibility (slope, proximity to water bodies, infrastructure and buildings), depth below ground of contaminant, excavation depth, ground conditions (permafrost, groundwater, soil particle size and distribution, bedrock morphology, previous disturbance, etc.) and that excavation activities can be managed such that any re-mobilisation of contaminant is controlled and contained.
- The contaminant is amenable to bioremediation. Commonly used petroleum contaminants found in the Antarctic that are most amenable to bioremediation are diesel, *aviation gasoline* and petrol as opposed to heavier petroleum products such as lubricants;
- Other above ground remediation techniques, such as landfarming, are not suitable (either due to site disturbance, lack of space, wildlife interactions, or the risk of offsite impacts);
- There is a suitable location for the construction of the biopile and its construction will not cause undue environmental impact(s).

Purpose of this document

Whilst there are many existing resources on biopile performance and construction (*eg*, 2), polar environments present unique challenges for biopiles. This document provides guidance for Antarctic biopile construction and maintenance, for the remediation of petroleum contaminated soils.

This non-mandatory guidance is based on Antarctic-specific research and practical experience with biopile construction and operation.

The guidance identifies general considerations and principles, which will support decision making, planning and management, and the conduct of remediation activities using biopile technology. It provides advice on the range of more detailed scientific, technical, design and management issues and adaptations that should be considered when applying this technique. Site specific assessments, environmental impact assessment of proposed remediation activities, and additional research and technical design support will be necessary elements of biopile remediation. Relevant references are provided to support these activities.

This document does not address emergency fuel spill response, contaminated site assessment, sampling design, effects of hydrocarbons on terrestrial, lacustrine or marine organisms, site specific risk assessment, human health risk assessment, or alternative *in situ* and *ex situ* remediation options.

Background

A growing body of research shows remediation of contaminated soil in biopiles under Antarctic conditions can be an effective tool for remediation (3-5). Whilst there are a variety of *in situ* containment techniques *(eg*, funnel-and-gate permeable reactive barriers), no other *in situ* soil remediation techniques have been successfully used in the Antarctic environment to date. Biopile treatment remains the only publicised *ex situ* remediation technology successfully applied to large volumes of soil in Antarctica (3), other than soil incineration (6).

The length of time required for biopile treatment is dependent upon the climate at the proposed location, and whether additional heat will be applied. In general, it is expected that an unheated Antarctic biopile would require a 3-5 year commitment and resourcing, the specifics of which are discussed in more detail below. The project length will also be determined by the proposed re-use requirements of the soil (*ie*, the extent to which contaminants have degraded and pass quality thresholds) and whether site-specific thresholds or national environmental guidelines are being applied. Reuse options range from highly specific and controlled use for engineering or building purposes to unrestricted re-use and return to the environment, either to the original excavation location or another assessed location.

Process

Steps leading up to construction of an Antarctic biopile

1) Identification of a contaminated site (triggered either by a new fuel release or through a site assessment which has uncovered past contamination):
    a. A site assessment is needed to quantify extent, volume, concentration and type of contaminated material;
2) A risk assessment that concludes that contamination is present at concentrations that pose an unacceptable environmental risk in that location, and/or through migration to other locations, and that soil remediation is required (as opposed to implementing an alternative risk management measure such as containment);
3) An assessment of remediation options and identification of biopiling as the most appropriate treatment technology;
4) Commitment of resources to site excavation, biopile site preparation, design and construction of containment area, and biopiling;
5) Conduct of the Environmental Impact Assessment process and application for relevant approvals and permits from the administering Competent Authority;
6) Detailed biopile project design and planning;
7) Implementation:
    a. Construction
    b. Operation
    c. Monitoring
    d. Re-use
    e. Decommissioning

Considerations

Contaminant source and soil characterisation

- Characterise the extent of contamination (*eg*, contaminant type(s), areal and volumetric extent);
- Assess whether the contaminant mass can be practically excavated (*eg*, consider equipment access, proximity to infrastructure, depth to groundwater);
- Assess whether the fuel type is amenable to bioremediation (*eg*, diesel, *aviation gasoline*, petrol), or whether it contains heavier petroleum products such as lubricants;
- Analyse enough soil samples so that there is adequate statistical confidence around the concentrations of hydrocarbons to be excavated;
- Analyse for co-contaminants (*eg*, metals) as well as expected fuel contaminants (*eg*, Total Recoverable Hydrocarbons, *BTEXN*, *MAH* and *PAH*'s);
- Measure soil moisture content, soil texture and type (pH, organic carbon content and nutrient content);
- Identify the volatile and soluble components of the contaminant;
- When calculating the average starting concentration of hydrocarbons in the biopile, account for volatilisation and homogenisation that will occur during excavation and placement within the biopile (*eg*, in the order of 50% mass loss depending upon the contaminant type, excavation and homogenisation method, age of the spill, and temperature).

Key references:
How to Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites – Chapter IV (Biopiles) – US EPA (2017)

Desirable requirements for selection of a biopile site

- A sufficient area of already disturbed, reasonably flat land not required for other activities for the duration of the project;
- Suitable access for environmental monitoring down-gradient or down-wind of the site if required;
- Vehicle access to the site for the summer period;
- Sufficient distance from wildlife colonies or wallows, pathways or congregation areas (noise disturbance from heavy equipment);
- Sufficient distance from watercourses, melt water streams, lakes and/or ocean;
- Good solar exposure for passive heating of soil (no steep hills or tall buildings to the north of the site);
- Good drainage underneath (or around) the site to minimise seasonal melt water flowing under the biopile and affecting the liner systems or compromising the subgrade integrity (*eg*, a biopile built on an excavated and backfilled site can experience settlement over subsequent seasons);
- Adequate space on the leeward side of the biopile site to remove accumulated snow-drift;
- Minimisation of vehicle traffic through the area, particularly when the area is snow covered, so that barrier systems are not damaged;
- Characterisation (baseline sampling) of the area to ensure that it is not already contaminated, and to demonstrate the environmental performance of the biopile once decommissioned;

	• Assess whether the area should be secured for safety, liner protection, inadvertent damage and for the regulation of contaminated soil entering and leaving the biopile remediation site; Ensure personnel present are appropriately trained to maintain and monitor the biopiles; • Proximity to power supply for operational and monitoring equipment.
Considerations for Design and Construction	
Operational lifetime	• Hydrocarbon degradation is a temperature limited reaction, therefore, consider using previously collected soil temperature data or meteorological data to model soil temperature to predict project lifespan; • Plan for a longer project time-frame than theoretically calculated, due to project delays (Antarctic operational constraints, weather); • Allocate resources to the construction, monitoring, maintenance, and decommissioning of the biopile for the full project time-frame; • At a minimum, plan for regular visual monitoring of the biopile, berms, liner system, covers and levels of snow/water/ice to loss of containment of contaminated soil or water, or the breakdown of liner/cover material. If the integrity of containment is regularly established, biopiles could be left dormant until additional resources can be deployed for more active biopile operation and management.
Location, orientation and size	• Seek to orient the biopiles so that the long axis is parallel to the prevailing wind to minimise the accumulation of snow-drift; • Design the biopile width so that the available heavy machinery (*eg*, excavator) has sufficient reach such that it does not need to drive on the liner system to place and turn the soil, or alternatively design the biopile to allow heavy vehicle access such that the liner system is not damaged; • Consider options to transport liners to the intended site (weight and size of material rolls).
Subgrade and berms	• The properties of the subgrade and berms influence the performance of the liner system. A geosynthetic clay liner (GCL) requires adequate hydration from the subgrade to create a hydraulic barrier and minimise contaminant transport: - Assess the particle size/texture of subgrade. If it is too coarse, then it may be necessary to source finer-grade soil for an artificial subgrade or to use a soil retention layer below the GCL; - If possible, grade and/or roll the subgrade to remove angular rocks and minimise the risk of settling; • Subgrade should be graded so that there is a low-point in one corner. Once the base barrier is constructed, this will be the location of a sump to pump snow melt and leachate in the biopile; • Construct berms using uncontaminated soil material from the site. Berms are required to be high enough to contain leachate, and hold anticipated annual and cumulative snow melt. Width and height of soil/gravel berms should be designed on a case-by-case basis according to the required storage volume and at angles consistent with best practice design such that the geomembrane liner performance is not compromised.
Base liner system	• Best practice for a base composite liner system mimics a landfill design where the primary barrier is a plastic *geomembrane* underlain by the secondary barrier, a GCL placed directly on the subgrade; • When multiple GCL panels are used, the panels are overlapped for added protection. Overlaps should be 30 cm and sealed with bentonite slurry as per manufacturer's installation guidelines;

	• Standard geomembranes come in 5-8 m widths. Depending upon the size of the containment area, it may be necessary to heat weld the geomembrane, which will require specialist equipment and expertise; • Installation of the flexible geomembranes can be challenging in the corners of berms. Heat welded corners may assist here; • The base liner system should have a protection layer above to reduce damage to the geomembrane (*eg*, holes from angular rocks or accidental puncture by excavator bucket/ripper or other sharp tools). Best practice for a protection layer is 30 cm of sand. However, in Antarctica, depending on the site, sand may not be available. In these instances, the protection layer may be coarse sand (sterilised and imported), fine-grained soil from the site, or fine-grained contaminated soil; • The protection layer soil is not mechanically turned, but will be in contact with contaminated leachate. If contaminated soil is used as the soil protection layer, it will likely have slower rates of degradation than soil in the active layer of the biopile; • A geotextile is used as a separator between the geomembrane and soil protection layer. Geotextiles with higher thickness and density provide better protection for the geomembrane; • Follow the manufacturer's installation guidelines to avoid damage or puncture to the liners. **Key references:** • *Geosynthetics in Antarctica: Performance of a composite barrier system to contain hydrocarbon-contaminated soil after 3 years in the field*
Biopile soil	• Excavated soil will typically contain a mixture of coarse and fine particles. • Using an excavator screening bucket (approx. 200 mm mesh size) prior to filling the biopile will reduce the volume of the biopile and enable treatment of the most contaminated soil; • Coarse rock screened out of the excavated soil should be assessed for residual contamination in any adhering soil. Consider water washing the coarse rocks using a tumbling bucket in a water filled, open-topped container to remove adhering soil and contaminants prior to reuse; • Bioremediation rates in soils will vary depending upon the biopile design: soil permeability, pile height, aeration and drainage systems.
Cover system	• A cover can be used to prevent off-site contaminant migration (*eg*, dust) or loss of soil moisture, as well as provide a wildlife barrier; • Permeable covers (*eg*, geotextiles, canvas) will enable water ingress (snow melt) and egress (evaporation/ablation), as well as air ingress (oxygen required for biodegradation), and also enables wind that gets under the cover to partially dissipate; • Impermeable covers (*eg*, geomembranes) will prevent water ingress and egress, but depending upon how they are affixed, they may inhibit oxygen diffusion; • Consider how best to fix the biopile covers. Using rocks as weights is manually intensive, but enables covers to be manually removed and replaced easily; • Covers experience significant damage from winds and UV exposure. Coarse soil (*ie*, exposed rocks) can quickly abrade covers in high winds. Lifespan depends on polymer type, manufacturing techniques and density. In Antarctic conditions, geotextile covers typically last 2-3 years. Two covers may be used to prolong the life of the geotextiles and reduce abrasion;

	• Geotextiles should be monitored if they are prone to fragmenting to prevent plastic fragments and fibres dispersing into the environment.
Aeration	• If the soil is fine-grained and/or an impermeable cover is used, then an aeration system may be required to maintain aerobic conditions; • The aeration system could be designed to blow air (which also allows for humidification if selected) or it could pull ambient air through the biopile (which allows for the capture of volatile contaminants); • Consider the design (including stack height) of any volatile catchment system in relation to anticipated wind speeds; • Aeration pipes are at risk of filling with water/ice if installed too low in the biopile, or removal of annual melt is not carefully managed leading to a cumulative build-up of ice, eventually blocking aeration piping. It is very difficult to remove ice from these pipes. **Key references:** • *Biopile Design, Operation, and Maintenance Handbook for Treating Hydrocarbon-Contaminated Soils (von Vahnestock et al., 1997)*
Operation and Amendments	
Nutrients	• If the soils are nitrogen limited, then it will be necessary to add a nitrogen based fertiliser. Similarly, potassium and phosphorous may also be required; • Calculate additional nutrients required using either a generic (*ie*, *Redfield*) or site-optimised ratio; • Inorganic or appropriately sterile organic fertiliser is required to avoid any risks of non-native species or wildlife disease; • Addition of dry fertiliser (powder or granulated) may result in a delay in nutrient distribution depending upon circulation of water and freeze/thaw conditions. Consider the use of liquid fertiliser addition to better mix the nutrients through the contaminated soil, particularly if the soil retains little moisture; • Account for the evaporation of hydrocarbons and be conservative about the addition of nitrogen to avoid soil eutrophication and ammonium/nitrite toxicity; • Be aware that controlled release fertilisers behave differently in freeze-thaw conditions compared to temperate climates (7) and that nutrient capsules may not degrade as rapidly as expected.
Other amendments	• If the soil pH is outside the optimum range (6-8), then it may be necessary to use an amendment to adjust the pH; • Depending upon project requirements, other sterile organic or inorganic biopile amendments may be considered, including organic carbon to help retain moisture and provide a substrate for microbial growth; • Possible options for consideration that have not been trialled in Antarctica include: - Non-ionic surfactants have been used for bioremediation in laboratory trials, but not in the Antarctic context (8); - If the project is time-limited, then it may be possible to accelerate the process by culturing endemic (hydrocarbon degrading) bacteria and adding to the biopile.
Temperature	• Temperature can be increased in the biopile by using a dark coloured geosynthetic cover, and by mechanically breaking up frozen soil early in the summer;

Leachate management	• Ideally, the biopile should be designed with a system to pump water (snow-melt and leachate) from the sump; • The water can be recirculated within the biopile using pumps and hoses during summer months, providing that consideration is given to freezing during the Antarctic night. Recirculation aids in maintaining the required soil moisture contents and redistributing nutrients and oxygen thereby aiding bioremediation; • Excess water (more than can be contained within the liner and berms) should be removed and treated to remove any *LNAPL* and *dissolved phase* contaminants, as well as dissolved amendments (*eg*, nutrients); • Excess freezing of water within the containment area may lead to long term loss of storage capacity over several years, reduce biopile temperature and slow remediation processes.
Physical turning	• Physical turning of biopile soil using an excavator will aid evaporative hydrocarbon losses, as well as assisting passive solar heat gain in frozen soils; • An excavator is useful to get representative soil samples from the entire biopile, including different depths rather than only the near-surface; • Use of a hydraulic tilt-bucket on the excavator will enable the excavator operator more flexibility when turning the soil. **Key references:** • *Nitrogen requirements for maximizing petroleum bioremediation in a sub-Antarctic soil (Cold Regions Science and Technology, 2007)*
Monitoring	
Sensors	• Electronic sensors can be used for monitoring (*eg*, oxygen, temperature, moisture). Electronic sensors add to cost and complexity, and can be prone to damage. If research is not being conducted in tandem with the remediation, sensor monitoring is probably not required; • If sensors are used, and rely upon wires to carry power and/or signal, then they must be placed so that they are not damaged by turning of the soil, and will likely require waterproofing and conduit tubing to protect cables from damage.
Analysis	• Bioremediation progress can be assessed annually (or more regularly if desired) by taking representative samples from the biopile and analysing for the contaminants of interest; • Sample density will depend upon soil heterogeneity and regulatory requirements, but generally one sample per $5m^3$ (for a 100 m^3 biopile) should provide statistically robust results; • Field blanks, rinsate blanks and sample duplicates are considered basic Quality Assurance/Quality Control requirements for any analytical sample plan; • Sample analytes should consider including: *TRH*, *TRH (SGC), BTEXN*, leachable and more toxic components (*eg*, *1 MN*, *2MN*, *1-2-3 TMB*); • The US EPA software ProUCL can be used to estimate average contaminant concentration at various confidence levels. **Key references:** • *ProUCL software* https://www.epa.gov/land-research/proucl-software • Victorian EPA Industrial Waste Resource Guidelines – Soil Sampling http://www.epa.vic.gov.au/~/media/Publications/IWRG702.pdf

End Points and Soil Reuse	
	• The extent of required remediation will be determined by an assessment of residual environmental and/or human health risk of re-using the remediated soil; • Reuse options range from highly specific and controlled use for engineering or building purposes to unrestricted re-use and return to the environment; • Residual risk should be determined based on: - the concentration, chemistry, leachability and biological availability of residual fuel and amendments (*eg*, nutrients), if any, in the soil; - the proposed re-use option; - the proposed re-use location, and proximity to, and sensitivity of, environmental or human health receptors; - any additional management or engineering measures put in place to minimise risk, such as drainage or in-ground containment. • Any future land-use or infrastructure changes that will increase the risk profile at the reuse site should be considered. For example: soil reused under a building may meet *volatile* (human health) risk guidelines. However, removal of the building in the future may expose the soil to increased groundwater flow, and the subsequent mobilisation of *soluble* contaminants. **Key references:** • *CRC Care Health Screening Levels* https://www.crccare.com/products-and-services/health-screening-levels • *Ecological Considerations in Setting Soil Criteria for Total Petroleum Hydrocarbons (<C_{15}) and Naphthalene* (Environment Protection and Heritage Council, 2003) • A framework for Ecological Risk Assessment: General Guidance (Canadian Council of Ministers of the Environment, 1996 and updates).
Decommissioning	
	• Remove soil for its intended (assessed) reuse purpose; • Physical removal, transport and long-term staging of the remediated soil may cause an environmental impact via dust or leaching if not appropriately controlled and managed; • Plan for the removal of containment materials (*eg*, liners and covers) outside Antarctica for proper disposal or recycling; • Liners themselves will likely have adhering soil and minor residual fuel concentrations (adsorbed to liners or within adhering soil) that will result in biosecurity and waste disposal considerations; • Undertake soil sampling within the exposed subgrade to obtain confirmation that the site/subgrade remains uncontaminated, or that contamination levels are below the desired remediation end-point; • Physically rehabilitate modified areas of the biopile site to return to natural landform and aesthetic values; • Record and report as appropriate, and ensure completion of regulatory and environmental approval processes; • Ensure that station and engineering plans are updated with the location and volume of the reused soil with caveats outlining any changes to risk profile documented; • Consider reporting on lessons learned in appropriate Antarctic forums including, for example, COMNAP and the CEP.

Personnel

The design, construction and maintenance of Antarctic biopiles require a variety of specialist and non-specialist personnel, and these may vary according to the clean-up objective and National Antarctic Programme. Likely key roles and responsibilities are identified in the table below.

Contaminant source and soil characterisation	
	• Field - Environmental scientist and/or staff with scientific training acting under the instructions of an experienced environmental scientist. • Laboratory – Samples processed and analysed by an appropriately accredited laboratory with expertise in hydrocarbon analysis. • Interpretation – Environmental scientist(s) with experience in the interpretation of hydrocarbon analyses.
Desirable requirements for selection of a biopile site	
	• Field - Site visit by personnel planning the biopile, and consultation with key Antarctic programme personnel. • Decision making and approvals – National Antarctic Programme planners/managers, environmental management and operations personnel, National Competent Authority.
Design and Construction	
	• Design – Geotechnical engineer for liner systems, preferably supported by consultation with geotechnical engineer with experience in the installation of liner systems in Arctic/Antarctic environments. • Design - Environmental scientist or remediation professional for aeration, soil and remediation aspects. • Field – Construction personnel supervised or trained by a geotechnical engineer with experience in the installation of liner systems. • Field - Construction personnel skilled in plant operation as required (*eg*, rolling subgrade, obtaining necessary gradients for drainage, excavation and screening of contaminated soil).
Operation and Amendments	
	• Design and Field – Environmental/Remediation scientist to determine type and amount of amendments to use, leachate management, and supervision of implementation/operation. • Field – Station/Antarctic programme personnel can be trained to operate and maintain biopiles by the supervising project manager using standard operating procedures. • Field - Construction personnel skilled in plant operation as required (*eg*, physical turning).
Monitoring	
	• Laboratory – Samples processed and analysed by an appropriately accredited laboratory with expertise in hydrocarbon analysis. • Field and Interpretation – Environmental/Remediation scientist(s).
End Points and Soil Reuse	
	• Interpretation - Environmental risk assessment professional. • Decision making and approvals – National Antarctic Programme planners/managers, environmental management and operations personnel, National Competent Authority.

Decommissioning	
	• Field - Station personnel can be trained and supervised to decommission biopiles and in the placement of soil in allocated location(s) by the supervising project manager.

Pictures

Photo 1: Compacted biopile subgrade with earthen berms prior to installing the other components of the composite liner system (geosynthetic clay liner, geomembrane and geotextiles).

Photo 2: Installing GCL (white) and Geomembrane (black)

Photo 3: Geomembrane (black) installed over GCL and berms. Note the heat welded seam running through the centre of the geomembrane showing two panels joined together.

Photo 4: Completed construction of the composite liner system showing geotextile (black) overlaying geomembrane (black/grey) and GCL below.

Photo 5: Protection layer of finer soil placed in biopile containment area

Photo 6: Manually circulating biopile leachate over soil during summer.

Photo 7: Showing multiple constructed biopiles in operation. Note uncovered for sampling purposes.

Photo 8: Biopiles under snow.

Glossary

Aviation gasoline - Aircraft jet fuel, commonly known as Avgas, Jet A-1, Jet TS-1, ATK (aviation turbine kerosene).

Base liner system - A composite liner system to prevent contaminant dispersal, consisting of a geosynthetic clay liner and geomembrane, covered by geotextile and underlain by an appropriate subgrade.

Berm - A landscaped ridge of earth used to stop the surface flow of water.

Bioaugmentation - A remediation technique which involves adding bacteria and/or fungi to accelerate the biodegradation of contaminants.

Biopile - A biopile is a remediation technology where contaminated soil is placed in a contained mound and soil conditions are modified to enhance microbial degradation of the contaminant. Aerobic microbial activity is typically stimulated within a biopile through aeration and/or mixing, and/or addition of nutrients, minerals, heat or moisture.

Bioremediation - A process that uses living organisms (usually naturally occurring or native) such as plants, bacteria, yeast, and fungi to break down hazardous substances into less toxic or nontoxic substances.

Biostimulation - Modifications to stimulate existing bacteria capable of bioremediation. This can be done by addition of various forms of rate limiting nutrients (*eg*, nitrogen, phosphorous, potassium) and electron acceptors or donors (*eg*, oxygen, carbon).

BTEXN - A commonly used abbreviation for benzene, toluene, ethylbenzene, xylenes and napthalene compounds, commonly occurring in fuel and crude oil. They are aromatic compounds and have carcinogenic, teratogenic or mutagenic properties.

Ex situ - excavated or removed from its original place. In the remediation context, this usually means removed from the ground.

Geomembrane - a very low permeability and flexible synthetic membrane liner (barrier) that is used to stop advective, and limit diffusive, contaminant transport. Typically made out of high density polyethylene (HDPE).

Geotextile - permeable fabric which, when used in association with soil, have the ability to separate, filter, reinforce, protect, or drain**.**

GCL - Geosynthetic Clay Liner. A manufactured hydraulic barrier containing bentonite (clay) sandwiched between two geotextiles and held together by needle punching and stitching. The active ingredient in a GCL is a swelling clay (smectite), which typically represents 70-90% of the clay core of the GCL. When the clay comes into contact with water it swells and develops very low permeability (*ie*, high resistance to the flow of liquids and gases).

In situ - In its original place, unexcavated, or unmoved.

Landfarming - The spreading and biostimulation of contaminated soil to stimulate bioremediation, involving soil tilling inside or outside a treatment cell.

LNAPL - A Light Non-Aqueous Phase Liquid is less dense than water and is mostly insoluble in water. It will sit above the water table in the subsurface, as well as ganglia (blobs) in soil voids. An example is petrol (gasoline).

MAH - Monocyclic Aromatic Hydrocarbon. Organic compounds containing only carbon and hydrogen comprised of a single aromatic ring.

PAH - Polycyclic Aromatic Hydrocarbon. Organic compounds containing only carbon and hydrogen comprised of multiple aromatic rings. These occur naturally in petroleum hydrocarbons, coal, crude oil and are released into the air during incomplete burning of fuels, rubbish and organic waste. These can be carcinogenic compounds.

Redfield Ratio - Atomic ratio of carbon to nitrogen to phosphorous (C:N:P) of approximately 117:14:1, often simplified to 100:10:1.

Removal from Antarctica - A technique which excavates soil at source and transports it somewhere else, normally a home country, for disposal or treatment. Normally considered cost prohibitive in the Antarctic context nor a sustainable form of Antarctic remediation.

Subgrade - Earthen material underneath a biopile, typically compacted in order to provide an even, stable, appropriately sloped surface.

Sump - A low point/depression in which to collect liquid.

TRH - Total Recoverable Hydrocarbons. Sometimes used interchangeably with TPH – Total Petroleum Hydrocarbons. Analytical techniques that measure TRH will specify the carbon range of the analysis.

TRH (SGC) - Total Recoverable Hydrocarbons with a Silica Gel Clean up step. The clean-up step is used during analysis to remove natural organic matter or polar metabolites that may be contributing to the quantification of the TRH.

Volatiles - Volatile Organic Compounds (VOCs) are organic chemicals that have a high vapour pressure and readily evaporate at room temperature.

1 MN - 1-Methylnaphthalene, a PAH hydrocarbon compound.

2 MN - 2-Methylnaphthalene, a PAH hydrocarbon compound.

1-2-3 TMB - 1,2,3-Trimethylbenzene, an aromatic hydrocarbon compound

Annex 3: Guidance for Construction and Management of Permeable Reactive Barriers for the Treatment of Hydrocarbon Contaminated Groundwater in the Antarctic

Definitions

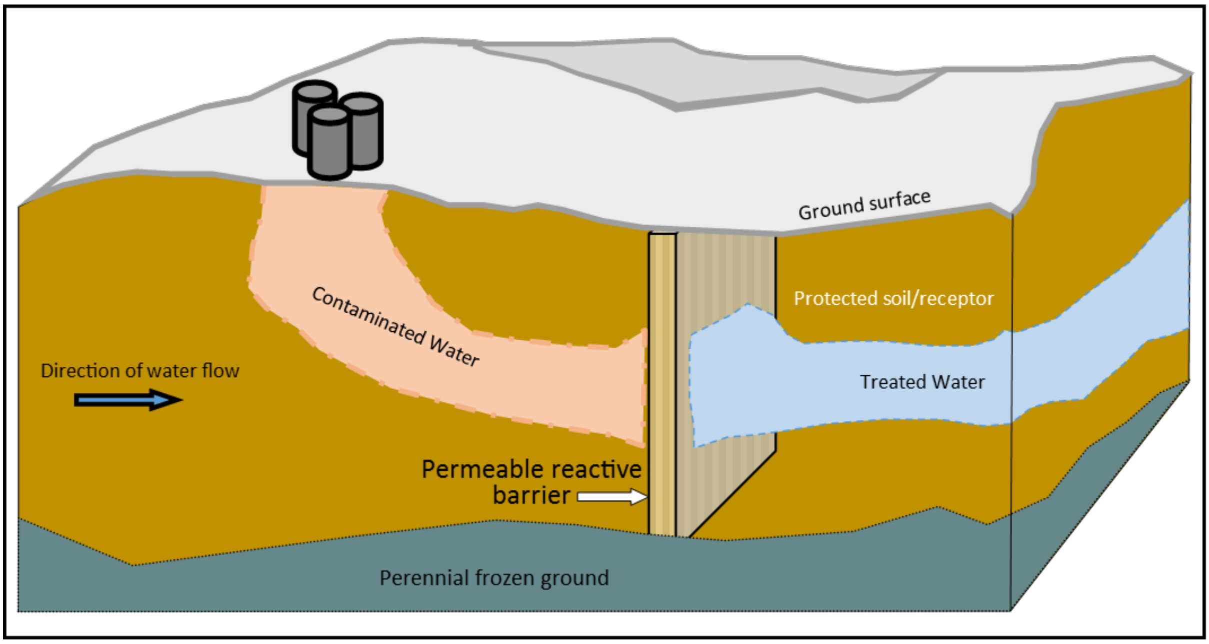
A *Permeable Reactive Barrier* (PRB) is an in-ground groundwater treatment technology designed to prevent the migration of contaminants. PRBs can *adsorb* and degrade hydrocarbons, utilising native microbes to degrade contaminants through a process known as *biostimulation* and *bioremediation* or can be used to adsorb and capture contaminants such as metals and other contaminants not amenable to *biodegradation*, or a mix thereof.

PRBs are used in situations where a decision has been made to control migration of contaminants from a contaminated site, either as (1) a temporary or semi-permanent measure to mitigate further environmental damage while remediation and/or further management options are considered and implemented, or (2) in situations where remediation of the primary contaminant source is not practicable at that time. PRBs can also be installed in ice/snow under certain conditions.

PRBs can either be "funnel and gate" or "continuous wall". Funnel and gate systems intercept contaminated groundwater using an impermeable "funnel" (also known as "wings") and direct it towards the permeable "gate". The gate is designed to treat the contaminated water, resulting in clean water exiting the site. Continuous wall systems forgo the installation of an artificial "funnel" and use a wall of reactive and non-reactive material ("*media*") to treat contaminated water as it passes through. A variety of groundwater monitoring points and/or sensors may be installed to monitor the PRB's performance.

This guidance document addresses the use of "funnel and gate" PRBs in the Antarctic for the treatment of hydrocarbon contaminated groundwater.

Figure 1: Schematic showing PRB concept (adapted from US EPA 2002 (1))



Purpose of this document

Whilst there are many existing resources on PRB performance and construction, polar environments present unique challenges for their operation. This document is intended to provide guidance for Antarctic PRB construction and maintenance, specifically for the remediation of petroleum contaminated groundwater, although many of the concepts and design considerations could apply to PRBs used for metals or other organic contaminants (*eg*, PCBs). This non-mandatory guidance is based on Antarctic-specific research and practical experience with PRB construction and operation.

The guidance identifies general considerations and principles, which will support decision making, planning and management of a contaminated site using PRB technology. It provides advice on the range of more detailed scientific, technical, design and management issues and adaptations that should be considered when applying this technique. Site specific assessments, environmental impact assessment of proposed remediation activities, and additional research and technical design support will be necessary elements of a PRB installation. Relevant references are provided to support these activities.

This document does not address emergency fuel spill response, contaminated site assessment, sampling design, effects of hydrocarbons on terrestrial, lacustrine or marine organisms, site specific risk assessment, human health risk assessment, or alternative remediation options.

When to use PRB technology

PRBs are frequently used in temperate environments as an environmental protection technology to capture and, where possible, degrade contaminants. PRBs will not remediate the contaminant source, but are specifically employed to prevent off-site contamination. PRBs are one of several environmental management techniques that have been successfully used to reduce the environmental risk associated with fuel spills and petroleum-contaminated soil in Antarctica.

The decision to use a PRB in Antarctic conditions occurs once a site assessment has been conducted and an environmental risk assessment process has identified the following:

- The presence of contaminant in soil and shallow groundwater (*eg*, diesel fuel) at concentrations which pose an unacceptable environmental risk through migration. Common petroleum contaminants used in the Antarctic that have the most mobile and potentially toxic components are diesel, *aviation gasoline* and petrol. Heavier petroleum products such as lubricants are less likely to pose an environmental risk via migration through groundwater;
- The contaminated soil will not or cannot be practically excavated for further remediation or cannot be excavated within a timeframe that might prevent off-site migration.
    - Practicality is site specific but could include: site accessibility (slope, proximity to water bodies, infrastructure and buildings), depth below ground of contaminant, excavation depth, ground conditions (permafrost, groundwater, soil particle size and distribution, bedrock morphology, previous disturbance, etc.).
- The contaminant in soil is likely to degrade slowly *in situ* via *natural attenuation*, and an in-ground treatment technique (*eg*, soil vapour extraction, chemical oxidation, electro-kinetic oxidation, or in-ground aeration/nutrient addition) is also deemed unsuitable.
    - Examples of factors that affect the suitability of these techniques may include: ground conditions, the distribution of contaminant, limitations or uncertainty of ensuring the remediation treatment reaches the contamination, and/or the environmental risk of applying amendments in an uncontained manner.

- If excavation and above ground remediation or an *in situ* remediation option are planned or implemented and there remains an unacceptable environmental risk through migration of contaminated water during remediation activities; or
- There is a suitable location for the construction of the PRB wings and gate, and the PRB can be properly installed ("*keyed in*") to bedrock or permafrost to minimise the flow of contaminants beneath or around the system.

Background

Natural attenuation of hydrocarbons in Antarctica is generally very slow and can lead to on-going mobilisation and transport of hydrocarbons from a contaminated site for decades to centuries (2). A growing body of research shows that PRBs can be an effective tool for the containment and remediation of contaminated groundwater in Antarctic and subantarctic conditions (3-10).

Typically, a variety of coarse granular *media* are used within the PRB gate. These media are mixed or sequenced within the PRB and serve specific purposes depending on the contaminant to be intercepted. For PRBs used to treat hydrocarbon contaminated water, typical media include sand (for removal of fines), granular activated carbon (to capture hydrocarbons), nutrient amended zeolites or other source of nutrient release (to encourage bioremediation of adsorbed hydrocarbons) and natural zeolites (to capture any excess added nutrients before the water exits the PRB).

The materials used in a PRB gate have a finite lifespan and need to be regenerated or replaced in order to ensure their efficacy. A well designed monitoring programme will inform decisions about when PRB media needs to be replaced (11, 12).

PRBs work on the concept that the barrier is more permeable than the surrounding area, and is therefore the preferential flow path for contaminated water. As a result, although the correct selection of the granular PRB media is important, equally important is the design and monitoring of the PRB itself such that contaminated water preferentially flows to and through the PRB gate over the course of its operational life, and that loss of permeability, either through freezing, clogging or break down of media particle size, is minimised. This includes ensuring the PRB remains unfrozen during times of peak melt and contaminant mobility.

It is expected that design and installation of a PRB in Antarctica would require a two-year commitment, with ongoing resourcing required for annual monitoring. With regular monitoring and periodic changes of the media, PRBs can function effectively for time-spans of several years through to decades.

Process

Steps leading to construction of an Antarctic PRB

1) Identification of a contaminated site (triggered either by a new fuel release or through a site assessment which has uncovered past contamination):
    a. A site assessment is needed to quantify extent, volume, concentration and types of contaminant, including water-borne contamination;
2) A risk assessment that concludes that off-site migration of contaminants poses an unacceptable environmental risk;
3) An assessment of remediation options and identification of a PRB as the most appropriate technology to minimise continued off-site migration of contaminants;
4) Commitment of resources to site preparation, excavation of trenches and a pit for the PRB wings and gate;
5) Detailed PRB project design and planning;
6) Conduct of the Environmental Impact Assessment process and application for relevant approvals from the administering Competent Authority; and
7) Implementation:
    a. Installation
    b. Operation
    c. Monitoring
    d. Regeneration or replacement of media
    e. Decommissioning

Considerations

Contaminant source and site characterisation	
	• Characterise the extent of contamination (*eg*, contaminant type(s), areal and volumetric extent); • Characterise contaminant and meltwater flowpaths and flow rates through and exiting the site; • Characterise the condition of frozen ground, seasonal active layer depths, bedrock, and suitability for "*keying in*" a PRB; • Analyse for co-contaminants (*eg*, metals, *PFAs*, *BFR*s) as well as expected fuel contaminants (*eg*, Total Recoverable Hydrocarbons, *BTEXN*, *MAH* and *PAH*s).
Desirable characteristics for a PRB site	
	• A suitable area to install the PRB wings and gates that adequately captures the contaminated ground-water exiting the site; • Suitable access for environmental monitoring down-gradient of the site; • Vehicle access to the site for the summer period; • Sufficient distance from wildlife colonies or wallows, pathways or congregation areas (noise disturbance from heavy equipment); • Sufficient distance from watercourses, melt water streams, lakes and/or ocean so that installation does not cause greater environmental damage; • Minimisation of vehicle traffic through the area, particularly when the area is snow covered, so that the PRB cage and wings are not damaged; • Ensure personnel present are appropriately trained to maintain and monitor the PRB; • Proximity to power supply for operational and monitoring equipment (may be temporary or permanent).

Design	
Operational lifetime	• Plan for a longer project time-frame than theoretically calculated, due to project delays (Antarctic operational constraints, weather); • Design should accommodate treatment capacity of PRB for seasonal "pulses" of contaminated water of potentially high volume and high flow rate; • Allocate resources to the construction, monitoring, maintenance, and decommissioning of the PRB for the full project time-frame; • Plan for the removal of PRB materials (*eg*, granular media, liners etc.) outside Antarctica for proper disposal or recycling; • At a minimum, plan for regular visual monitoring of the PRB wings and gate. If the integrity and performance of the PRB is established, it could be left to operate passively for several years.
Location, orientation	• A PRB, or series of PRBs, should be located and orientated such to maximise catchment of contaminated water from the site.
Design of Funnel/Wings	• Wings should include: - an impermeable *geomembrane* or barrier such as High Density Polyethylene (HDPE). It is recommended HDPE is a minimum 2 mm in thickness; - Prefabricated "engineered" drainage material (*eg*, Megaflo™) or coarse gravel. • Wings should extend to the gate at a minimum gradient of 1:20, with a preference of 1:10; • The ratio of the length of wings to the width of the gate should be less than 10, measured perpendicular to the water flow path; • Wings can be "keyed in" to frozen ground. However, consider the use of concrete (min. 10 cm) at the base of the wing excavation in which to "key in" the impermeable liner to reduce the potential for underflow of contaminated water below the wing if permafrost depth is variable; • Backfill using coarse gravel placed upgradient and fine material downgradient of the wings; • Independently controlled heat trace can be placed along the drainage material of the wings to improve thawing and water flow to the gate during peak melt; • Piezometers and temperature sensors can be placed along the wings to monitor wing temperature, water flow, and obtain water samples for analysis; • Avoid the use of loose materials, such as bentonite, as part of the "keying in" process, as these materials will be washed towards the gate causing clogging and impeding flow.
Design of Gate **See Figures 2 and 3**	• A suitable cage or geofabric that can simultaneously contain selected PRB media while still allowing sufficient permeability and water flow is required. Cage pallets, used for supply transport to/from stations and geotubes (see pictures) have been successfully used in Antarctica; • Identify a location for a sump(s) within and/or upgradient of the gate as it may be required later during the installation for removal of excess water during excavation and gate installation; • Design for the gate to have sufficient gradient to freely drain, to minimise likelihood of water remaining in the gate after seasonal meltwater flow and freezing, thereby causing blockage, freeze/thaw, and breaking of granular

	media. This also minimises the need for heat trace to be used to maintain hydraulic conductivity; • Coarse gravel should be placed downgradient of the gate to promote flow at the outlet, and to insulate the base of the cage from melting and undermining; • Insulation on the sidewalls and base of the gate is recommended if using heat trace or other means to warm the gate. This reduces warming of surrounding frozen ground and the risk of water bypassing the gate. - Insulation wrapped in solvent resistant polymer is recommended as insulation exposed directly to hydrocarbons will deform and degrade. • Design for installation and operation of heat trace if possible. Heat trace allows for warming of the PRB prior to the start of seasonal melt and ensures performance both in maintaining permeability for water flow and treatment as well as improving conditions for bioremediation. - If installing heat trace at various depths, it is recommended that heat trace is installed on separate circuits such that if heat trace fails in one area/depth, it can be isolated while maintaining heating of other areas in the cage. - Passive heating options should also be considered. • Consider whether the addition of oxygen, to enhance biodegradation, will be needed. Ports or tubes in which air can be introduced into the PRB are options to consider. **Key references:** • *Application of reactive barriers operated in frozen ground (In R. Margesin (ed.): Permafrost soils. 2009.)* • *Design, installation and preliminary testing of a permeable reactive barrier for diesel fuel remediation at Casey Station, Antarctica (Cold Regions Science and Technology, 2013)*
Selection of Reactive Media	• The selection of reactive material is based on site specific factors and the contaminant of concern; • For PRBs used to treat hydrocarbon contaminated water, typical media include a combination of sequence of the following: - sand (for removal of fines); - granular activated carbon (to capture hydrocarbons); - nutrient amended zeolites or other source of nutrient release (to encourage bioremediation of adsorbed hydrocarbons); and - natural zeolites (to capture any excess nutrients before the water exits the PRB). • Other materials known to have been used or trialled in Antarctica include: - Zero-valent iron for the removal of heavy metal contaminants. • Consideration should be given to potential toxic effects of materials used, and necessary testing if required prior to deployment to Antarctica; • Any media to be imported to Antarctica should be sterile / treated and inspected to ensure that it is free of non-native species. **Key references:** • *Evaluation of a permeable reactive barrier to capture and degrade hydrocarbon contaminants (Environmental Science Pollution Research, 2015).* • *A permeable reactive barrier (PRB) media sequence for the remediation of heavy metal and hydrocarbon contaminated water: A field assessment at Casey Station, Antarctica (Chemosphere, 2016)*

Sensors and Monitoring	• Electronic sensors can be used for monitoring (*eg*, dissolved oxygen, temperature, moisture). Electronic sensors add to cost and complexity, and can be prone to damage. If research is not being conducted in tandem with the remediation, sensor monitoring can be minimised, although temperature monitoring is recommended. - It is recommended that, at a minimum, temperature be monitored to ensure ground temperatures on the outside and below the gate are not above 0°C, otherwise there is a risk that water will bypass the gate. • If sensors are used, and rely upon wires to carry power and/or signal, then they must be placed so that they are not damaged by sampling, and will likely require waterproofing and conduit tubing to protect cables from damage.
Considerations for construction and installation	

Timing	• Excavation and installation of PRB wing and gate will likely cause mobilisation of contaminants. Reduce environmental risk by:
	  - Choosing timing of installation to minimise melt and contaminant liberation.
	  - Designing systems to recover and treat contaminated water and sediment during installation phase.

Installation of Wings	• In frozen ground, excavation for the PRB wing requires a trench approximately 1 m wide, although thinner trenching may be achieved in seasonally thawed ground, with suitable trenching bucket;
	• Ensure wing trench slopes at the suggested minimum gradient of 1:20, with a preference of 1:10;
	• If a decision is made to use concrete, cover the bottom of the trench with a minimum of 10 cm of concrete. Ensure the concrete is levelled to 1 cm and slopes at the minimum suggested gradient;
	• Place the HDPE liner along the length of the trench as close to upright as possible.
	  - To minimise leaks, if possible, use a continuous length of HDPE or, alternatively, heat-weld sections together (if personnel capability and equipment availability exist).
	• Wings should be placed so that they run smoothly and evenly (no buckles) so no water pooling (and freezing) occurs;
	• Place engineered drainage material on upgradient side of HDPE.
	  - The engineered drainage material should pass from the tip of the wing, along the wing, along the entire front of the gate and along the other wing to its tip. The base of the drainage material sits level to the reactive material in the gate, not below it.
	• Place any temperature sensors or piezometers as per developed project specific monitoring plan;
	• Place coarse rock as backfill around engineered drainage material and along the length and depth of the HDPE, taking care not to puncture HDPE during backfilling.

Installation of Gate	• High volumes of water may be encountered during installation and a sump can be installed to pump and manage water during PRB installation. Contaminated water should be managed accordingly; • Excavate at the location of the PRB gate to bedrock or permafrost (depth which has remained frozen longer than two years). The excavation area is recommended to be 20 cm larger than the base of the gate in each direction (front, rear and sides) to allow for installation of auxiliary equipment; • If a decision is made to use concrete, cover the bottom of the trench with a

	minimum of 10 cm of concrete. Ensure the concrete is levelled to 1 cm and drains to the down-gradient side; • Place insulation, wrapped in solvent resistant plastic, on concrete pad or place on ground level; • Place the gate (cage pallet or alternative) on top of the insulation; • Place and attach insulation along the sides of the gate (perpendicular to flow); • Placement of temperature sensors: - Place temperatures sensor beneath the gate or concrete to monitor ground temperatures below the gate during operation; - Place temperature sensors between insulation and gate in order to monitoring temperatures at the base of the PRB; - Place temperature sensors at front and back of PRB to monitor freezing/thawing at gate entrance and exit; and - Place temperature sensors at desired depths with PRB for selected monitoring purposes. • Place HDPE liner along the front of the excavation *ie*, from the base of the excavation, up along the concrete and insulation and into the front of the modified cage pallet (prevents underflow); • Backfill the front and rear of the gate excavation with coarse material to ground surface; • Fill the sides of the gate excavation with fine material to ground surface.
Monitoring	
Water Sampling	• Consider addition of piezometers at front and rear of gate for water level measurement and also as a location for the removal of water samples. The water level measurements can be used to evaluate hydraulic conductivity, whilst the water samples may be used to determine contaminant and/or nutrient concentrations and the inlet and outlet and hence test treatment efficacy.
Material Sampling	• Identify suitable locations for the removal of reactive media from the reactive gate. Ideally, cores of materials that demonstrate variation with depth to be taken along the length of the barrier gate; • These cores may be analysed to determine the concentration of nutrient remaining on the materials and additionally the concentrations of contaminant at these locations. These are important samples to assist in evaluating if the reactive material is close to its end of life.
Tracer test	• Salt tracer tests may be used to evaluate the residence time and/or whether there is preferential flow or blockages within the gate. This aids in evaluating whether there is sufficient time available for desired reactions to take place and if the barrier is close to its end of life. **Key references:** • *Hydraulic performance of a permeable reactive barrier at Casey Station, Antarctica (Chemosphere 2014)*
Analysis	• PRB performance can be assessed annually (or more regularly if desired) by taking representative samples from the media throughout the PRB, as well as from water taken at selected locations throughout the PRB (*eg*, entering, within and discharging) and analysing for the contaminants of interest; • Field blanks, rinsate blanks and sample duplicates are considered basic Quality Assurance/Quality Control requirements for any analytical sample plan; • Sample analytes should consider including: *TRH*, *TRH (SGC), BTEXN*, leachable

	and more toxic components (*eg*, *1 MN*, *2MN*, *1-2-3 TMB*); • If unsure of which analytes to sample, it is recommended that a sample of the spilled fuel (neat product) be submitted to a specialist laboratory for identification of the most eco-toxic components; • The US EPA software ProUCL can be used to estimate average contaminant concentration at various confidence levels. **Key references:** • *ProUCL software https://www.epa.gov/land-research/proucl-software*
End of life / removal	
	• PRBs will have a finite operational life that will be determined by: - Granular media performance in removing (and, where designed for, the biodegradation of) contaminant is no longer effective. - When permeability through the cage is restricted through freezing, sediment, excessive biofilms or reduction in grain size of granular media such that water no longer flows through the gate. • Regeneration options include: - Removal and replacement of new granular media. - *In situ* regeneration of granular media via ultrasound or electrokinetics. Note, regeneration of material by this method does not resolve permeability issues resulting from freezing or reduction in grain size. • PRBs can be removed when the concentration of contaminant in the contaminated site upgradient of the PRB are no longer assessed as having an unacceptable environmental risk, which could be a result of: - active remediation of contaminated soil source upgradient of PRB; - further risk assessment deems risk acceptable (more information on source, pathway, receptor); - natural attenuation; or - potential for PRB as installed to cause further environmental harm (unlikely) • Remove and dispose or recycle PRB materials (*eg*, granular media, liners etc) outside Antarctica at an appropriate facility; • Physically rehabilitate modified areas of the PRB cage and wings to return to natural landform and aesthetic values; • Record and report as appropriate, and ensure completion of regulatory and environmental approval processes; • Consider reporting on lessons learned in appropriate Antarctic forums including, for example, COMNAP and the CEP; • Any future land-use or infrastructure changes that will change the risk profile used to justify PRB removal should be considered. For example: will meltwater conditions change, or will snow clearing or removal of buildings cause a remobilisation of contaminants to occur? *Eg*, removal of a building in the future may expose the soil to increased groundwater flow, and the subsequent mobilisation of soluble contaminants. **Key references:** • *The electrochemical regeneration of granular activated carbons: A review (Journal of Hazardous Materials) (in press)*

Personnel

The design, construction and maintenance of Antarctic PRBs require a variety of specialist and non-specialist personnel, and these may vary according to the clean-up objective and National Antarctic Programme. Likely key roles and responsibilities are identified in the table below.

Contaminant source and site characterisation	
	• Field - Environmental scientist/engineer and/or staff with scientific training acting under the instructions of an experienced environmental scientist. • Laboratory – Samples processed and analysed by an appropriately accredited laboratory with expertise in the analysis of the contaminants. • Interpretation – Environmental scientist(s) with experience in the interpretation of contaminant data.
Desirable characteristics for a PRB site	
	• Field - Site visit by personnel planning the PRB, and consultation with key Antarctic programme personnel. • Field – Assessment of the site hydrology by an experienced geologist, geomorphologist or engineer. • Decision making and approvals – National Antarctic Programme planners/managers, environmental management and operations personnel, National Competent Authority.
Design	
	• Design –Engineer/hydrogeologist, preferably supported by consultation with parties experienced in the installation of PRBs.
Construction and Installation	
	• Field – Construction personnel supervised or trained by an engineer/environmental scientist with experience in the installation of PRBs. • Field - Construction personnel skilled in plant operation as required (*eg*, excavation of trenches, obtaining necessary gradients, placement of barriers and permeable gate).
Monitoring	
	• Field – Station/Antarctic programme personnel can be trained to monitor and sample PRBs by the supervising project manager using standard operating procedures. • Laboratory – Samples processed and analysed by an appropriately accredited laboratory with expertise in hydrocarbon analysis. • Interpretation – Environmental scientist(s) with experience in the interpretation of contaminant data.
End of Life / Removal	
	• Decision making and approvals – National Antarctic Programme planners/managers, environmental management and operations personnel, National Competent Authority. • Field - Station personnel can be trained and supervised to decommission the PRB infrastructure.

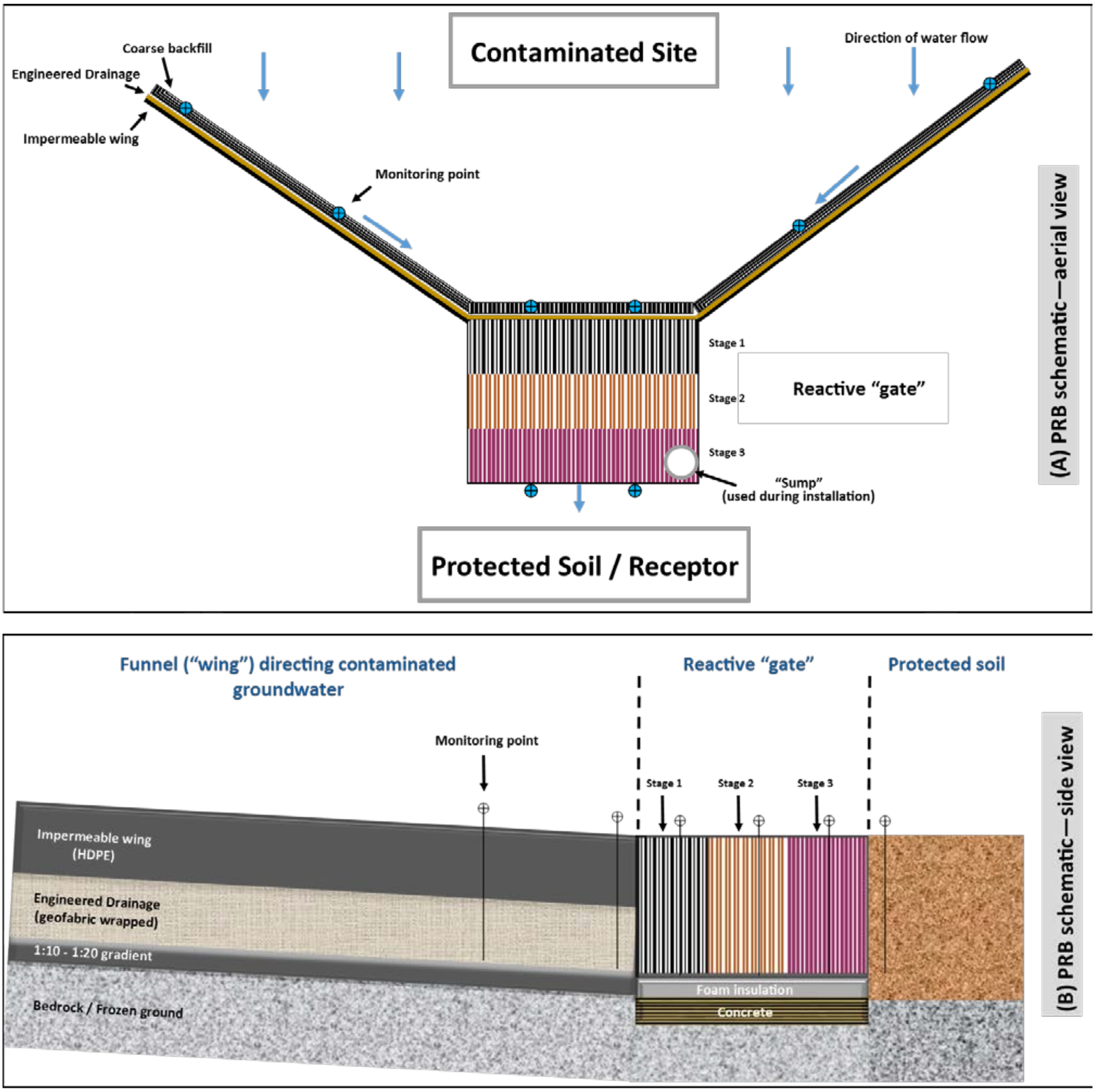


Figure 2: Schematic showing typical features of an Antarctic PRB in (A) aerial and (B) side view

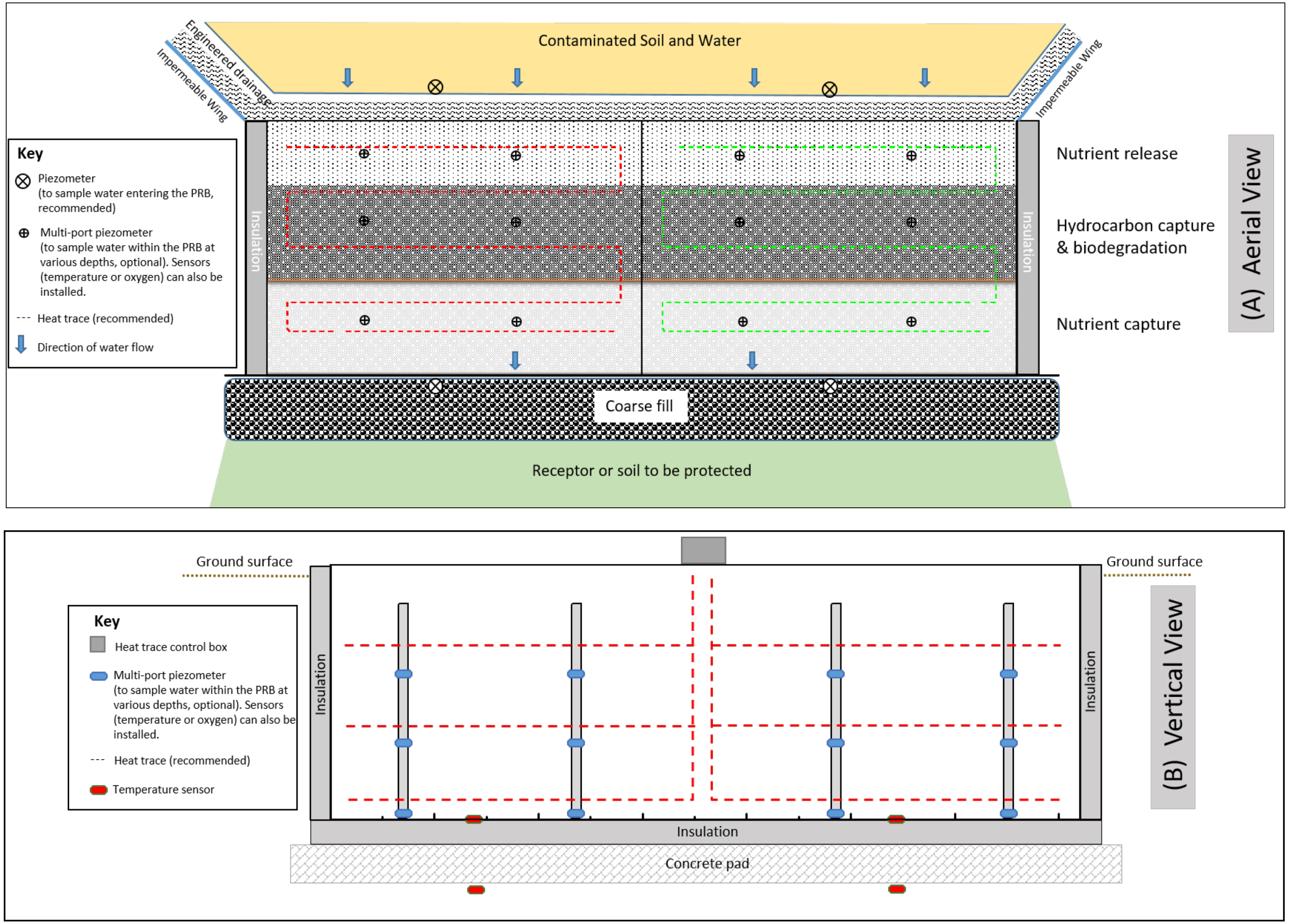


Figure 3: (A) aerial and (B) vertical view showing detailed design considerations for an Antarctic PRB

Pictures

Photo 1: Digging trench for PRB wing in frozen ground

Photo 2: Installing wings and gate. Note: gate is heavily instrumented for research purposes

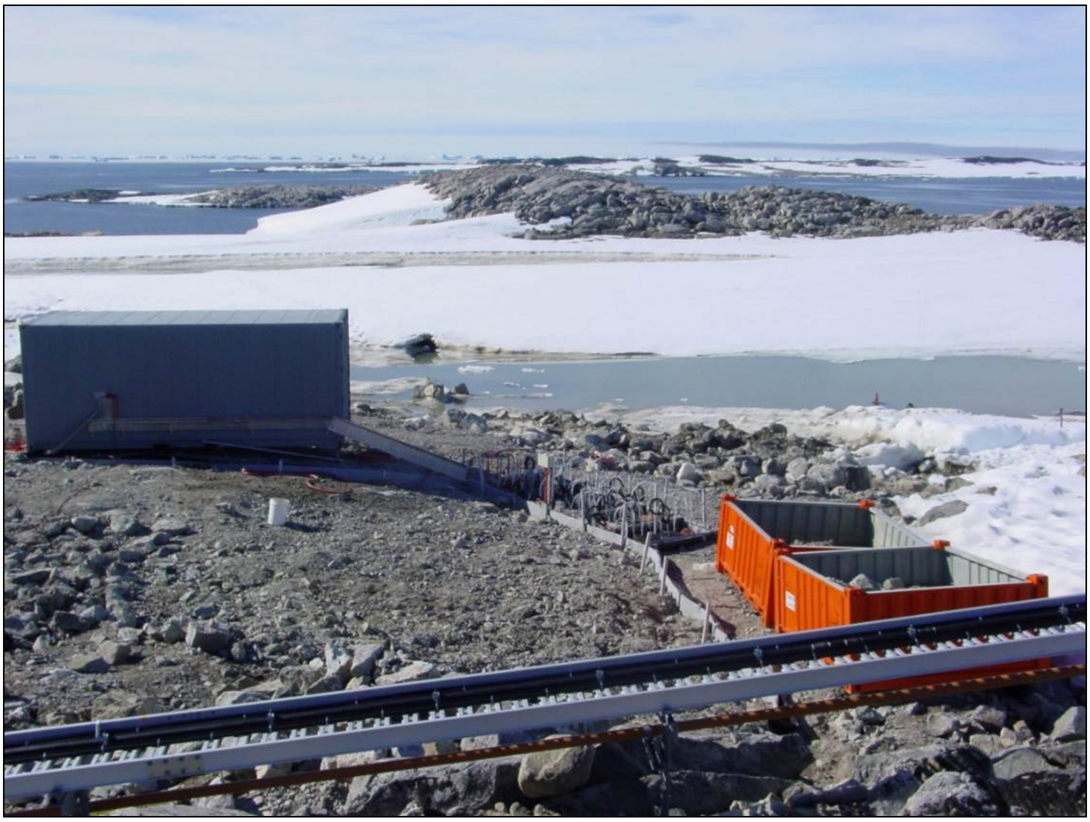


Photo 3: Backfilled wings and gate

Photo 4: PRB gate being constructed using "cage pallet" showing piezometers (white tubes) for water monitoring and sequenced granular reactive media. Black wire is heat trace to be connected.

Photo 5: Top view of sequenced granular media in PRB. In this instance, showing zeolite (orange), granular activated carbon (black) and nutrient enriched zeolite (white). Water flow is from bottom of picture towards the top.

Photo 6: PRB gate installed using geotube (black fabric). Note: once operational the top covers are closed to prevent granular media dispersing into the environment

Photo 7: Heavily instrumented gate used for research purposes and trialling a variety of granular media

Glossary

Adsorb - the retention of a solute by the surface of a solid rather than within its mass.

Aviation gasoline - Aircraft jet fuel, commonly known as Avgas, Jet A-1, Jet TS-1, ATK (aviation turbine kerosene).

BFR - Brominated flame retardant

Biodegradation - the breakdown of intermolecular bonds of organic substances by microorganisms to derive energy.

Bioremediation - A process that uses living organisms (usually naturally occurring or native) such as plants, bacteria, yeast, and fungi to break down hazardous substances into less toxic or nontoxic substances.

Biostimulation - Modifications to stimulate existing bacteria capable of bioremediation. This can be done by addition of various forms of rate limiting nutrients (*eg*, nitrogen, phosphorous, potassium) and electron acceptors or donors (*eg*, oxygen, carbon).

BTEXN - A commonly used abbreviation for benzene, toluene, ethylbenzene, xylenes and napthalene compounds, commonly occurring in fuel and crude oil. They are aromatic compounds and have carcinogenic, teratogenic or mutagenic properties.

Geomembrane - a very low permeability and flexible synthetic membrane liner (barrier) that is used to stop advective, and limit diffusive, contaminant transport. Typically made out of high density polyethylene (HDPE).

In situ - In its original place, unexcavated, or unmoved.

Key-in - in the context of construction or geotechnical engineering used here, to fix or attach liner, wing or gate system into underlying bedrock, frozen ground or ice such that water flow around or beneath such systems is minimised.

Media - in the context of PRBs, coarse granular material used to adsorb contaminants, release and recover nutrients or amendments, encourage bioremediation, and/or filter fine particles from groundwater.

MAH - Monocyclic Aromatic Hydrocarbon. Organic compounds containing only carbon and hydrogen comprised of a single aromatic ring.

Natural Attenuation - a reduction in mass, toxicity, mobility, volume or concentration of contaminants in soil or groundwater by a variety of physical, chemical, or biological processes without human intervention.

PAH - Polycyclic Aromatic Hydrocarbon. Organic compounds containing only carbon and hydrogen comprised of multiple aromatic rings. These occur naturally in petroleum hydrocarbons, coal, and crude oil and are released into the air during incomplete burning of fuels, rubbish and organic waste. These can be carcinogenic compounds.

PFAs - Per- and polyfluoroalkyl substances (PFAs) are a group of manufactured chemicals. Compounds resistant to heat, water, and oil. There are many types of PFAs, with the best known examples being perfluorooctane sulfonate, known as “PFOS”; perfluorooctanoic acid, known as “PFOA”; and perfluorohexane sulfonate, known as PFHxS.

Sump - A low point/depression in which to collect liquid.

TRH - Total Recoverable Hydrocarbons. Sometimes used interchangeably with TPH – Total Petroleum Hydrocarbons. Analytical techniques that measure TRH will specify the carbon range of the analysis.

TRH (SGC) - Total Recoverable Hydrocarbons with a Silica Gel Clean up step. The clean-up step is used during analysis to remove natural organic matter or polar metabolites that may be contributing to the quantification of the TRH.

1 MN - 1-Methylnaphthalene, a PAH hydrocarbon compound.
2 MN - 2-Methylnaphthalene, a PAH hydrocarbon compound.

1-2-3 TMB - 1,2,3-Trimethylbenzene, an aromatic hydrocarbon compound

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