Technical guide: Validation of PFAS soil treatment technologies

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Executive summary

This guide is for those who plan and put in place soil treatment technologies for per- and poly-fluorinated alkyl substances (PFAS).

It supports the use of innovative PFAS soil treatment technologies.

It provides:

- guidance on assessing the feasibility of PFAS soil treatment technologies; and
- a framework to confirm the effectiveness of PFAS soil treatment technologies.

This guide applies to:

- treatment conducted for a specific site;
- temporary treatment facilities;
- permanent treatment facilities; and
- a range of non-destructive and destructive soil treatment techniques.

This guide identifies best practice approaches about:

- how to plan for PFAS soil treatment;
- how to conduct treatability studies; and
- how to validate and verify full-scale treatment.

The 'state of knowledge' relevant to PFAS soil treatment is evolving. When using this guide, also consider relevant advances since its publication.

Disclaimer

EPA guidance including this guide do not impose compliance obligations. Guidance is designed to provide information to help duty holders understand their obligations under the *Environment Protection Act 2017* and subordinate instruments, including by providing examples of approaches to compliance. In doing so, guidance may refer to, restate or clarify EPA's approach to statutory obligations in general terms. It does not constitute legal or other professional advice and should not be relied on as a statement of the law. Because EPA guidance has broad application, it may contain generalisations that are not applicable to you or your particular circumstances. You should obtain professional advice or contact EPA if you have any specific concern. EPA Victoria has made every reasonable effort to provide current and accurate information, but does not make any guarantees regarding the accuracy, currency or completeness of the information.

Abbreviations

AFFF	Aqueous film forming foam	NEMP	PFAS National Environment Management Plan
APC	Air pollution control	NEPM	National Environment Protection (Assessment of Site Contamination) Measure
BAT	Best available techniques	NRF	National remediation framework
BATT	Best available techniques or technologies	OECD	Organisation for Economic Co-operation and Development
BFD	Block flow diagram	P&ID	Pipping and instrumentation diagram
BREFs	Best available techniques reference documents	PFAA	Perfluoroalkyl acids
CCP	Critical control point	PFAS	Per- and poly-fluoroalkyl substances
CEMS	Continuous emissions monitoring system	PFASTT	PFAS Thermal Treatment Database
COPC	Contaminant of potential concern	PFD	Process flow diagram
CRC	Co-operative research centre	PFHxS	Perfluorohexane sulfonate
CSM	Conceptual site model	PFOA	Perfluorooctanoic acid
DE	Destructive efficiency	PFOS	Perfluorooctane sulfonate
ECF	Electrochemical fluorination	POP	Persistent organic pollutant
EMP	Environmental management plan	RE	Remediation/removal efficiency
EP	Environment protection	TE	Thermal efficiency
ERS	Environment reference standard	TRL	Technical readiness level
EU	European Union	TSMP	Treated Soil Management Plan
GED	General environmental duty	TTM	Thermally treated material
HEPA	Heads of EPA Australia and New Zealand	QA	Quality assurance
HF	Hydrogen fluoride	QC	Quality control
ISO	International Organisation for Standardisation		
ITRC	Interstate Technology and Regulatory Council		

Refer to Appendix A for a glossary of key terms.

1. Introduction

1.1. Overview

Per- and poly-fluorinated alkyl substances (PFAS) are a group of manufactured chemicals. There are thousands of different PFAS, which have been used throughout the world since the 1950s. Due to their resistance to grease, water, and heat, PFAS have been used for a wide range of products such as:

- non-stick cookware
- cleaning products
- fabric stain protection
- food packaging
- firefighting foams.

PFAS have never been manufactured in Australia. However, PFAS can enter the environment due to the use of PFAS-containing products.

Low concentrations of PFAS are present in the environment across Victoria (Sardina et al. 2019; EPA 2022). This is due to migration from diffuse non-point sources.

Further information about the concentrations of PFAS in the environment in Victoria; and the impacts to human health and the environment is provided:

- on the EPA webpage, Environmental information about PFAS
- in the EPA publication Summary of PFAS concentrations detected in the environment in Victoria (EPA publication 2049).

EPA has regulations (detailed below) to ensure that PFAS in soil is safely managed, transported and disposed. These are in line with the principles of the PFAS National Environmental Management Plan (PFAS NEMP), published by Heads of EPA Australia and New Zealand (HEPA 2020), which are revised from time to time.[1]

EPA takes a precautionary approach to PFAS as they are persistent, accumulative, and mobile. EPA advises Victorians to reduce their exposure to PFAS. Soils containing PFAS should be managed to minimise the risk of harm to human health and the environment. When managing PFAS, the following should be considered:

- Environment Protection Act 2017 (the EP Act)
- Environment Protection Regulations 2021 (the Regulations)
- other EPA guidance, as referred to on the EPA webpage About PFAS.

Under the Regulations, PFAS contaminated materials including soil and waste are classified as priority and reportable priority waste.

The Regulations require a person who has management or control of priority waste to take all reasonable steps to classify and consider alternatives to waste disposal for the priority waste. In instances where PFAS has resulted in land being contaminated land (as defined in the EP Act), the contaminated land duties under the EP Act apply.

Evaluation of treatment options should be undertaken in consideration of the preferred hierarchy of treatment and remediation options provided in the PFAS NEMP (HEPA 2020). The preferred treatment hierarchy starts with treatment of the PFAS-contaminated material so that it is destroyed, removed, or the associated risk is reduced so far as reasonably practicable. The PFAS NEMP also differentiates between on-site treatment, offsite treatment and disposal to landfill due to the potential impact of each of these activities (HEPA 2020). The treatment of PFAS-impacted waste may be subject to EPA approval under the EP Act and the Regulations.[2]

Notes

1. At the time of preparation PFAS NEMP 2.0 (HEPA 2020) was the current version. The draft PFAS NEMP 3.0 was undergoing public consultation.

2. The re-use of waste soil containing PFAS may require EPA approval subject to the conditions provided in an EPA designation or permission.

1.2. Purpose of the technical guide

The overall objective of this guide is to support the development and use of innovative PFAS soil treatment technologies.

It aims to achieve this objective by providing:

- a framework on protocols to assess the feasibility of, and validate the effectiveness of, PFAS soil treatment technologies
- guidance on approaches to demonstrate the effectiveness of PFAS soil treatment (both in-situ and ex-situ)
- clarity on EPA's expectations of the information to support EPA approval processes (such as permissions) for PFAS soil treatment.

This guide is a non-statutory guidance document which provides 'state of knowledge' information related to the feasibility assessment and validation of PFAS soil treatment technologies.

1.3. Guide scope

This guide provides information to support the development and use of PFAS soil treatment technologies. Guidance is provided on the feasibility assessment and validation of PFAS soil treatment technologies.

The guide does not address the following:

- Other solid waste spoil, such as sediment and biosolids.
- Solid industrial waste, such as construction and demolition waste (e.g. concrete).
- Wastewater, other than those wastewaters which may be generated as part of a soil treatment technology, such as leachates from soil washing.
- Contaminants other than PFAS.

While this guide has not been prepared to address the items above, the general framework and principles presented may be applicable to those scenarios. It is the duty holder's responsibility to assess whether different matrices require further treatment or management not considered in this document.

The guidance provided is applicable to:

- site-specific treatment
- temporary treatment facilities
- permanent treatment facilities
- a range of non-destructive and destructive soil treatment techniques,

What do we mean by treatment?

For this guidance document:

- treatment refers to the application of a specific technology to destroy, modify, immobilise and/or contain contaminants of concern in soil (in this case, PFAS)
- treatment does not refer to other more general contaminated soil management measures, such as excavation, stockpiling/storage and transport
- containment is considered to be long-term encapsulation in an area or facility with engineered containment measures (e.g. barriers)
- treatment uses technologies that may be considered and/or implemented as part of a site remediation approach. This guide focuses on the treatment technologies, but not other aspects related to the overall site remediation.

1.4. Users of the guide

This guide is intended to be used by people involved in preparing plans and EPA approval applications for the use of PFAS soil treatment technologies including:

- waste generators
- remediation contractors
- technology providers
- operators of treatment facilities
- environmental consultants
- environmental auditors
- project managers
- business case developers.

The information in this guide may also be of interest to others, such as:

- planners
- construction and development project managers
- environmental managers
- research and development organisations
- regulatory decision makers.

The 'state of knowledge' relevant to PFAS soil treatment is evolving. When using this guide, also consider relevant advances since its publication.

1.5. How to use this guide

This guide is intended to be used to support other EPA regulatory tools related to the treatment of soil containing PFAS.

It is divided into two main parts:

Part A (Chapters 2 to 3)	Part B (Chapters 4 to 6)
• Provides background information on PFAS and soil treatment technologies. • Explains how this guide interacts with relevant aspects of the Victorian and national environmental protection framework. • Introduces key concepts to be considered for validation of PFAS soil treatment approaches.	Identifies current best practice related to PFAS soil treatment technologies and approaches for: • planning and feasibility assessment; • treatability studies; • full-scale validation and verification; and • provides guidance on the information helpful to inform PFAS soil treatment approvals.

PART A

2. Overview of PFAS and soil treatment technologies

2.1. PFAS chemical family

Internationally recognised naming conventions have been developed to describe the classification of chemicals within the PFAS family (OECD 2021; ITRC 2022). There are two classes of PFAS:

- Polymer
- Non-polymer

The non-polymer PFAS are the class of PFAS most commonly analysed in environmental samples. They are associated with the most widely used PFAS-containing products, such as aqueous film forming foam (AFFF). They are also highly persistent in the environment (ITRC 2022). As such, the non-polymer PFAS are the focus of this technical guide.

The non-polymer PFAS include two sub-classes:

- Perfluoroalkyl substances
- Polyfluoroalkyl substances

These PFAS are further classified by groups and sub-groups. The classification of the main non-polymer PFAS is summarised in **Table 1**.

The most well-known non-polymer PFAS are:

- perfluorooctane sulfonate (PFOS)
- perfluorooctanoic acid (PFOA)
- perfluorohexane sulfonate (PFHxS).

PFOS, PFOA and PFHxS are part of the perfluoroalkyl acids (PFAAs) group within the perfluoroalkyl substances sub-class.

The perfluoroalkyl class also includes perfluoroalkyl ether carboxylic acids (PFECAs). PFECAs, are commonly referred to as 'Gen X' chemicals. The Gen X chemicals include hexafluoropropylene oxide (HFPO), dimer acid and HFPO dimer acid ammonium salt. Gen X PFAS are associated with the manufacture of PFAS products as replacements for PFOA.

The polyfluoroalkyl class includes fluorotelomer substances. These are potential sources of perfluoroalkyl carboxylic acids (PFCAs) in the environment (ITRC 2022). The main fluorotelomer substances are listed in Table 1. Other fluorotelomer PFAS include the polyfluoroalkyl phosphate diesters (diPAPs), including 6:2 diPAP and 8:2 diPAP. The diPAPs have been associated with grease- and water-repellent paper and cardboard (CL:AIRE 2023).

PFAS are also described based on the length of the fluorinated carbon chain as this can influence their behaviour and toxicity (ITRC 2022). PFAAs are formally categorised into short-chain and long-chain PFAS (OECD 2021) (**Table 1**).

Table 1. Classification of the most common non-polymer PFAS [1,2]

PFAS compound	Sub class	Group	Sub group	Fluorinated carbon chain length
Precursors & intermediates				
4:2 Fluorotelomer sulfonic acid (4:2 FTS)	Polyfluoroalkyl substances	Fluorotelomer substances	n:2 Fluorotelomer sulfonic acids (FTSAs)	4
6:2 Fluorotelomer sulfonic acid (6:2 FTS)				6
8:2 Fluorotelomer sulfonic acid (8:2 FTS)				8
10:2 Fluorotelomer sulfonic acid (10:2 FTS)			n:2 Fluorotelomer alcohols (FTOHs)	10
2-(N-ethylperfluoro-1-octane sulfonamido)-ethanol (N-EtFOSE)		Perfluoroalkane sulfonamido substances	Perfluoroalkane sulfonamido acetic acids	8
N-ethylperfluoro-1-octane sulfonamide (N-EtFOSA)				8
2-(N-methylperfluoro-1-octane sulfonamido)-ethanol (N-MeFOSE)				8
N-methylperfluoro-1-octane sulfonamide (N-MeFOSA)				8
N-Methyl perfluorooctane sulfonamido acetic acid (N-MeFOSAA)				8
N-Ethyl perfluorooctane sulfonamido acetic acid (N-EtFOSAA)				8
Perfluorooctane sulfonamide (FOSA)	Perfluoroalkyl substances	Perfluoroalkane sulfonamides (FASAs)		8
Terminal degradation products				
Perfluorobutanoic acid (PFBA)	Perfluoroalkyl substances	Perfluoroalkyl acids (PFAAs)	Perfluoroalkyl carboxylic acids (PFCAs)	4
Perfluoropentanoic acid (PFPeA)				5
Perfluorohexanoic acid (PFHxA)				6
Perfluoroheptanoic acid (PFHpA)				7
Perfluorooctanoic acid (PFOA)				8
Perfluorononanoic acid (PFNA)				9
Perfluorodecanoic acid (PFDA)				10
Perfluoroundecanoic acid (PFUnDA)				11
Perfluorododecanoic acid (PFDoDA)				12
Perfluorotridecanoic acid (PFTrDA)				13
Perfluorotetradecanoic acid (PFTeDA)				14

Table 1 continued

PFAS compound	Sub class	Group	Sub group	Fluorinated carbon chain length
Perfluoropropanesulfonic acid (PFPrS)			Perfluoroalkane sulfonic acids (PFSAs)	3
Perfluorobutane sulfonic acid (PFBS)				4
Perfluoropentane sulfonic acid (PFPeS)				5
Perfluorohexane sulfonic acid (PFHxS)				6
Perfluoroheptane sulfonic acid (PFHpS)				7
Perfluorooctane sulfonic acid (PFOS)				8
Perfluorononane sulfonic acid (PFNS)				9
Perfluorodecane sulfonic acid (PFDS)				10

Notes:

(light shading)	Short-chain PFAS as defined by OECD (2021)
(dark shading)	Long-chain PFAS as defined by OECD (2021)

1. Based on information in OECD (2021) and ITRC (2022).
2.Typical suite of PFAS analysed by commercial laboratories.

PFAS, in particular the PFAAs, are highly resistant to chemical and biological processes. Hence, they are stable and persistent in the environment (CRC CARE 2018; ITRC 2022). The highly stable nature of PFAAs is related to the strength of the carbon-fluorine bonds in the chemical structure (CRC CARE 2018; ITRC, 2022).

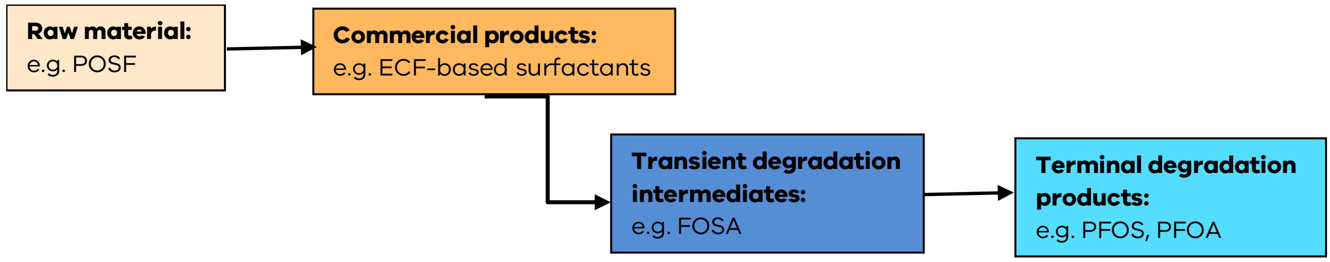
The short-chain PFAS are typically more water-soluble. As such, they are more likely to be mobilised in soil with the introduction of water, such as rainfall (CRC CARE 2018; ITRC 2022). Conversely, the long-chain PFAS have a high tendency to bind to clay minerals and organic matter in soil and are, hence, less likely to be mobilised.

In the environment, PFAS are present as mixtures of different PFAS. These mixtures can be related to the components of the original commercial PFAS product/s, degradation products and precursors related to degradation of PFAS.

Polyfluoroalkyl PFAS typically represent the key components of raw materials used for the manufacture of commercial PFAS products. Polyfluoroalkyl PFAS are also key precursors that degrade to PFAA's terminal degradation products, such as PFOS and PFOA (ITRC 2022). Polyfluoroalkyls and some perfluoroalkyl PFAS (e.g. perfluorooctane sulfonamide (FOSA)) are considered to be transient degradation intermediates, related to the degradation of raw PFAS materials into terminal degradation products.

Example of PFAS raw material degradation to terminal degradation products

The degradation of a PFAS material to terminal degradation products is illustrated below. This example details the degradation for perfluorooctane sulfonyl fluoride (POSF), a PFAS material produced from the electrochemical fluorination (ECF) process (ITRC 2022).



2.2. Soil treatment technologies

The PFAS NEMP (HEPA 2020) provides guidance on treatment techniques to destroy, remove and/or contain PFAS in contaminated materials, including soil.

The PFAS NEMP (HEPA, 2020) states that the availability, practicability, and feasibility of treatment options is to be considered when evaluating options for PFAS treatment/remediation. The treatment options should be considered in the context of the preferred hierarchy of treatment and remediation options listed in the PFAS NEMP (HEPA, 2020):

1. Separation, treatment and destruction;
2. On-site encapsulation (with or without immobilisation); and
3. Off-site removal to a specific landfill cell (with or without immobilisation).

The preferred treatment hierarchy starts with treatment of the PFAS-contaminated material so that it is destroyed, removed, or the associated risk is reduced so far as reasonably practicable. There are a range of treatment technologies related to separation, treatment and destruction. These are the primary focus of this technical guide.

The waste management and treatment hierarchy is discussed further in Section 4.3.

General information on available PFAS soil treatment technologies is provided in the following documents:

- ITRC (2022) PFAS Technical and Regulatory Guidance Document.
- PFAS NEMP (HEPA 2020).
- CRC CARE (2018) Technical Report No. 43. Practitioner guide for risk-based assessment, remediation and management of PFAS site contamination.

Further information on PFAS soil treatment technologies is available from scientific review publications. Examples of review publications are:

- Ross et al. (2018)
- Bolan et al. (2021)
- Berg et al. (2022).

The available PFAS soil treatment technologies can be applied in-situ (that is treating soil in its original position) and/or ex-situ (that is excavating soil from its original position for treatment) (Ross et al. 2018; Bolan et al. 2021; ITRC 2022).

To meet overall remediation/treatment targets, it is typically necessary to combine multiple treatment technologies, such as in a treatment train (Ross et al. 2018; Bolan et al. 2021; ITRC 2022).

PFAS soil treatment technologies can be divided into two major categories: destructive and non-destructive. They key features and examples of the two main categories of PFAS soil treatment technologies are summarised in **Table 2**.

Table 2. Key features of destructive and non-destructive PFAS soil treatment technologies [1]

	Key features of treatment	Examples of treatment technologies
Destructive treatment	• PFAS are destroyed or defluorinated to lower-toxicity compounds • Treatment is usually through physiochemical or thermal treatment	• Thermal: - Desorption and destruction - Incineration - Smouldering/combustion • Physiochemical: - Oxidation-reduction - Ball milling
Non-destructive treatment	• Treatments only reduce total and/or available concentrations of PFAS in a medium without changing their chemical composition • Treatment may move PFAS from one medium to another (i.e. from soil to water) • Treatments reduce the potential for PFAS migration by separation and/or immobilisation	• Immobilisation: - Sorption/stabilisation • Separation/extraction: - Soil washing - Electrokinetic - Phytoremediation • Physical separation: - Containment - Capping

1. Based on information in Ross et al. (2018), Bolan et al. (2021), and ITRC (2022).

The example treatment technologies identified in **Table 2** are detailed further in Appendix B, including:

- details of the treatment processes
- advantages
- disadvantages.

2.3. Treatment mechanisms

The different treatment technologies identified employ a range of specific mechanisms to **destroy**, **transform** and/or **control** PFAS in soil.

The main destructive and non-destructive mechanistic actions to treat PFAS in soil are summarised in **Table 3**

Table 3. Summary of PFAS soil treatment mechanisms [1]

Mechanism	Description
Destructive treatment mechanism	
Chemical oxidation	Transformation of PFAS by hydroxyl radical and other strong oxidants
Chemical reduction	Use of solvated electrons, generated using ultraviolet (UV) light to initiate the defluorination process, such as by cleaving carbon fluoride bonds adjacent to functional groups of the PFAS
Electrochemical	Electrochemical oxidation of PFAS to cleave carbon fluoride bonds
Incineration/thermal degradation	Destruction of PFAS by oxidation (catalytic and thermal) following thermal desorption
Sonochemical oxidation/ultrasound	Use of acoustic waves to achieve localised thermal treatment and free radical destruction
Mechano-chemical destruction	Mechanical energy is used to create a chemical reaction to destroy PFAS
Biological	Use of biological agents, such as microorganisms to break down PFAS
Non-destructive treatment mechanisms	
Sorption/complexation	Sorption/complexation to organic carbon, minerals and other molecules
Stabilisation/solidification	Encapsulation of contaminant to form a solid and restrict the movement of water through the soil/solid media
Separation/size fraction	Physical mechanism of separating soil by particle size, or use of water to physically separate solid and liquid phases
Phytoextraction	Use of plants and associated microorganism to remove and/or degrade PFAS.
Containment	Use of physically engineered barriers to contain soils impacted by PFAS. Use of reactive barriers to restrict migration of leachable PFAS

1. Adapted from information in Bolan et al. (2021), Deeb et al. (2021) and ITRC (2022).

3. How this technical guide interacts with the Victorian environment protection framework

This section outlines how this technical guide aligns with the Victorian environment protection framework and existing national-level best-practice guidance, relevant to the management and treatment of PFAS-impacted soils.

3.1. Overview

EPA Victoria is an independent statutory authority. The laws and regulations we operate under include the *Environment Protection Act 2017* and Regulations, and other instruments made under the EP Act.

3.2. State of knowledge

'State of knowledge' is all the information you should reasonably know about managing the risk(s) of your activity. EPA has developed a range of guidance documents designed to help duty holders understand their obligations under the EP Act and Environment Protection Regulations. Guidance can be found on EPA Victoria's website.

Information on the state of knowledge as it relates to the general environmental duty (GED) is provided in Industry guidance: supporting you to comply with the general environmental duty (EPA publication 1741.1).

A note about international conventions, directives and best practices

International conventions, directives and best practice guidance may be considered when meeting obligations under the EP Act, as they could represent current 'state of knowledge'.

Examples of international conventions, directives and best practice guidance that may need to be considered in relation to PFAS soil treatment are:

- The Stockholm Convention on Persistent Organic Pollutants (POPs), which includes PFOS, its salts and PFOS related chemicals
- Guidance on best available techniques and best environmental practices for the use of PFOS, PFOA, and their related substances listed under the Stockholm Convention (2021)
- European Union (EU) Industrial Emissions Directive (IED) 2010/75/EU
- EU Best Available Techniques reference documents (BREFs)
- ITRC (2022) PFAS Technical and Regulatory Guidance Document, Interstate Technology Regulatory Council (ITRC), Washington DC, USA
- Deeb et al. (2021) Guidance Document: Lines of evidence and best practices to assess the effectiveness of PFAS remediation technologies. Strategic Environmental Research and Development Program (SERDP), Virginia, USA.

3.3. EPA approvals for soil treatment

3.3.1. Permission scheme

The implementation of a PFAS soil treatment approach may require EPA approval through the permissions scheme established under the EP Act and Regulations.

The permissions scheme is described in Permissions scheme policy (EPA publication 1799.2). Further information on permissions is available on EPA Victoria's website.

Key items that EPA take into account when determining whether to issue a permission related to soil treatment are presented in Table 4. For other matters not listed in Table 4 would also be considered by EPA, refer to EPA's Permissions webpage for further information.

Community and stakeholder engagement may be required as part of the permissioning process.

Where PFAS containing soil is transported and treated at another site, EPA approvals and permissions may be required to transport the reportable priority waste related to soil treatment. Information on obligations when moving waste from place to place is available on the EPA Victoria's webpage, Transporting waste.

Table 4. Key items that EPA take into account when determining whether to issue a permission (pilot project licence, development licence, operating licence) for soil treatment.

Key item	Description
Measures to comply with the general environmental duty (GED)	The GED requires anyone engaging in any activity that may give rise to risks of harm to human health of the environment from pollution or waste, to minimise those risks, so far as reasonably practicable. Guidance on how to determine what is reasonably practicable is provided in Reasonably practicable (EPA publication 1856). Refer to EPA webpage Understanding your environmental obligations for further information on the GED and other duties related to environment protection.
The impact of the activity on human health and the environment	Refer to EPA webpage Manage your environmental risk for guidance on managing the risks activities may pose to human health and the environment. Specific guidance on the assessment of risk of harm to human health and the environment is provided in the PFAS NEMP (HEPA 2020).
Principles of environment protection	Part 2.3 of the EP Act details the 11 principles of environmental protection that are central to Victoria's legislative environment protection framework.
Best available techniques or technologies (BATT)	Information on BATT in relation to Licences is provided in EPA Victoria's website. Further information is provided in Development licence application guidance (EPA publication 2011).

3.3.1.1. How do I obtain an approval?

Information on how to obtain an approval is provided on EPA webpage Check if you need a permission, and in Permissions proposal pathway guideline (EPA publication 1995).

Depending on the nature of the soil treatment activities undertaken (including whether they are undertaken on-site or off-site), different permissions and/or waste designations may be required. Different permissions may be required for different stages of the soil treatment process.

If you are not sure what type of permission you might need, you can complete and submit a Permission pathway form.

Completing the permission pathway process is not compulsory. It is free and it is there to help you to prepare your final permission application. It is also not a formal or legal decision.

Once soil treatment has been completed, it may also be necessary to surrender a permission for the prescribed activity. Information is available on EPA's website on how to surrender your licence or permit.

3.3.2. Environmental audits and verification

Consideration should be given to the need to engage an EPA-appointed auditor for the soil treatment.

Under the EP Act, EPA appoints environmental auditors to allow them to conduct environmental audits where they are engaged by a person to undertake an environmental audit and perform certain legislative and prescribed functions under the Regulations.

Environmental audits are performed by EPA-appointed environmental auditors. The purpose of an environmental audit as set out in the EP Act is to:

- assess the nature and extent of the risk of harm to human health or the environment from contaminated land, waste, pollution or any activity
- recommend measures to manage the risk of harm to human health or the environment from contaminated land, waste, pollution or any activity
- make recommendations to manage the contaminated land, waste, pollution or activity.

In conducting an environmental audit, the EPA-appointed environmental auditor may independently review and verify any contaminated soil remediation and/or treatment. This will be dependent on the purpose and scope of the environmental audit.

In addition to environmental audits, an EPA-appointed environmental auditor may perform other actions in relation to the treatment of contaminated soils. This may include independently verifying actions and measures to comply with:

- a remedial notice (e.g. improvement notice, prohibition notice, environmental action notice)
- a site management order (SMO)
- condition(s) of a permission
- guidelines issued by the EPA under the EP Act.

PART B

4. Planning for PFAS soil treatment

When planning for soil treatment, regardless of the contaminant(s) of concern, the chosen treatment technology (or technologies if using a treatment train approach) should include a feasibility assessment. Further, the end product(s) should be fit for purpose for the intended use/end-point.

This section provides information on key aspects that should be considered and documented in developing a treatment approach related to PFAS soil technologies. These key aspects are broadly applicable to both site-specific treatment approaches and soil treatment facilities (which treat soil from various sources).

The following documents provide useful guidance on the development of a treatment approach for contaminated soil:

- National Remediation Framework (CRC CARE 2019a–h)
- PFAS NEMP (HEPA 2020)
- Practitioner guide for risk-based assessment, remediation and management of PFAS site contamination (CRC CARE 2018)
- Australian Standard AS ISO 18504:2022 Soil quality – Sustainable remediation (Standards Australia 2022)

4.1. Understanding risk of harm to human health and the environment

A key step in planning a treatment approach is to understand the hazard and risk that the treatment is intended to address (CRC CARE 2018; CRC CARE 2019a). This should define the specific risks of harm to human health and/or the environment.

For a site-specific scenario, this will typically be determined through an evaluation of risk, such as a Tier 1 screening level risk assessment or Tier 2 site-specific risk assessment. Guidance on conducting Tier 1 and Tier 2 risk assessment is provided in the National Environment Protection (Assessment of Site Contamination) Amendment Measure 2018 (No. 1) (ASC NEPM) (NEPC 2013) and PFAS NEMP (HEPA 2020).

In accordance with the waste management duties and the general environmental duty (GED) in the EP Act, the assessment of risk should consider factors relevant to the specific soil treatment and management response. For example, if the soil is to be treated for re-use, then risks to human health and the environment associated with the specific re-use setting should be evaluated.

The risk assessment should characterise the scenarios that potentially present a risk of harm to human health and the environment. This should then be used to define the treatment objectives (refer to Section 4.2).

The risks should also be considered in relation to the source of the contamination. This will assist in identifying the specific PFAS and co-contaminants of concern. Information on considering the source/s of PFAS is provided in PFAS NEMP (HEPA 2020), ITRC (2022) and CL:AIRE (2023).

Guidance on characterising risk of harm to inform PFAS treatment objectives is provided in:

- PFAS NEMP (HEPA 2020)
- ASC NEPM (NEPC, 2013)
- enHealth (2012a) Guidelines for assessing human health risks from environmental hazards
- enHealth (2012b) Australian exposure factor guide

- enHealth (2019a) Fact sheet: revised enHealth Guidance statements on per- and poly-fluoroalkyl substances (PFAS)
- enHealth (2019b) Per- and poly-fluoroalkyl substances (PFAS) health effects and exposure pathways
- CRC CARE Practitioner guide to risk-based assessment, remediation and management of PFAS site contamination (CRC CARE 2018)
- PFAS Technical and Regulatory Guidance Document (ITRC 2022).

4.2. Treatment objectives

It is important to define the objectives for the treatment of contaminated soil. Guidance on establishing treatment objectives is provided in the PFAS NEMP (HEPA 2020) and National Remediation Framework (CRC CARE, 2019a).

In relation to soil treatment, the objectives should be defined based on what the overall treatment approach aims to achieve in relation to:

- reducing the risk of harm to human health and the environment in relation to the contamination
- meeting requirements for the intended management of the treated soil
- meeting the requirement of the EP Act and Regulations.

The objectives should include specific and measurable endpoints, so that the effectiveness of the treatment can be validated following implementation. It may be necessary to define several objectives for multistage treatment approaches.

In defining the objectives, it may also be necessary to consider and nominate numerical treatment criteria to be met. For contaminated soil treatment, this may include:

- industrial waste classification and categorisation thresholds
- site-specific risk-based criteria.

The need for and nature of numerical treatment criteria should be determined on a case-base-case basis. Where significant PFAS are present beyond PFOS, PFHxS and PFOA treatment objectives for those other PFAS may be required. EPA assesses PFAS for which there are no regulatory criteria on a risk basis. Further information on approaches to assessing risks for PFAS beyond PFOS, PFHxS and PFOA, is provided in PFAS NEMP (HEPA 2020).

Notes about PFAS treatment criteria

Industrial waste classification:

In relation to soil, classification of the waste must be determined by schedule 5 of the Environment Protection Regulations and waste codes (IWRG 822.4). The Guide to classifying industrial waste (EPA publication 1968.1) steps through the process for classifying industrial waste. The classification is as per Waste disposal categories – characteristics and thresholds (EPA publication 1828.2) and any designations issued by EPA. Further information about Waste classification is provided on the EPA website.

Site-specific risk-based levels:

The PFAS NEMP (HEPA, 2020) and the National Remediation Framework (CRC, 2019a-h) provide guidance on establishing and adopting site-specific risk-based levels as treatment (or remediation) end-points.

Site-specific risk-based levels can be numerical criteria based on site- (or scenario-) specific considerations. They should be informed by site- (or scenario-) specific risk assessment and requirements for the intended end use of the treated soil.

4.3. Waste management and treatment hierarchy

The waste management hierarchy is one of the principles of environment protection in the EP Act. EPA will have regard to the principles of the waste management hierarchy when administrating the EP Act. This includes in relation to soil contaminated by PFAS.

The PFAS NEMP (HEPA 2020) provides a preferred hierarchy of treatment options, including a preference for on-site treatment over off-site treatment.

The waste management and soil treatment hierarchies are detailed in **Table 5**. These hierarchies should be considered in developing soil treatment strategies.

Table 5. Waste management and soil treatment hierarchies

Waste management hierarchy, order of preference [1]	
Avoidance	
Re-use	
Recycling	
Recovery of energy	
Containment	
Waste disposal	
PFAS NEMP soil treatment hierarchy, order of preference [2]	
1. Separation, treatment and destruction	On-site or off-site treatment of PFAS-contaminated material soil that it is destroyed, removed, or associated risk is reduced to an acceptable level
2. On-site encapsulation	Encapsulated in constructed stockpiles or engineered storage and containment facilities, with or without chemical immobilisation
3. Off-site removal to a specific landfill cell	Removal of PFAS-contaminated material to a specific landfill cell. This may or may not include immobilisation prior to landfill disposal

1. Environment Protection Act 2017, Part 2.3 Principles of environmental protection
2. PFAS NEMP (HEPA 2020)

Documented plans for treatment approaches, such as within a remediation action plan or any application to the EPA for a Permission for the treatment of soil containing PFAS or related activity (if required), should detail the various options considered in determining the preferred treatment approach being proposed. This should include a summary of the following:

- Consideration of the principles of environment protection in the EP Act.
- Consideration of PFAS waste management and treatment hierarchy (Refer to Table 5)
- Treatment options analysis. (Refer to Section 4.6)
- Overall rationale and decision making to support the preferred treatment option.

Information should be provided to explain how the principles of environment protection have been considered across the whole treatment approach.

4.4. Key principles and technical factors for treatment and management

PFAS have unique properties, which presents challenges for soil treatment (HEPA 2020; ITRC 2022; CL:AIRE 2019) due to the:

- relatively high resistance of some PFAS to physical, chemical and biological processes (such as PFOS, PFOA, PFHxS)
- solubility and mobility of some PFAS in the environment (such as PFOS, PFOA, PFHxS)
- potential for production of other PFAS during the treatment process (such as the transformation of precursors)
- potential generation of additional contaminated by-products (such as hydrogen fluoride, HF).

The PFAS NEMP (HEPA 2020) outlines the key aspects that should be considered when selecting PFAS remediation and management options.

These aspects are summarised in **Table 6** and should be considered when setting treatment objectives/targets, undertaking treatment options assessments, and developing the overall treatment strategy.

Table 6. Key aspects for considering PFAS soil remediation and management options [1]

Aspect	Description
Proportionate to risk	Selection of an option should be proportionate to the risks being managed.
Sustainability of option (costs and benefits)	When deciding which option to choose, the sustainability (environmental, economic and social) of each option should be considered in term of achieving an appropriate balance between benefits and effects. A cost-benefit analysis may be undertaken to inform the options assessments.
Suitability and practicality of options	The suitability and practicality of implementing treatment/remediation options should be considered, such as: • management of waste materials/streams • availability of space, services and resources at the treatment site • potential for undesirable effects associated with the treatment.
Views of affected communities and jurisdictional regulators	Stakeholders' views will contribute to a comprehensive understanding of the context and potential impacts of options.
Availability of the best treatment or remediation technologies	Best available techniques should be considered based on what options are practicable and feasible for the specific site/scenario.
Site-specific issues	The appropriateness of any site-specific option will vary depending on a range of local factors.
Effectiveness of technology as demonstrated by destruction efficiency or the reduction in PFAS concentration (total and/or leachable) and/or mass.	This should be considered when choosing an option in combination with appropriate remediation/treatment criteria. Reduction in PFAS concentrations (total and/or leachable) and/or mass should be considered.
Treatment strategy	The selection of a remediation approach should consider the preferred hierarchy for treatment and remediation in combination with other contaminants that may pre-present. It may be important to consider a multistage treatment (also referred to as a treatment train).
Validation	Consideration should be given to independent validation of the treatment or remediation outcomes, to determine whether the measures of success (including remediation objectives) have been achieved.
Understanding PFAS precursors and transformation products	Some treatment process transform precursors, creating an apparent increase in PFAS following remediation. Understanding the range of potential PFAS present, including precursors, is also necessary to identify all contaminants of potential concern.

1. Adopted from information in PFAS NEMP (HEPA 2020)

In addition to the key principles for PFAS treatment, there are key technical factors related to PFAS that should be considered in evaluating the suitability of soil treatment options (see **Table 7**).

Table 7. Key technical factors for PFAS soil treatment [1]

Factor	Description
Target PFAS and characteristics of PFAS	It is important to understand the specific PFAS that are the target for treatment, as this may influence the suitability of different treatment options. This includes: • an understanding of the PFAS present, how they relate to the degradation pathway from the original source contamination and the presence of precursors • an understanding of the chemical and physical characteristics of the target PFAS, such as the chain length, strength of carbon-fluorine bonds and types of ionic groups.
PFAS transformation	The application of treatment processes can cause PFAS to be transformed into different: • PFAS (e.g. destruction of precursors into degradation products) • media/phases (e.g. from soil to water) • by-products of PFAS degradation (e.g. fluorine) This may occur as a direct result of the treatment (e.g. destruction of carbon-fluorine bonds from thermal treatment), or indirectly due to changes in physical-chemical properties of soil (e.g. transfer of PFAS from solid to aqueous phase during soil washing treatment). It is important to understand transformations as this may influence the overall target PFAS for treatment.
PFAS mass-balance	As treatments can result in transformations of PFAS, it is important to understand how the whole treatment process is decreasing, and/or managing the overall mass-balance of PFAS. For non-destructive techniques, such as immobilisation, PFAS mass-balance may be considered in the context of reduced leachable PFAS.
Treatment mechanism	In the context of the properties and potential transformations of target PFAS, it is important to understand the intended mechanistic actions of specific treatment techniques.
Co-contaminants	The presence of co-contaminants in the soil should be considered as this may influence the: • behaviour of PFAS (e.g. elevated concentrations of organic compounds (e.g. petroleum hydrocarbons) in soil may occupy binding sites in immobilisation sorbents intended for PFAS). This may alter the application rate and/or type of amendment required for immobilisation. • whether treatment and/or management of other contaminants is required to meet the overall remediation objectives/targets (e.g. concentrations of hydrocarbons associated with fuels and oils may be exceeding priority waste thresholds, and may also require treatment to meet the desired end use of the treated soil).

Table 7 continued

Factor	Description
Soil characteristics	The specific physical-chemical characteristics of the soil to be treated may influence the suitability of different treatment technologies. For example, soil washing may not be suitable for soils with a high clay content, as PFAS sorbed to the clay minerals may not be easily 'washed' out.
Soil treatment waste by-products	Soil treatment technologies may produce by-products that require treatment and/or management. For example, soil washing produces wastewaters containing PFAS and fines from particle separation that require management. The anticipated by-products should be considered at the planning phase for the remediation strategy and when evaluating available options.
Characteristics of soil following treatment	PFAS soil treatment techniques can significantly alter the characteristics of the soil. This should be considered, as it may influence the post-treatment management options for the soil. For example, thermal treatment significantly alters the physical and biological characteristics of the soil. This may impact the suitability of the treatment material for plant health and/or the geotechnical suitability for engineering functions.

1. Based on information in CRC CARE (2018), Deeb et al (2021) and ITRC (2022).

4.5. Best available techniques or technologies

Depending on the nature of the soil treatment activity a Permission may be required for the activity. For example, under the EP Act and the Regulations off-site storing, treatment, reprocessing, containing or disposing of reportable priority waste (transport) such as PFAS containing material,. requires an operating and development licence.[1]

When determining whether to issue a development licence, operating licence or pilot project licence, the authority, EPA Victoria, must consider the best available techniques or technologies (BATT), along with other matters (see Table 4).

BATT can be understood as the most effective and advanced stage in the development of activities and their methods of operation. This should consider the technology readiness of the BATT. For example, has the technique/technology been demonstrated to be effective at the required scale, and is it commercially viable? Information that may be included in licence applications in relation to state of knowledge on BATT is provided in Development licence application guidance (EPA publication 2011).

Published guidance material and technical notes from regulators, government and independent organisations may be used to inform state of knowledge related to BATT.

1 Assuming that all the other requirements of item 1 of Schedule 1 of the Regulations are met.

Some examples of guidance material and technical notes that may be relevant to PFAS soil treatment are:

- Guidance on best available techniques and best environmental practices for the use of PFOS, PFOA and their related substances listed under the Stockholm Convention
- European Union (EU) Industrial Emissions Directive (IED) 2010/75/EU
- European Union (EU) Best Available Techniques reference documents (BREFs)
- CRC CARE Practitioner guide to risk-based assessment, remediation and management of PFAS site contamination (CRC CARE, 2018)
- National Remediation Framework (CRC CARE, 2019d-g)
- PFAS Technical and Regulatory Guidance Document (ITRC 2022), including Table 12-2 Solids technologies – remediation technologies and methods comparison
- Guidance document: Lines of evidence and best practices to assess the effectiveness of PFAS remediation technologies (Deeb et al. 2021)
- Stabilisation and solidification of contaminated soil and waste: A manual of practice (Bates and Hills 2015)
- A review of emerging technologies for remediation of PFASs (Ross et al. 2018).

Refer to EPA's website for further information on state of knowledge and industry guidance.

4.6. Treatment options assessment

A key aspect to the planning for soil treatment is conducting a thorough options assessment.

General guidance on conducting a treatment options assessment is provided in:

- Australian Standard AS ISO 18504:2022 Soil quality – Sustainable remediation (Standards Australia 2022)
- National Remediation Framework (CRC CARE 2019b)
- Practitioner guide to risk-based assessment, remediation and management of PFAS site contamination (CRC CARE 2018)
- Federal Remediation Technologies Roundtable (FRTR) website (https://www.frtr.gov/default.cfm).

Information on PFAS treatment technology specific considerations when evaluating remediation options is provided in the ITRC (2022) and in scientific review publications (e.g. Ross et al. 2018; Mahinroosta and Senervirathna 2020; Bolan et al. 2021; Berg et al. 2022).

The options assessment should consider:

- the available PFAS soil treatment technologies (Section 2)
- key aspects of the Victorian legislative framework (Section 3)
- risk of harm to human health and the environment (Section 4.1)
- waste management and PFAS treatment hierarchies (Section 4.3)
- key principles for PFAS remediation and management (Section 4.4)
- key technical factors for PFAS treatment (Section 4.4)
- suitability and practicality (Section 4.4)
- sustainability and cost-benefit (Section 4.4).

The options assessment should consider a range of different treatment technologies and strategies (e.g. multi-treatment trains). The different options should be considered in relation to:

- how well they are likely to meet the overall treatment objectives
- other key factors, such as regulatory requirements and stakeholder needs.

The options assessments should include a rating system to enable the various options to be compared to each other. AS ISO 18504:2022 Soil Quality – Sustainable remediation provides information on various rating systems including:

- qualitative
- semi-quantitative
- quantitative.

The options assessment may also include a cost-benefit analysis, which includes environmental, economic and social factors. Guidance on conducting cost-benefit analysis is provided in:

- AS ISO 18504:2022 Soil Quality – Sustainable remediation
- National Remediation Framework – Guideline on performing cost-benefit and sustainability analysis of remediation options (CRC CARE, 2019b)
- Federal Remediation Technologies Roundtable (FRTR) website (https://www.frtr.gov/default.cfm) – Decision Support Tools.

4.7. Technology readiness level

A key component to evaluating the feasibility of a preferred treatment approach is the demonstrated maturity and availability of the technology to be adopted.

A technology readiness assessment should be undertaken as part of the feasibility assessment. This can involve consideration of the technology readiness level (TRL) (e.g. US Government Accountability Office 2020; Berg et al. 2022; ITRC 2022).

The TRL relates to how far a treatment technology has matured to be able to:

- effectively treat PFAS-contaminated soil (i.e. conceptual to mature technology) (as shown in ***Table 8***)
- quantify impacts of PFAS and PFAS by-products produced during treatment
- adopt proven available measures to control PFAS and its associated health and environmental risks during processing
- meet regulatory approval requirements.

TRLs describe increasing levels of technical maturity based on demonstrable capabilities. (US Government Accountability Office 2020; Berg et al. 2022). The TRL should consider available information on applicability and feasibility of implementation (e.g. constructability).

The TRL should also be considered when applying a mature technology for a new treatment scenario.

TRLs may be described as any of the following:

- Conceptual
- Development and demonstration
- Full-scale deployment
- Mature technology

These TRLs are described further in Table 8.

Assignment to TRLs depends on the available information on the:

- scope
- technology design

- effectiveness of the technology (as demonstrated by data)
- measures to control risks and safety.

(Environment Canada 2012; US Government Accountability Office 2020; Berg et al. 2022):

Table 8. Technology readiness levels [1]

Technology readiness level	Scope and design of the technology	Demonstration data	Environmental and health risk management
Conceptual	Technology concept formulated and tested at the laboratory/bench scale: • Experiments in a limited and controlled environment	Proof of concept: • Reviewed by theory and limited planning.	Conceptual understanding of risks. High uncertainty about controls to manage risks.
Development and demonstration	Pilot-scale: • Demonstration with limited scale, dimension, purpose, and duration in controlled environment	Theory in practice by research and development: • Reviewed by practical demonstration through feasibility assessment (supported by pilot-scale data).	Demonstrated understanding of key risks. Limited risk management controls implemented.
Full-scale deployment	Full-scale application of technology deployed • No limit to the scale, dimension, and duration	Technology verification: • Reviewed with treatment validation and demonstrated data.	Detailed understanding of risks and risk management controls. Data collected to validation and refine risk management controls.
Mature technology	Widely used, proven technology: • Off the shelf • Demonstrated effectiveness at various facilities/sites	Fully-developed engineering technology: • Reviewed with treatment validation and demonstrated data, and all related equipment efficiencies.	High confidence in risks. Effectiveness of risk management controls are well proven.

1. Based on information in safety (US Government Accountability Office2020; Berg et al. 2022; ITRC 2022).

Further guidance on conducting a technology readiness assessment is provided in:

- Technology readiness assessment guide – Best practices for evaluating the readiness of technology for use in acquisition programs and projects (US Government Accountability Office 2020)
- Environmental Technology Verification, General Verification Protocol (GVP): Review of Application & Assessment of Technology (Environment Canada 2012).

Information in the literature on specific technologies can be used to support an evaluation of the TRLs. Some useful resources are:

- the US EPA PFAS Thermal Treatment Database (PFASTT) database. This database includes records on the scope and effectiveness of various thermal treatment processes. The records provided in the database include scientific journal articles, government reports and conference reports. Each record provides details on the test scale (i.e. laboratory, pilot or full), which can be used to inform a technology readiness assessment.
- ITRC PFAS Technical and Regulatory Guidance document (https://pfas-1.itrcweb.org/).
- This provides details on various PFAS soil treatment technologies, including an evaluation rating of the maturity of technology.

These are example of resources; other resources should be considered where appropriate.

Information to support technical readiness level assessment

The table below provides a summary of the type of information that could be used to support a technical readiness level assessment.

Evidence	Description
Scientific basis	Information to support that the proposed technology is based on sound and demonstrated science. Consideration of available and relevant scientific information, focusing on ensuring current best-practice has been identified and considered. Consideration of the scientific basis through guidance documents, technical reports and journal articles.
Case studies	Clear and relevant case study information should be provided to show that the proposed technology has been demonstrated as suitable for other similar such applications.

4.8. Management of treated soil and by-products

As part of the planning for soil treatment it is important to consider the requirements for managing treated soil and by-products from the treatment process (CRC CARE 2018; CRC CARE 2019a-h). This should include how the following will be managed:

- The treated soil/material.
- By-products and additional waste streams produced as a result of the treatment (such as liquids generated from soil washing or combustion by-products from thermal treatment).

This should include an understanding of the waste duties as they relate to your proposed activity. Further information on waste duties can be found on the EPA Victoria website. This includes information on:

- how to classify industrial wastes other than soil
- management of industrial wastewater.

The risk of harm to the human health and the environment from any residual contaminants should be considered. This is of relevance where soil is to be treated in-situ and/or treated material is to be re-used on-site. This may require the development of a risk management and monitoring program (RMMP). This should include details of how the residual risks will be managed and monitored and the contingency actions if/when the conditions change.

Other environmental, geotechnical or engineering specifications required to meet the intended post-treatment management of waste streams should also be defined. These specifications should be incorporated into the treatment/remediation objectives (see Section 4.2 for details).

Refer to the following resources for further information on managing the risk of harm to human health and the environment:

- Guide to the duty to manage (EPA publication 1977.1)
- Implementing the general environmental duty (EPA webpage)
- How to manage environmental risk (EPA webpage)

Refer to EPA webpage, Permissions, for further information on permissions that may apply to the management of treated soil.

5. Treatability studies

Treatability studies may assist in confirming the feasibility of a selected technology for full-scale application (CRC CARE 2019d-g; Deeb et al. 2021). Conducting treatability studies may assist with:

- evaluating the ability of the proposed treatment technologies to meet the required purpose and objectives of the treatment
- refining the treatment process to optimise treatment effectiveness/efficiency
- helping industry and regulators to determine whether a technology is effective and fit for purpose
- defining data gaps and uncertainties to be addressed through further research, treatability studies or full-scale treatment design elements
- understanding technology process for validating treatment technologies from laboratory/bench-scale to pilot-scale to full-scale.

A treatability study typically involves conducting trials under various treatment conditions to evaluate the technology's effectiveness. Effectiveness is evaluated by collecting data from various stages/locations of the treatment process. This can include collection and analysis of samples as wells as other lines of evidence.

Treatability studies can be undertaken at different treatment scales, as outlined in **Table 9**.

The need for and scale of the treatability study should be determined on a case-by-case basis. This should be informed by the planning stage of the feasibility (see Section 4).

Treatability study requirements should be based on the type and technology readiness level of the treatment approach (see Section 4.7). For example, laboratory and pilot-scale treatability studies may not be required for mature and proven technologies. Technologies that are conceptual and/or developing are more likely to require laboratory and/or pilot-scale treatability studies to confirm feasibility.

Table 9. Differences between laboratory/bench, pilot and full-scale treatment

Treatment scale	Description
Laboratory/bench-scale treatment or small-scale	Treatment studied within a laboratory under controlled conditions. Undertaken to test proof of concept under a range of treatment parameters or to determine the best treatment methods to use in a specific, small-scale case.
Pilot-scale	Treatment studied at a scalable treatment process/system that is likely to progress to full or commercial scale. Typically undertaken using a prototype system and/or through field studies. Undertaken to refine the proof of concept and optimise treatment performance.
Full-scale implementation	Treatment undertaken using a full-scale process/system. Testing undertaken to confirm proof of performance of as part of commissioning the process/system.

The key steps for undertaking a treatability study are:

1. defining the purpose of treatability study
2. treatable PFAS and other contaminants
3. influence of physical-chemical soil properties
4. treatment mechanism/technology/process
5. trial study design and methodology
6. sampling plan
7. evaluating performance.

Guidance on the treatability study steps is provided in the sub-sections below. This includes key principles and information relevant to a variety of different technologies.

5.1. Purpose of treatability study

It is important to understand and document the purpose of the study. This should include how this links to the defined objectives for the full-scale treatment.

Laboratory/bench-scale or small-scale studies are typically undertaken to test a wide range of treatment parameters. This enables the key parameters to be refined before the best treatment method is chosen for a specific case on a small-scale basis. Laboratory/bench-scale or small-scale studies are conducted under highly controlled conditions.

Pilot studies, requiring a Pilot Project Licence (refer section 5.5: Limits to scale, dimension, and duration for pilot-scale treatability studies), can be conducted at various scales and complexities, to progress a full-scale or commercial operation. They are generally undertaken to test and demonstrate the outcomes from the bench-scale study using treatment approaches more representative of actual full-scale conditions.

Table 10 provides an overview of the purpose of laboratory/bench or small-scale studies, and pilot-scale treatability studies for selected treatment technologies.

Table 10. Overview of purpose of treatability studies for selected treatment technologies [1]

Treatment technology	Laboratory/bench or small scale	Pilot scale	Best practice treatability study resources
Immobilisation	• Assess effectiveness of various sorbents' formulations • Test treatment-sorbents' combination and rate optimisation • Evaluate longevity of immobilisation • Assess effectiveness of treatment using soils representative of full-scale (e.g. soil type, contaminant concentrations) • Assess ability to immobilise the relevant range of PFAS species (e.g. short-chain versus long-chain)	• Further evaluate most successful treatment formulations (sorbents and dosage) from bench testing • Evaluate treatment and mixing effectiveness using full-scale treatment equipment/processes • Refine process for full-scale treatment • Confirm performance criteria for full-scale or commercial treatment	CRC CARE (2019d) ITRC (2011) Bates and Hills (2015) Sleep and Juhasz (2021) Kabiri and McLaughlin (2021) McDonough et al. (2022) Navarro et al. (2023)
Soil washing	• Assess effectiveness of various particle separation techniques • Assess effectiveness of various soil washing reagents • Soil washing optimisation tests • Evaluate the contaminant mass-balance • Assess effectiveness of treatment using soils representative of full-scale (e.g. soil type, contaminant concentrations) • Assess residual total and leachable PFAS in fines	• Further evaluate most successful treatment conditions from bench testing • Obtain further information to design full-scale treatment system • Confirm contaminant mass-balance and water balance • Pilot-scale study typically conducted using a pilot-scale test system	CRC CARE (2019e) CL:AIRE (2007) Grimison. et al. (2023) Quinnan et al. (2022)

Table 10 continued

Treatment technology	Laboratory/bench or small scale	Pilot scale	Best practice treatability study resources
Thermal desorption and destruction	• Assess treatment effectiveness at different temperature conditions and residence times • Assess effectiveness of treatment using soils representative of full-scale (e.g. soil type, contaminant concentrations) • Obtain preliminary performance data for off-gas treatment systems • Assess a wide range of PFAS and breakdown products in the emissions • Assess the suitability of the treated soil for potential post-treatment management options (e.g. due to chances to the physio-chemical and biological characteristics of the soil)	• Further evaluate most successful treatment conditions from bench testing • Obtain further information to design full-scale treatment system	CRC CARE (2019f) Barranco et al. (2020) Weber et al. (2021) Weber et al. (2022)

Note: These are examples of different treatment technologies. Other options treatment options are possible, refer to Section 2.2.

5.2. Treatable PFAS and other contaminants

A clear description of the PFAS being targeted for treatment should be documented (ITRC 2022; Deeb et al. 2021). This should be described in the context of the PFAS chemical family, as outlined in Section 2.1 and include:

- precursors and intermediates
- transformation products
- terminal degradation products.

The PFAS NEMP (HEPA 2020) has further information on how to define the target PFAS for treatment. This includes guidance on considering PFAS source characterisation to identify the PFAS likely to require treatment.

The target PFAS for treatment should be identified in the context of the treatment objectives and criteria defined for the proposed treatment approach (refer to Section 4.2).

A clear understanding of the contamination status of the soil for treatment should be established to define the target PFAS for treatment. This can be achieved through sampling and analysis of the soil to be treated. This may be through contaminated site investigation works or for waste classification purposes. Refer to Appendix C for further information on sampling and analysis.

Specific details on the contamination status of the soil may not be known at the treatability study stage. In such cases, it is necessary to identify the contamination status and the types of soils expected to be subject to full-scale treatment. This is so that the treatability study can be designed in a way to accommodate the nature of contaminated soil sources that will be subject to full-scale treatment.

For treatment facilities that are to receive waste soil from various sources, information should be documented as to:

- how the target PFAS for each treatment batch will be determined
- how variability in feedstock has been considered during the feasibility assessment stage.

Soil treatment technologies for PFAS have known limitations (see Section 2 and Appendix B). It is important to understand the limitations of a specific technology/approach as part of the feasibility assessment. This is to ensure that the proposed technology can achieve the overall treatment objectives.

The description of the target PFAS should identify any PFAS that the treatment technology is not intending to target (or not capable of treating) (Deeb et al. 2021). Details of co-occurring contaminants present in the soil to be treated should also be provided. This should include whether the proposed treatment technology is intended to treat these co-occurring contaminants and waste materials.

Examples about describing target PFAS for non-destructive and destructive techniques

Non-destructive: Immobilisation

Some immobilisation amendments are less effective at immobilising short-chain PFAS, compared with long-chain PFAS (e.g. activated carbon, biochar). Other amendments (e.g. carbon/mineral blends, organoclays) are more effective at immobilising short-chain PFAS (Kabiri and McLaughlin 2021; Sleep and Juhasz, 2021). Known limitations in immobilisation effectiveness as identified from specific treatability trials should be acknowledged and described.

Destructive: Thermal desorption and destruction

PFAS volatilise from soils at temperatures in the range of 350 – 650°C (e.g. Barranco et al. 2020; Sorengard et al. 2020; ITRC 2022). Destruction of the PFAS in the off-gas from thermal desorption requires temperatures greater than 850°C (Ross et al. 2018; Barranco et al. 2020; Bolan et al. 2021; Weber et al. 2023).

The EU Directive 20010/75/EU on industrial emissions has specific requirements for flue gas treatment containing volatilised substances. The directive states that if hazardous waste with more than 1% of halogenated organic substances (expressed as chlorine), is incinerated (or co-incinerated) then the temperature to volatilise the organic substances is at least 1,100°C with a two-second residence time.

As such, the **content of halogenated organic substances in the soil** should be considered when determining the optimal treatment conditions for a thermal treatment system. This is because a higher temperature may be required to achieve the required destruction efficiency for both PFAS and the halogenated organic substances in the off-gas.

5.3. Influence of physical-chemical soil properties

An understanding of the physical-chemical properties of the soil to be treated is important. This is because these may influence the feasibility of different treatment techniques (CRC CARE 2019d-g; Bolan et al. 2021; ITRC 2022).

The feasibility assessment should consider the influence of physical-chemical soil properties and soil types on the effectiveness of the treatment techniques proposed.

Examples of how different physical-chemical soil properties may influence the feasibility of soil treatment techniques are provided in **Table 11**.

Table 11. Examples of physical-chemical properties of soil that may influence feasibility for selected non-destructive and destructive soil treatment techniques [1,2]

Soil property/factor	Non destructive		Destructive
	Immobilisation	Soil washing	Thermal desorption and destruction
Particle size	Immobilisation is suitable for a range of different soil types. Some soil types, such as soils with high clay content may require pre-treatment to reduce the particle size prior to treatment. This may influence the type of mixing equipment required for the immobilisation treatment.	Soil washing is generally best suited to coarse material (i.e. >0.2 to 2mm particle size). Pre-treatment of soils may be required to separate finer fractions (e.g. clays, silts). The fines from pre-treatment may contain residual PFAS concentrations, requiring treatment.	Thermal treatment of soils with various particle sizes or big lumps may affect the uniformity of heat distribution. To make the soil homogeneous, crushing and removing the oversized particles may be required.
Moisture content	Immobilisation treatment requires some soil moisture to activate the sorbents. If soil is too dry, sorbents may not be activated. If soil is too wet, the sorbents may not be effectively retained in the soil.	May affect performance of physical separation and processes to dissolve contaminants in water. Soil washing typically requires an optimum soil:water ratio. Higher moisture content soils are generally more suited to soil washing. Wet/saturated soils may require different treatment approaches.	The moisture content of the soil influences the heat and energy cost required to vaporise water. The heat and energy required increases with increases moisture content.

Table 11 continued

Soil property/factor	Non destructive Immobilisation	 Soil washing	Destructive Thermal desorption and destruction
Organic carbon/organic matter content (i.e. natural organic carbon)	Organic contaminants can sorb to organic carbon in soil, which may assist in reducing leachable PFAS. However, relatively high organic content in soil may compete for binding sites on immobilisation sorbents. It is noted that most Australian soils contain relatively low organic carbon content (<5%) (https://www.soilquality.org.au)	Contaminants sorb to organic material in soil. Soil washing may not be suited to soils with high organic content, as this may impede the ability to wash contaminants from soil.	The organic carbon/organic matter content of the soil may influence the energy inputs required for thermal treatment. Thermal desorption and destruction is suitable for soils with a wide range of organic carbon/matter contents. Thermal treatment significantly reduces the organic carbon/organic matter content of the soil. This may impact on the suitability of the soil for post-treatment uses.
pH	Soil pH is a key factor that may influence contaminant retention mechanisms associated with immobilisation sorbents. Amendment of soil pH may be required to achieve optimum immobilisation.	Soil pH is a key factor influencing contaminant desorption mechanisms. Amendment of pH may be required to optimise contaminant desorption during washing.	Soil pH is not a key factor influencing suitability for thermal treatment. Management of pH levels during treatment may be required to control the pH in the treated material. For example, during thermal treatment, soil pH may decrease at low temperatures due to breakdown of organic acids, but this can be buffered by carbonates (Vidonish et al. 2016).
Permeability	Low-permeability soils may impede the distribution of the treatment sorbents for in-situ treatments.	Low-permeability soils may impede the distribution of the soil wash water.	Low-permeability soils may impede the distribution of heat and vapour migration through the soil.

Table 11 continued

Soil property/factor	Non destructive Immobilisation	 Soil washing	Destructive Thermal desorption and destruction
Soil heterogeneity	Immobilisation treatment is most effective in soils with uniform particle size. Pre-treatment may be required to remove extraneous material (e.g. rocks), grind soil to even particle size and improve homogeneity of the soils. The heterogeneity of the soil may influence the type of mixing equipment required for the immobilisation treatment.	Chemical extraction as part of the washing process is most effective in soil with uniform particle sizes as this provides even distribution of the chemical extractant. Pre-treatment may be required to physically separate different particle sizes.	Variability in grain sizes can affect the uniformity of heat distribution. Large particles >50mm may require pre-treatment to improve homogeneity.

1. Based on information in CL:Aire (2011), Bates and Hills, (2015); CRC CARE (2019d-g), ITRC (2020), Bolan et al. (2021), Kabiri et al. (2021), Sleep and Juhasz (2021), US EPA (2021), Berg et al. (2022) and Kumar et al. (2022).
2. These are examples of different treatment technologies; other options treatment options are possible, refer to Section 2.2.

5.4. Treatment mechanism/technology/process

The mechanism(s) and technologies for the treatment process should be defined in relation to:

- the target contaminants for treatment
- control measures to reduce risks to human health and the environment (e.g. from emissions).

The description of the treatment mechanism(s) and process(es) should be refined as the treatment process progresses from laboratory/bench-scale or small-scale to pilot-scale or full-scale.

5.4.1. Treatment mechanism

A description of specific treatment mechanisms for the proposed treatment approach should be provided. For example, oxidation, reduction, separation, or biological treatment.

Information should be provided to demonstrate that the treatment mechanisms are plausible. This may include relevant scientific literature, case studies and/or information from prior treatability studies.

It is acknowledged that some treatment of PFAS may occur because of non-mechanistic artefacts of the treatment approach. This means that PFAS may be removed, transformed or contained due to general soil processing steps rather than the action of the specific treatment technology. Where this is likely to occur, a statement should be provided to explain these non-mechanistic actions and the extent to which these may contribute to achieving the treatment objectives.

For example, immobilisation treatment involves application of sorbents to reduce leachable concentrations of PFAS by binding to the solid phases of the soil. The addition of the sorbent can impede the ability for total PFAS concentrations to be accurately recovered. This is because standard laboratory soil analytical methods are not able to extract as much of the total PFAS in soils with sorbents added, compared to those without. This may make it appear that leachable concentrations have been decreased due to a decrease in total PFAS concentrations.

Example treatment mechanisms for a non-destructive and a destructive treatment technology

Non-destructive

Immobilisation treatment involves the application of treatment sorbents to the soil. The sorbents act by immobilising the PFAS via various sorption interactions. This includes between the PFAS, constituents of the sorbents and components of the soil. The specific mechanism will vary depending on the treatment sorbents used. The treatment sorbents are not intended to destroy or transform the PFAS. Detailed descriptions of specific immobilisation treatment mechanisms are provided in the scientific literature (e.g. Lath et al. 2018; Bolan et al. 2021; Sleep and Juhasz 2021, Kabiri et al. 2022).

Destructive

Thermal desorption and destruction treatment works by applying heat to desorb PFAS from soil and increase the volatility of PFAS. The PFAS is destroyed through heat treatment of the off-gases collected, which breaks down the carbon-fluorine bound in the PFAS. The specific destructive treatment mechanism varies based on the types of treatment technologies and processes employed. Detailed descriptions of thermal treatment mechanisms are provided in the scientific literature (e.g. US EPA PFAS Thermal Treatment Database).

5.4.2. Treatment process

While appropriate steps in the treatment process will be determined by whether the treatment is occurring on site, off-site or as disposal to landfill, all steps should be clearly described. Steps in the treatment process could include:

- pre-treatment waste classification
- ensuring any Permissions required for off-site transport are in place
- ensuring any Permissions required by the receiving site (i.e. at a Lawful place) are in place
- ensuring any Permissions required for the on-site activities are in place
- pre-treatment steps
- specific PFAS treatment processes/technologies
- emission-control technologies (e.g. to treat and/or control flue-gas, dust, odour, stormwater runoff, leachate)
- details of treatment equipment and plant to be used
- treatment and management of by-products, additional waste streams and other contaminants
- post-treatment management
- how the PFAS will be transferred between different phases (e.g. solid, liquid, air) and how this will be tracked (e.g. through sampling and analysis)
- critical control points (CCPs)
- points in the process where samples will be collected to support demonstration of effectiveness and validation of treatment objects. This should include points within the treatment process to demonstrate effectiveness of specific treatment steps. Sampling points required to characterise and/or classify waste streams/by-products from the treatment should also be identified.

The process flow description could be supported by a graphical representation of the treatment process, such as:

- **block flow diagram** (BFD): Simple process flow diagram to understand the basic structure of a system/process. Block flow diagrams break up a complicated system into more reasonable main stages/sectors.
- **process flow diagram** (PFD): Indicates the general flow of plant processes and equipment. PFDs should show:
    - relationships between major equipment
    - inputs (e.g. waste feedstock, raw material, chemical sorbents/reagents, heat)
    - outputs (e.g. treated soil, by-products, emissions)
    - potential emission sources (e.g. stacks, discharge points)
    - physical environmental controls (e.g. biofilters)
    - flowrates, temperatures, pressures, and critical process conditions.
- **piping and instrumentation diagram** (P&IDs): This is a detailed diagram, which shows the piping and process equipment **together with the instrumentation and control devices**.

The basics and types of diagrams (in order of complexity) are described further in Turton et al. (2008).

5.5. Trial methodology

The treatment trial methodology should be designed on a case-by-case basis. This is to ensure:

- it meets the purpose and objectives of the trial
- required data/information is collected to enable performance to be evaluated.

An overview of the key elements to be considered in designing a treatability trial is provided in Table 12. These key elements broadly relate to on-site treatment, temporary mobile treatment and fixed treatment facilities.

Table 12. Key elements for treatability trial design [1]

Treatability study element	Description
1. Study objectives	The specific objective of the treatability trial should be documented. The objectives should be based on the identified purpose of the treatment study (refer to Table 10). The treatability trial study objectives should also relate to how these objectives will be evaluated and demonstrated. Note: Treatability studies and trials during a small-scale or pilot-scale study are only considered as demonstration projects with limited volumes of wastes to be treated solely for purposes of the treatability study and are not a full-scale activity.
2. Study area/facility	Detail where the treatability study will be conducted, such as project site or premises. This should be supported by a site location and layout plan.
3. Treatment groups/batches	A key purpose for all treatability studies is to evaluate performance under varying parameters. This is so that the optimum full-scale treatment conditions can be determined. As such, the study design should include different experimental 'treatment groups (or batches)'. Treatment groups/batches can be based on a combination of varying: • soil types • contaminant concentrations • treatment 'settings' (for example sorbent rates for immobilisation, operation parameters for thermal treatment). The treatment groupings/batches should be structured in a manner to enable statistical evaluation of the results from the treatability study. For continuous treatment systems it may be necessary to collect data at different stages and/or time-periods for the process to enable 'treatment groups/batches' to be evaluated.
3.1. Soil types	The soil to be used in the treatability study should be representative of the main soil types anticipated to be subject to the full-scale treatment. Experiment treatment groups/batches should be formed based on different soil types and key soil properties. Refer to Section 5.3 for information on physical-chemical soil properties that may influence performance of different treatment technologies.

Table 12 continued

Treatability study element	Description
3.2. Contaminant concentrations	The soils to be used in the treatability study should be representative of the range of contaminant concentrations anticipated to be subject to treatment. The experiment treatment groups/batches should be formed based on a range of contaminant concentrations. This is important as the treatment technology/approach may perform differently at differing contaminant concentration ranges. As a minimum, the experiment grouping should include: • samples representative of the maximum anticipated concentration for treatment • samples representative of the average or typical anticipated concentration for treatment.
3.3. Treatment settings/process variables	Experiment treatment groups/batches should be formed based on different treatment settings/process variables to be tested. For example, this may be different sorbent types and concentrations for immobilisation treatment, or different temperatures and residence times for thermal treatment. Initial screening treatability experiments could be conducted to understand the key treatment process variables influencing treatment performance.
4. Replication/repeatability	The treatment study design should include replication to evaluate the reproducibility of the treatment performance and statistical significance between experiment treatment groups. As a minimum, the study should include duplicates for the experimental treatment groups/batches. Increasing the number of replicates and repeated experiments increases the confidence in the results from the study.
5. Volume of soil to be treated	The total volume of soil proposed to be treated in the study should be specified. For pilot-scale studies, the volume of soil to be treated should be justified in relation to the number of treatment batches considered necessary to demonstrate the study objectives.
6. Treatment batches	The treatability study design should specify how many different treatment batches are proposed and the rationale for this. The number of batches should be sufficient to enable consistency in the treatment approach to be evaluated. For example, multiple treatment batches are typically required for pilot-scale studies to treat the same soil types. This will provide reasonable data to demonstrate the efficacy of the treatment process for treating the particular soil type. The number of treatment batches required for pilot-scale studies should be considered in the context of the volume of treated material that will require management on a commercial scale.

Table 12 continued

Treatability study element	Description
7. Duration of treatment trial	The overall anticipated duration of the treatability study should be specified. This should relate to the number of treatment batches considered necessary to achieve the study objectives. For a pilot scale study requiring a licence, the maximum duration of a pilot project licence is five years.
8. Treated soil and waste management	Details should be provided on how the treated soil and other wastes generated from the study will be managed. This is important for pilot-scale studies where larger volumes of treated soil and waste are likely to be generated. For pilot-scale studies, a treated soil management plan (TSMP) can be prepared.
9. Dust, air emissions. Leachate and effluent	Details should be provided on how the dust, air emissions, leachate and effluent from the treatment/processing facility will managed.
10. Preparation of soils to be used in the trial	Consideration should be given to how the test soils in the trial will be selected and prepared. The preference is to use representative samples of actual soils to be subjected to full-scale treatment (e.g. field-collected soils). This is because the soils are more representative of the actual composition and field-aged nature of the contaminant. Replicate treatment test soils will typically be created by splitting up bulk test soils into the required test aliquots. As such, the bulk test soils will typically require pre-treatment to sufficiently homogenise them prior to splitting into test aliquots. The methodology, and rationale, for preparation of soils to be used in the trials should be documented. This could be documented in a sampling and analysis plan.
11. Sampling and analysis plan	A clearly-defined sampling and analysis plan is a critical component of trial design. Collection and analysis of samples during the trial treatment process should be undertaken to gather data to enable the performance of the treatment to be evaluated. Further information on sampling and analysis plans is provided in Section 5.6 and Appendix C.

Table 12 continued

Treatability study element	Description
12. Quality control	Quality control samples should be incorporated into the study design to support the integrity and confidence of the study results. The quality control samples may include: • sorbent/reagent blanks (e.g. to assess concentrations of contaminants of concern in any sorbents/reagents introduced during treatment) • sorbent/reagent application verification samples (e.g. to assess homogeneity of sorbent/reagent mixing) • equipment/handling rinsate blanks (e.g. to assess cross contamination during the treatment) • sample replicates (e.g. to assess the accuracy and precision of sample collection and analysis).
13. Evaluating performance	The trial design should consider and document how the performance of the treatment process will be evaluated. This should include how the results from sampling and analysis, and other lines of evidence, will be used to demonstrate performance. The trial design should also consider how statistical differences between different experimental treatment groups/batches will be determined. This should include consideration of mass balances appropriate to the technology/treatment approach being used. Performance evaluation should also include how the treated soil meets overall objectives for the intended end use. For example, consideration of physical-chemical and/or geotechnical parameters that related to the intended use of the treated soil. Further information on evaluating performance is provided in Section 5.7 and mass-balance considerations in Section 5.8.
14. Evaluating success of treatability study	The treatability study design should consider how the success of the overall study will be evaluated with demonstratable data gathered during the study. This should consider how well the study has met the stated objectives. This is an important consideration in the context of the duration of the treatability study.
15. Risk assessment and contingency planning	Treatability studies are typically testing new technologies, processes and/or scenarios. As such, consideration should be given to the possibility of unplanned events and emergencies. A risk assessment should be undertaken to identify and assess risks to human health and the environment while conducting the trial/study. This should identify risk management controls. A contingency plan should also be developed. The contingency plan should also consider how batches of soil that do not meet the required treatment specifications will be managed.

1. Based on information in: Bates and Hills (2015), CRC CARE (2019d-g), and Deeb et al (2021).

Limits to scale, dimension, and duration for pilot-scale treatability studies

Pilot-scale treatability studies are typically undertaken using treatment processes/systems and volumes of contaminated soil likely to be applied at full-scale or commercially. As such, they may require EPA permission to proceed.

Under the EP Act 2017, EPA may issue a Pilot project licence where a development licence, operating licence or permit is required for an activity. These licences are intended to allow duty holders to demonstrate technology, process and monitoring environmental performance via a pilot-scale study prior to proceeding to a full-scale commercial operation.

A key consideration that EPA must take into account when issuing a pilot project licence is being satisfied that the activity (technology or technique) is for research, development or demonstration. To meet this requirement the pilot project needs to have clearly defined limits in relation to scale, dimension and duration. This is because EPA must only issue pilot project licences for research development or demonstration activities. Further permissions would be required for full-scale commercial operation.

The key aspects that EPA considers in relation to limits to scale, dimension and duration include the following:

- The project should not be considered as mini-commercial operations or as a chance to develop a commercial market.
- The pilot project is not to be used for ongoing operations.
- The scale and duration of the pilot project is consistent with the pilot project objectives.
- The duration of the pilot project should be defined and normally expected to be months rather than years.
- Continuous operations over long periods may not be appropriate, for example where the objective is to test a single process.
- The duration of the pilot project should be justified in the context of the number of different processes and feedstocks to be trialled and the data required to meet the pilot project objectives.

5.6. Sampling and analysis plan

A sampling and analysis plan should be prepared as part of the treatability study. This should identify and document the sampling to support evaluation of treatment performance. The sampling and analysis plan should be informed by the description of treatment process (refer to Section 5.4) and link to the study/trial objectives (refer to Section 4.2 and 5.1).

The specifics of the sampling and analysis plan will vary depending on the technologies or techniques being used and the purpose and objectives of the study/trial.

The extent of sampling and analysis will generally be greater for bench trials relative to pilot-scale trials. This is to evaluate the specific treatment mechanism/s and to refine the key parameters influencing treatment performance.

The key components of a treatability trial sampling and analysis plan, taken from the PFAS NEMP, are outlined in **Table 13**. Further considerations for sampling and analysis are provided in Appendix C.

Table 13. Key components of a sampling and analysis plan for a treatability study

Sampling and analysis plan component		Description
Data quality objectives (DQOs)		The sampling and analysis plan should identify and document the DQOs for the study. These are qualitative and quantitative statements that define the type, quantity and quality of data to inform decisions from the treatability study. For example, this may include statements on the data required to meet the statistical confidence level requirements for decision making. Further information on defining DQOs is provided in Schedule B2 of the ASC NEPM (NEPC 2013).
Sample collection points	General	Different sample collection points within the treatment process should be nominated. This is to collect multiple lines of evidence data for evaluating treatment performance. The specific sampling points will vary depending on the technology, treatment process and treatability study design. However, the most common types of sample collection points are detailed further below. The nominated sampling points should be identified on process flow diagrams for the treatability study.
	Pre-treatment	Representative samples of the nominated treatment groups/batches should be collected prior to commencing of any treatment steps. This is to establish the baseline soil condition prior to application of the treatment process. This may require sampling different soil fractions to establish a suitable baseline for evaluating performance. For example, soil washing is based on separating soil into differing particle size fractions (e.g. gravel, sand, silt, clay), which are presumed to have differing contaminant statuses. As such, the baseline contamination concentration in different soil fractions may be needed for true comparisons post-treatment.
	Post-treatment	Collection of representative samples following the treatment process is critical to determine overall treatment performance (i.e. comparison to pre-treatment). Post-treatment samples will typically be collected when all treatment processes have been applied, so the samples are representative of fully-treated material. As in pre-treatment, this may require sampling different soil fractions.

Table 13 continued

Sampling and analysis plan component		Description
Sample collection points (continued)	Within treatment process	Samples should be collected within the treatment process to help evaluate the performance of specific steps and treatment mechanisms. This should be based on the critical control points for the treatment process as identified in the overall treatment process and associated process diagrams (see Section 5.4). The within-treatment-process sampling points may be related to different physical treatment steps. For example, in relation to soil washing, samples may need to be collected at the following points in the process: following physical separation following a chemical-extraction step steps related to the treatment of the liquids produced from the washing.
	Treatment process inputs	It may be necessary to collect samples of additional resource inputs into the treatment process (i.e. beyond the contaminated soil to be treated). For example, this may be any process waters and/or sorbents/reagents required as part of the treatment process. Sampling of these treatment process inputs may be required to confirm that they are not introducing contaminants into the treatment process.
	Treatment by-products	The plan should consider collection of samples of treatment by-products. This will typically be required where these by-products require specific management as part of the overall treatment approach. The common by-products requiring sampling are: • wastewaters • leachates • air emissions and dust • solids (e.g. ash, soil screenings).

Table 13 continued

Sampling and analysis plan component	Description
Sampling frequency/density	The sampling plan should define the number of samples to be collected from each sampling point, for each treatment batch and for each treatability trial proposed. The sampling frequency should be sufficient to meet the requirements of statistical analysis methods to evaluate performance of the treatment process and between different treatment groups in the trial. This should be informed by the data quality objectives. The sampling density should also consider the heterogeneity of the soil. This is to ensure the sampling provides a sufficient representation of the variability in the soil. It can be useful to present the proposed sampling frequencies in a tabulated format in relation to the sample collections points and treatment groups/batches. The sampling plan should detail whether the samples will be collected as discrete and/or composite samples. Discrete sampling is preferred, however there are situations where composite sampling may be appropriate. Composite sampling requires representative sub-subsamples to be combined in a single sample for analysis. Composite sampling is generally considered not suitable for: clay or fine-grained soils, due to difficulties in homogenising samples volatile contaminants, due to the increased potential for losses during compositing. Refer to Appendix C for further information.
Sample collection methods	The sampling plan should detail the specific methods to be used for sample collection. This should include the physical methods and techniques for collecting the samples. The sampling plan should also identify whether samples will be collected as discrete and/or composite samples. Further information on sample collection methods is provided in Appendix C.

Table 13 continued

Sampling and analysis plan component	Description
Sample analysis	The sampling plan should clearly define the analytical suite(s) to be adopted for the various samples to be collected. This should include the contaminants to be analysed for and any other parameters consider important for interpretating the results of the treatability study (e.g. physical-chemical soil properties). The analytical suite should be based on the treatable PFAS and other contaminants (see Section 5.2). For PFAS, the analytical suite should be considered in the context of the treatment objectives and key lines of evidence for evaluating treatment performance. This may require consideration of: • the composition of the PFAS mixture (i.e. not just the regulated and targeted PFAS) • precursors • intermediates • terminal degradation products • transformations of PFAS during the various treatment steps. The collected samples should be analysed at a laboratory accredited for the relevant tests by the National Association of Testing Authorities Australia (NATA) or an equivalent accreditation body in accordance with Sampling and analysis of waters, wastewaters, soils and wastes (EPA publication IWRG701). Note: Duty holders are strongly encouraged to contact the EPA if a NATA-accredited laboratory cannot be engaged for relevant tests.

Table 13 continued

Sampling and analysis plan component	Description
Quality Assurance/Quality Control	The sampling plan should outline the quality assurance (QA) and quality control (QC) actions, procedures and monitoring to ensure the accuracy and reliability of the analytical results. The QA/QC requirements should be determined on a case by-case basis specific to the purpose of the sampling and analysis and treatability trial to be undertaken. The following QA/QC measures should be considered: • Sample containers and preservation methods. • Decontamination procedures (e.g. cleaning of re-useable sampling equipment). • Sampling handling and delivery to laboratories, including chain of custody procedures. • QC samples, (e.g. duplicate samples, split samples, trip blanks, field blanks, rinsate samples). • Analytical laboratory requirements including NATA-accreditation and laboratory QA/QC requirements. • Data quality assessment approach including data quality indicators (DQIs). Refer to Appendix C and the following documents for further information on QA/QC: • Sampling and analysis of waters, wastewaters, soils and wastes (EPA publication IWRG701) • Soil Sampling (EPA publication IWRG702) • ASC NEPM (NEPC 2013) • PFAS NEMP (HEPA 2020)
Additional parameters to be monitored	In addition to the collection and analysis of samples, it may be necessary to monitor other parameters in the treatment process to support the evaluation of treatment performance. This additional monitoring should be documented in the sampling plan. Additional monitoring parameters may be: • settings within treatment system (e.g. temperature, residence time) • visual inspections of physical soil screening and sorbent/reagent mixing steps • resource inputs (e.g. energy and water inputs) • performance of emission-control technologies • environmental monitoring of dust, leachates, stormwater runoff as part of pilot-scale trials.

Tabulation of sampling and analysis plans

An overview of the monitoring and sampling plan for the treatability study may be provided in a tabulated format. This may be particularly useful for pilot-scale studies to detail the sampling/monitoring points in relation to the treatment process. The treatment process can be to treat one batch or multiple batches of the same waste. An example table template for a monitoring and sampling plan is provided below.

Process	Sampling point location	Indicator measured	Monitoring type like air emission (dust, stack testing, continuous emissions monitoring system (CEMS), effluent, solids)	Monitoring frequency or number of samples taken

5.7. Evaluating performance

Upon completion of treatability trials and studies, the performance of the treatment technology and approach should be evaluated (CRC CARE 2019d-g). This can be achieved by analysing the monitoring and sampling data collected from treatability trials relative to the purpose and objectives of these trials and overall treatability study.

Demonstration of the performance of the treatability trials and studies should be presented in relation to multiple lines of evidence to support the attainment of treatment objectives. Information on the lines of evidence for different treatment technologies is provided in this section including:

- primary lines of evidence (Section 5.7.1)
- secondary lines of evidence (Section 5.7.2).

5.7.1. Primary lines of evidence

The primary lines of evidence relate to the treatment efficiency of the technology and approach used. Treatment efficiency refers to the efficiency (or effectiveness) of the treatment to destroy, remove, reduce or contain the target contaminant(s).

The treatment efficiency is typically presented in relation to the concentration of target PFAS for treatment. This can be in relation to the PFAS in the solid phase and/or leachable fraction, depending on the treatment approach. PFAS can transform into different PFAS, or associated degradation products, during treatment. As such, it may also be important to consider the total PFAS concentration, leachable PFAS and PFAS mass depending on the treatment technology/approach. Further considerations for total PFAS and mass-balance are provided in Section 5.8.

Primary lines of evidence are also used to confirm that the treatment efficiency observed is related to the intended treatment mechanism and not due to artefacts of the treatment process (e.g. due to dilution from sorbent addition).

The primary lines of evidence for evaluating treatment performance and treatment efficiency should be determined on a case-by-case basis specific to the treatment technologies used. **Table 14** provides an overview of key examples of primary lines of evidence for different treatment technologies.

The key primary lines of evidence for evaluating treatment performance should be centered around quantifying the treatment efficiencies relevant to the technologies used.

Examples of commonly used equations to quantify treatment efficiency for different technologies are provided in Appendix D.

Table 14. Examples of key primary lines of evidence for evaluating performance of different treatment technologies [1]

<table>
<tr><th rowspan="2">Treatment technology</th><th colspan="2">Evidence to demonstrate effectiveness of soil treatment of effect on treated soil</th></tr>
<tr><th>Total PFAS (i.e. solid phase) evidence</th><th>Leachable PFAS evidence</th></tr>
<tr><td>Immobilisation</td><td>Technology is not intended to reduce total PFAS concentrations in solid phase. Some reduction in concentrations may occur as an artefact of the laboratory process (i.e. common solvent extraction for total PFAS analysis may not desorb all of the PFAS from the amendment).

Evidence should quantify extent of dilution from treatment sorbents on total contaminant concentration/mass.</td><td>Evidence should quantify the reduction in leachable contaminant concentration/mass to demonstration effectiveness of immobilisation.

This could include appropriate lines of evidence to support the longevity of the immobilisation (i.e. potential desorption of PFAS). This could include:
• description of the soil conditions that would need to change to result in desorption of PFAS; including the likelihood of this occurring for the intended post-treatment management of the soil.
• results from leachability test methods designed to evaluate longevity of immobilisation, such as multi-batch leaching tests (see Appendix C; Sleep and Juhasz 2021; Rayner et al. 2022).</td></tr>
<tr><td>Soil washing</td><td>Evidence should quantify reduction in total concentrations/mass due to treatment.</td><td>Evidence should quantify reduction in leachable concentration/mass due to treatment. The leachable concentration/mass in the fines from the separation phase should also be quantified.</td></tr>
<tr><td>Thermal</td><td>Evidence should quantify reduction in total concentrations/mass due to treatment.</td><td>Evidence should confirm leachable concentrations for residual contaminant for waste classification and/or re-use (if required).</td></tr>
<tr><td>Containment (engineered barriers)</td><td>Technology is not intended to treat total PFAS concentrations in solid phase, so no evidence is possible.</td><td>Evidence should quantify the anticipated reduction in leachate generation associated with capping.

Evidence should be provided on the efficacy of barrier elements to contain the PFAS in leachate.

Include evidence to demonstrate serviceable design life and/or long-term performance of the barrier system.</td></tr>
</table>

1. Note: These are examples of different treatment technologies, other options treatment options are possible, refer to Section 2.2.

5.7.2. Secondary lines of evidence

The secondary lines of evidence relate to indirect measurements to evaluate the overall performance and efficiency of the treatment system (i.e. beyond the target treatable contaminants).

This should include evidence of the resource inputs that are intended to be used for the implementation of the treatment process. The types of resource inputs that require evidence to be demonstrated are summarised in **Table 15**.

Implementation of contaminated soil treatment technologies involves the appropriate environmental management of emissions and by-products (e.g. additional waste streams produced). This may include using specific emission-control technologies/treatment systems, or more generally through environmental management controls. **Table 15** provides an overview of the key emissions/by-products considerations, and associated evidence to support treatment performance for different technologies.

Other secondary lines of evidence may include QA/QC results/documentation and results from the monitoring of other treatment system parameters.

Table 15. Key secondary lines of evidence for evaluating performance for different treatment technologies [1]

Treatment technology	Resource inputs used	Evidence for emissions/by products			
		Wastewater	Waste solids	Air emissions	Noise emissions
Immobilisation	Sorbents	Treatment does not typically generate wastewaters requiring treatment. If stormwater runoff requires management, demonstrate attainment of performance targets for stormwater management.	Treatment does not typically generate waste solids.	Treatment process may generate dust (e.g. grinding, mixing): demonstrate attainment of performance targets for dust control.	Demonstrate attainment of performance targets for noise control for mixing equipment Follow Noise limit and assessment protocol (EPA publication 1826.4)
Soil washing	Water Energy Reagents	Attainment of performance targets for wastewater streams. Confirmation of waste classification for wastewater streams.	Attainment of performance targets for waste solids (by-products). Confirm waste classification of waste solids (by-products).	Treatment process may generate dust (e.g. physical separation steps): demonstrate attainment of performance targets for dust control.	Demonstrate attainment of performance targets of noise control for washing equipment. Follow Noise limit and assessment protocol (EPA publication 1826.4)

Table 15 continued

Treatment technology	Resource inputs used	Evidence for emissions/by products			
		Wastewater	Waste solids	Air emissions	Noise emissions
Thermal	Energy Water	Confirm concentration and mass of targeted and other fluorinated compounds scrubbed by wet scrubber. Confirm physical-chemical properties of scrubber water (e.g. pH).	Demonstrate attainment of performance targets for waste solids (by-products like cyclone dust, bag house dust, saturated carbon). Confirm waste classification of waste solids (by-products).	Quantify effectiveness of flue-gas treatment processes. Demonstrate attainment of performance targets for BAT air emissions.	Demonstrate attainment of performance targets for noise control for equipment used in pre-treatment, thermal treatment and flue-gas treatment technologies. Follow Noise limit and assessment protocol (EPA publication 1826.4).
Containment (engineered barriers)	Engineered barrier materials	Attainment of performance targets for stormwater management during construction phase.	Attainment of performance targets for waste solids/soils displaced during construction phase.	Demonstrate attainment of performance targets for dust control during construction phase.	Demonstrate attainment of performance targets for equipment/machinery use during construction. Follow Noise limit and assessment protocol (EPA publication 1826.4).

1. These are examples of different treatment technologies; other options treatment options are possible. Refer to Section 2.2.

5.8. PFAS mass-balance considerations

Lines of evidence to demonstrating the effectives of PFAS treatment may include considering how the whole treatment process is decreasing and/or managing the overall mass of PFAS (Deeb et al. 2021).

This recognises that the treatment process may cause PFAS to:

- transform into different PFAS (e.g. destruction of precursors and intermediates to degradation compounds)
- move into different media/phases (e.g. from soil to vapour during thermal desorption)
- produce by-products (e.g. fluorine-based compounds related to original PFAS).

It is also important to consider the range of PFAS present in the media being treated. This recognises that PFAS occur as mixtures and the range of PFAS concentrations may be more extensive and in greater concentrations than PFOS, PFHxS and PFOA. The PFAS NEMP (HEPA 2020) provides information on how to consider PFAS other than PFOS, PFHxS and PFOA.

Mass-balance considerations may assist in understanding and quantifying:

- decreases in target PFAS due to mechanisms both directly and indirectly related to the specific mechanism of the treatment applied (i.e. so that the effectiveness of the specific treatment technology can be evaluated)
- the residual mass of PFAS-related compounds present in the treated soil and other media requiring management post-treatment.

The specific mass-balance considerations for evaluating treatment performance should be determined on a case-by-case basis and for the specific treatment technologies used.

Table 16 provides examples of mass-balance considerations for selected destructive and non-destructive treatment technologies.

The applicability and reliability of PFAS mass-balance considerations may depend on the specific treatment technology/approach being used. It may not be possible to complete a full mass-balance. For example, due to uncertainties in the monitoring/analytical program and methods.

Table 16. Examples of mass-balance considerations for selected treatment technologies [1]

Treatment technology	Mass balance considerations
Immobilisation	Immobilisation treatment aims to reduce the mobility and bioavailability of contaminants in soil. This is achieved through application of 'treatment sorbents'. Mass-balance concepts may be used to demonstrate to what proportion the reduction in leachable concentrations is attributed to: • the treatment sorbents and associated binding mechanisms • other mechanisms, such as dilution, losses due to pre-treatment handling of the soil.
Soil washing	Soil washing aims to transfer contaminants in soil into a liquid phase. This is achieved through a series of physical separation and washing treatment processes. A mass-balance model should be used to demonstrate the proportion of the contaminant in the following phases attributed to the treatment: • Solids from dry screening • Solids from wet screening • Liquids from wet screening • By-products and emissions from water treatment

Table 16 continued

Treatment technology	Mass balance considerations
Thermal	Thermal treatment aims to transfer contaminants from the soil into a vapour phase and then apply treatment processes to degrade the chemical structures of organic compounds. A mass-balance model should be used to demonstrate the proportion of the contaminant in the following phases attributed to the treatment: • Vapour phase as a result of the soil desorption process • Flue gases following the thermal oxidising process • Treated material (i.e. treated soil) • By-products such as, cyclone dust, baghouse dust (fly ash), effluent, exhausted carbon Due to the destructive nature of the treatment technology, the mass-balance model requires validation by quantifying the breakdown products in addition to the original parent compounds.
Containment (engineered barriers)	Containment uses capping to reduce leachate generation, and engineered liners to contain leachates/leachable contaminants. For containment engineering, mass-balance concepts can be considered based on water-balances and leachate generation models. These models are typically undertaken as part of the containment engineering design.

Note: These are examples of different treatment technologies; other options treatment options are possible. Refer to Section 2.2.

Examples of mass-balance principles are listed below:

- Treatability trial methodology describes how the PFAS mass-balance will be tracked throughout the treatment process. Such as the location and number of samples to be collected for analysis, to determine the PFAS mass-balance.
- Presenting the results from the mass-balance assessment in a manner that clearly details how they relate to the different components of the treatment process, for example, linking to specific steps in the process flow diagram.
- Describe the calculations used to quantify the treatment efficiencies determined. This should include the overall treatment efficiency and the efficiency of specific treatment steps as appropriate.

To support PFAS mass-balance considerations, it may be necessary to quantify total PFAS. This is in addition to the analysis for target compounds. Examples of two approaches that could be used to quantify total PFAS are summarised in **Table 17**.

Table 17. Main approaches to quantify total PFAS [1]

Quantifying total PFAS	Quantifying total organofluorine
• Involves considering a broad suite of PFAS (i.e. beyond PFOS, PFOA, PFHxS). • Totality of PFAS can be defined as substances that contain a perfluoroalkyl moiety with three or more carbons or a perfluoroalkylether moiety (EU 2020). • Useful for evaluating the performance of treatment, by calculating the sum of PFAS using the analytical results from a broad suite of PFAS. • Suited to non-destructive treatment techniques where significant degradation of PFAS is not expected. • Should be used in conjunction with other mass-balance measurements, such as total organofluorine, for destructive techniques where degradation of PFAS is expected.	• Involves considering the total amount of fluorine associated with PFAS compounds. This is on the basis that PFAS compounds are organic molecules that contain carbon-fluorine bonds. • Useful for evaluating the performance of treatment by measuring total organic fluorine. This can be undertaken using assays such as the total organic fluorine (TOF) assay and extractable organic fluorine (EOF) assay. • Suited to destructive techniques where degradation of PFAS compounds is expected. • Requires consideration and quantification of non-PFAS sources of fluorine which may interfere with PFAS mass-balance interpretations.

1. Adapted from information in PFAS NEMP (HEPA 2020) and ITRC (2022)

Figure 1 illustrates the key PFAS mass-balance considerations for a thermal destructive treatment technique. Further considerations for mass-balance for thermal treatment is provided in Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances (US EPA 2020).

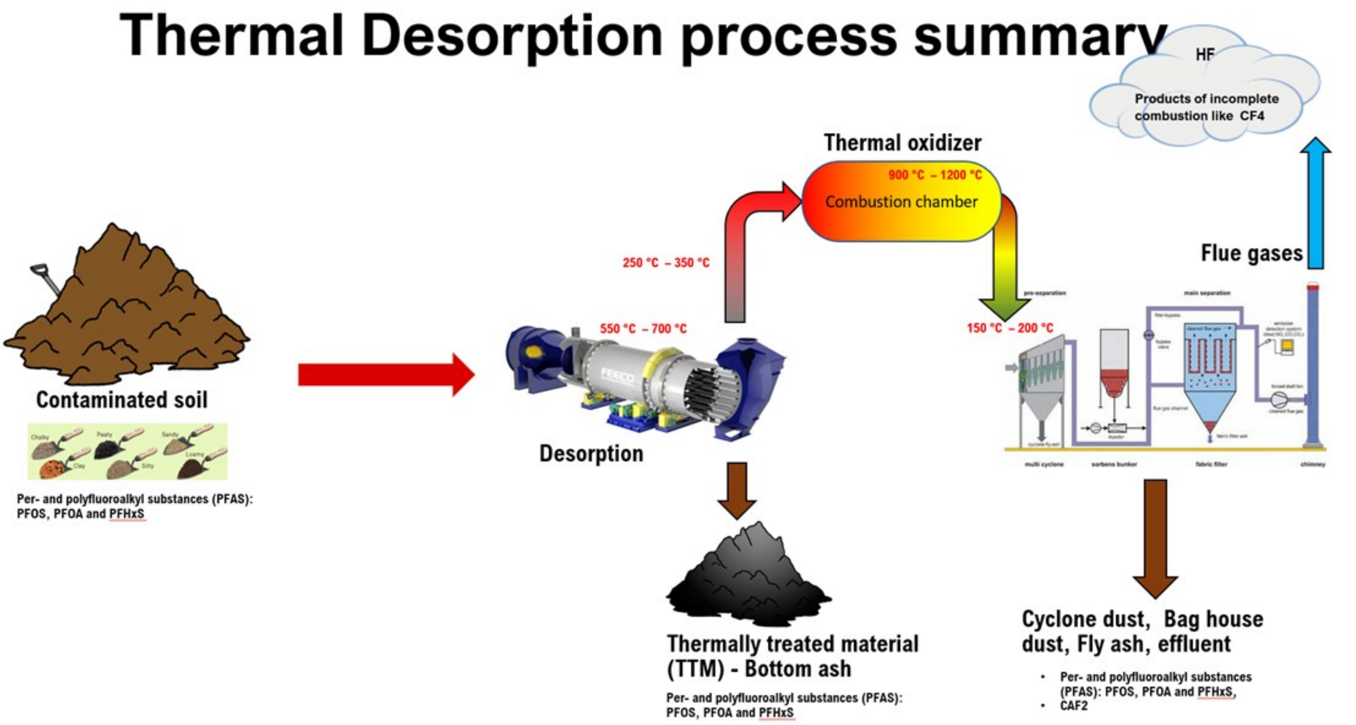


Figure 1. Illustration of key PFAS mass-balance consideration for a destructive thermal treatment process

5.9. Treatability study reporting

Upon completion of the treatability study, a report should be prepared that details aspects related to the design and implementation of the study, and information on evaluating and validating treatment performance. To inform further evaluation and implementation of the treatment approach, the study report should provide conclusions and recommendations on the following key aspects:

- The overall suitability for the treatment technology/approach to meet the intended treatment purpose and treatment objectives.
- How well the specific objectives of the treatability study have been met.
- Scope and limitations to the treatment approach.
- Critical control points/parameters for optimum treatment performance.
- Recommendations regarding the suitability to progress to the next scale of testing/implementation (e.g. from bench-scale to small testing scale, small testing scale to full-scale).
- Recommendations regarding further treatability testing or full-scale validation/verification requirements.

6. Validation of full-scale PFAS soil treatment

The performance of the selected treatment technology/approach should be demonstrated at full-scale. This involves undertaking activities to verify that treatment is performing as expected. Full-scale validation can also be referred to as proof of performance.

For treatment facilities, this forms part of the commissioning process (often as part of a Development Licence) before EPA issues an operating licence. The validation process for commissioning of a treatment process or facility may differ from that required for ongoing operation.

The approach for validating full-scale treatment should be informed by the findings of the feasibility assessment, including:

- desktop assessment; and/or
- treatability studies.

6.1. Description of proposed soil treatment approach and process

A detailed description of the proposed full-scale soil treatment approach and process should be documented.

The treatment approach should have previously been defined in the planning (see Section 4) and/or treatability study (see Section 5) stages. This description should be refined to reflect the full-scale approach. This should be informed by findings with demonstrated data from the previous planning and/or treatability study stages.

Table 18 outlines the key elements for describing the full-scale treatment approach. Further details are provided in Development licence application guidance (EPA publication 2011). This relates to situations where an EPA permission is required for the treatment.

Table 18. Summary of key elements for full-scale treatment approach description

Treatment approach element	Description
Treatment objective	Define the objectives of the treatment, including specific and measurable endpoints. Nominate specific numerical treatment criteria objectives (such as waste categorisation thresholds, specific soil re-use criteria). The treatment objectives and endpoints should be realistic and achievable. Refer to Section 4.2 for further information.
Treatable PFAS and other contaminants	Document the PFAS and other contaminants to be targeted for treatment. This should also include details on the limitations to the treatment approach, such as: • types of contaminants • concentration range of contaminants • specific soil types • co-contaminants that may influence treatment. Refer to Section 5.2 for further information.

Table 18 continued

Treatment approach element	Description
Treatment mechanism and process	A detailed description of the specific treatment mechanisms and processing steps is required. The key elements to describe the treatment process are outlined in Section 5.4 At the full-scale the critical control points (CCPs) in the treatment process should be clearly identified.
Best available techniques or technologies (BATT)	The BATT elements specific to the treatment technology/approach should be documented. This may require defining BATT for specific steps in the treatment process, such as emission-control equipment and targets. Refer to Section 4.5 for further information.
Validation sampling plan (or proof of performance testing plan)	Define the sampling and testing plan that is to be used as the basis for demonstrating treatment performance with mass-balance. This can also be referred to as a proof of performance (commissioning) testing plan. The validation sampling plan requirements are outlined further in Section 6.2.
Management of treated soil and by-products	Describe how the treated soil will be managed. This should also include any by-products or additional waste streams produced from the treatment. This can be presented in the form of a treated soil management plan. Refer to Section 6.5 for further information.
Environment risk management and contingency planning	Management measures to control environmental risk associated with the storage of contaminated soils, treatment process and storage of treated material should be documented. This should also include a contingency plan, should the treatment not meet the intended treatment objectives/end points. Refer to Section 6.4 for further information.

6.2. Validation sampling plan (proof of performance testing plan)

Validation of full-scale treatment requires sampling, analysis and testing to demonstrate treatment performance. A sampling and testing plan should be prepared to demonstrate the performance of the treatment. The plan should include the data to be collected, how it will be collected, and how the data will demonstrate proof of performance. This can also be referred to as a proof of performance testing plan.

The key elements of a sampling plan are detailed in Section 5.6 in relation to treatability studies. These key elements should also form the basis of the full-scale validation sampling plan.

It may be suitable to implement a more limited sampling plan for full-scale validation compared with that for a treatability study. This is because the purpose of the sampling is to verify treatment performance, rather than to obtain a detailed understanding of the treatment process.

Validation sampling undertaken as part of commissioning of a treatment process or facility may differ to the requirements for ongoing operation. In such cases, the sampling plan should state the duration of the validation sampling program.

The full-scale validation sampling plan should be designed around the approach to be used to demonstrate treatment performance (see Section 6.3). As a minimum, this should include the following sampling points:

- Pre-treatment (i.e. verifying waste classification and/or contamination status of soil to be treated).
- Critical control points of the treatment process (i.e. at steps in the treatment process considered to be critical for ensuring and demonstrating treatment performance).
- Post-treatment (i.e. verifying waste categorisation and/or contamination status relative to treatment objectives/end points. This should be linked to the requirements of the intended management approach for the treated soil).

Full-scale treatment typically involves processing multiple batches of soil. As such, the validation sampling plan should detail how the sampling and testing will be applied for different treatment batches.

Further sampling and analysis considerations for full-scale validation are provided in Appendix C, including:

- sampling frequency
- sample collection approaches and methods
- QA/QC
- laboratory analysis, including total contaminant analysis and leachability testing.

6.3. Demonstrating performance (proof of performance)

Demonstrating performance of the full-scale treatment involves using monitoring and sampling data to evaluate attainment of treatment objectives, end points, and re-use or disposal criteria. The specific approach to demonstrating performance should be determined on a case-by-case basis.

Information on approaches to evaluate treatment performance is provided in Section 5.7. The approaches are summarised below in the context of full-scale validation.

Demonstration of treatment performance should be presented in relation to multiple lines of evidence. This should be present in relation to treatment of the soil so far as reasonably practicable. Information on treatment of contamination so far as reasonably practicable, in relation to site contamination, is provided in Guide to the duty to manage contaminated land (EPA publication 1977.1).

Primary lines of evidence related to the efficiency or effectiveness of the treatment technology and approach to destroy, remove or reduce target contaminants of concern. This can be expressed in terms of:

- contaminant concentrations
- mass.

Treatment of target contaminants should be related back to the pre-defined treatment endpoints and associated numerical treatment criteria. Information related to total PFAS measurements and PFAS mass-balance considerations is provided in Section 5.8.

Secondary lines of evidence relate to evaluating the overall performance of the treatment system (i.e. beyond the target contaminants). This should include evidence of:

- resource inputs required for the treatment process
- performance of emissions control technologies
- effectiveness of environmental management measures.

Sampling data gathered during primary and secondary lines of evidence should be compared against compliance with the EP regulations and all relevant guidelines.

6.4. Risk assessment and contingency plan

A risk assessment should be undertaken to identify and assess risks to human health and the environment related to the full-scale validation stage. This could be undertaken using Licence assessment guidelines (EPA publication 1321.2), while considering best practice approaches in Assessing and controlling risk: A guide for business (EPA publication 1695.1) .

The risk assessment should be used to identify controls to manage risks to human health and the environment associated with certain treatment technology or approaches.

Measures to control the identified risks are to be implemented before and during the full-scale validation process.

As part of the risk assessment a contingency plan should be developed. This should outline the actions to be undertaken if the treatment does not perform as expected.

6.5. Treated soil management plan

Details should be provided regarding how the treated soil and other wastes generated from the study will be managed. This could be provided in the form of a treated soil management plan (TSMP). If choosing to complete a TSMP, it should include the following:

- Description and classification of the waste to be received and treated, including waste acceptance procedures (and associated sampling and analysis).
- Description and classification of the by-products and additional waste streams that may be produced as a result of the treatment process.
- Details of the anticipated contamination status and waste categorisation of the soil and other wastes from the treatment process.
- Details on the intended treated soil and waste management measures. This should include how these materials will be managed in accordance with the waste management hierarchy, and to prevent risk of harm to human health and the environment.
- Details on the procedures to be used for categorising the waste materials, including sampling and analysis.
- Contingency plans, including triggers, actions and responsibilities.
- Any requirements for obtaining EPA approvals for treated soil waste classification prior to management and/or disposal.

When dealing with the removal of treated waste, the treated waste must be taken to a place that can lawfully receive it. More information is provided on EPA's webpages Understanding lawful place and Your waste duties.

Where treatment has been undertaken as part of site-specific remediation, consideration should be given to the need for ongoing environmental management requirements. For example, to manage the risk of harm associated with residual contamination following treatment. This may require the implementation or amendment of an environmental management plan (EMP). More information about the duty to manage contaminated land in relation to site remediation is provided on EPA's website. This includes information in Guide to the duty to manage contaminated land (EPA publication 1977.1).

6.6. Full-scale validation reporting

Upon completion of the full-scale validation/proof of performance testing a report should be prepared to detail the findings from the validating testing. This should consider the key elements of full-scale treatment validation outlined in **Table 18**.

The validation report should provide conclusions and recommendations on the following key aspects:

- The overall suitability for the treatment technology/approach to meet the intended treatment purpose, treatment objectives and treatment endpoints.
- Recommendations regarding further treatment validation activities.
- Recommendations regarding the suitability to progress to ongoing full-scale treatment (for ongoing treatment facilities).
- Scope and limitations to the treatment approach for ongoing full-scale treatment (for ongoing treatment facilities).
- The success of the full-scale treatment in the context of the overall remediation strategy (for site-specific remediation). This should include information on how the soil has been treated so far as reasonably practicable.
- The need for ongoing environmental monitoring and/or management requirements (e.g. for residual contamination following site-specific remediation).

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Appendix A: Glossary of key terms

Bioremediation	Biodegradation and/or transformation of contaminants through the action of microorganisms. This can be achieved using either naturally occurring or introduced microorganisms.
Containment	Containment of contaminated material using physical barriers, including engineered capping and/or liners.
Full-scale treatment	Treatment undertaken using a full-scale process/system.
Harm	Harm in relation to human health or the environment, means an adverse effect on human health or the environment (of whatever degree or duration) (as defined in section 6 of the EP Act).
Immobilisation treatment	The addition of sorbents and/or additives to contaminated soil to either immobilise and/or solidify contaminants within soil.
Laboratory/bench treatment	Treatment studied within a laboratory, or under controlled conditions.
Line of evidence	Data or information used as the basis to support a conclusion. This may include to demonstrate the performance of treatment.
Permission	Permissions means any of the following: a) a development licence; or b) an operating licence; or c) a pilot project licence; or d) a permit; or (e) a registration. (as defined in section 42 of the EP Act)
Pilot-scale treatment	Treatment studied at a scalable treatment process/system that is likely to be applied at full or commercial scale.
Proof of performance	Proving that a treatment process/system is performing as expected, based on multiple lines of evidence.
Receptor	A 'receptor' the contamination could impact. Receptors include humans, plants, animals, groundwater and waterways.
Reuse	In relation to waste, means the use of the waste for a purpose that is the same or similar to the purpose for which it was used before it became waste.
State of knowledge	The body of accepted knowledge that is known or ought to be reasonably known about the harm or risks of harm to human health and the environment, and the controls for eliminating or reducing those risks.

Soil washing	A treatment method where contaminants in soil are separated from non-contaminated soil particles by physical separation and/or chemical extraction techniques.
Technology readiness level (TRL)	Relates to an approach to understand and define the technical maturity of a technology for the required purpose. The TRL can be defined on a scale ranging from conceptual to mature technology.
Treatability study	A study designed to evaluate the performance and suitability of a treatment. A treatability study can be undertaken at a laboratory/bench-scale and pilot scale. A treatability study can include a series of tests.
Treatment	For the purpose of this document treatment refers to the application of a specific technology to destroy, immobilise and/or contain contaminants. This includes via physical, thermal, chemical or biological processes.
Thermal treatment:	A generic term covering processes that involve the use of heat to treat waste. Incineration is the most common thermal treatment process.
Thermally treated material (TTM)	Waste materials after thermal treatment of contaminated soil with or without comingling with other hazardous waste.
Validation	A process to evaluate and confirm that treatment objectives, end points and/or targets have been met. This includes lines of evidence to demonstrate that the objectives, end point and/or targets have been met.
Waste	Waste includes any of the following: • Matter, including solid, liquid, gaseous or radioactive matter, that is deposited, discharged, emitted or disposed of into the environment in a manner that alters the environment. • A greenhouse gas substance emitted or discharged into the environment. • Matter that is discarded, rejected, abandoned, unwanted or surplus, irrespective of any potential use or value. • Matter prescribed to be waste. • Matter or a greenhouse gas substance referred to in paragraph a), b), c) or d) that is intended for, or is undergoing, resource recovery. (as defined in section 3 of the EP Act).

Appendix B: Description of example PFAS soil treatment technologies

Table B-1. Details of example destructive PFAS soil treatment technologies [1]

Technology (Treatment type)	Process	Advantages	Disadvantages
Oxidation-reduction (Physio-chemical)	Use of chemical oxidants/reducing agents for the abiotic breakdown of PFAS. Typically undertaken ex-situ by mixing soils with oxidants/reducing agents.	Potential for PFAS mineralisation. Effective for removal of PFOA.	High cost as requires a large volume of chemicals and specialised equipment. Not applicable for the treatment of all PFAS. Short-chain PFAS could result. Interferes with other contaminants. Advanced oxidation processes needed to cleave the PFAS carbon-fluorine bonds (e.g. electrochemical advanced oxidation processes), which have high energy inputs. Soil oxidation process can have adverse effects on soil geochemistry and biology.
Ball milling (Physio-chemical)	Destruction of PFAS via mechano-chemical processes. A ball is used to grind soil which detaches PFAS. The PFAS is then destroyed by mechanical energy (non-combustion). Co-milling agents are typically used.	Potential for PFAS degradation. Ease of use. Lower energy inputs required compared with other destructive technologies, such as thermal. Potential for effective destruction in a short treatment time (i.e. mins to hrs).	Limited studies have been performed for PFAS. The more mobile short-chained PFAS could remain or increase. Co-milling reagents may affect soil structure.

Table B-1 continued

Technology (Treatment type)	Process	Advantages	Disadvantages
Desorption and destruction (Thermal)	Thermal treatment using direct or indirect heat at temperatures ranging from 350 to 650°C to desorb PFAS from soil and increase the volatility of PFAS. The resulting PFAS gas (off-gas) is then captured and treated a high temperature (>900°C) to break down the carbon-fluorine bond.	Capable of achieving a destruction potential. Short-treatment time. Treatment facilities available in Victoria.	High cost and energy-intensive. Hydrogen fluoride (HF) by product needs to be captured and disposed of. Requires specialised treatment facility. Treatment significantly alters physical chemical and biological properties of soil which affects suitability of soil for many re-use options. Treated material may contain by-products if organic contaminants other than PFAS are in the feed material.
Incineration/vitrification (Thermal)	Thermal treatment of PFAS via incineration at temperatures ranging from 1,600 to 2,000°C.	Capable of achieving complete destruction of PFAS. Short-treatment time.	Very high temperatures and energy inputs required. Requires specialised treatment facility. Treatment significantly alters physical, chemical and biological properties of soil, which affects suitability of soil for many re-use options.
Bioremediation/ biological	Degradation of PFAS through microbial processes.	Simple technology with low inputs required. Cost-effective. Treatment may be able to occur in-situ.	Limited evidence that PFAS can be degraded. Long treatment time due to the slow biodegradation of PFAS. Not suitable for all PFAS.

1. Based on information in: CRC CARE (2018), Bolan et al. (2021), Deeb et al. (2021), Shahsavari et al. (2021), ITRC (2022), Vidonish et al. (2016).

Table B-2. Details of example non-destructive PFAS soil treatment technologies [1]

Technology (Treatment type)	Process	Advantages	Disadvantages
Soil washing (separation/extraction)	Physical and chemical process of detaching PFAS from soil by washing with water and surfactants.	Requires low-level/basic technology. Soil reuse may be possible. Effective for soils impacted with PFAS with high solubilities.	Expensive and time-consuming. Need to manage and treat high volumes of contaminated water. May require multiple treatment passes.
Soil flushing (separation/extraction)	In-situ treatment to extract PFAS from soil by injecting water, containing surfactants.	Can be undertaken in-situ. Effective for coarse-texture soil.	Need to manage and treat contaminated flushing solution. May require multiple treatment passes. Potential for mobilised PFAS to leach through the soil profile if not sufficiently captured by extraction of flushing solution.
Electrokinetic (separation/extraction)	Application of an electric field to soil so that PFAS migrates across a membrane to remove it from soil.	Can be undertaken in-situ. Effective at the removal of short-chain and long-chain PFAS as wells as common PFAA precursors. Low-cost relative to other intensive treatment technologies.	Can generate acidic and alkaline soil conditions at the anodes and cathodes. Requires site-specific design so as to maximise coverage and avoid short circuiting.
Phytoremediation (separation/extraction)	Use of plants and their associated microbial communities to remove, degrade or isolate PFAS in soil.	No energy or chemical inputs required. Generally improves the physical, chemical and biological quality of soils during remediation. Low cost.	Long treatment time Generally, only suitable for treatment of shallow soils (i.e. within plant root zone) In the case of phytoextraction will need to manage and treat contaminated plant material.

Table B-2 continued

Technology (Treatment type)	Process	Advantages	Disadvantages
Sorption/stabilisation (immobilisation)	Immobilisation of PFAS via adsorption of amendments (sorbents) to soil. Sorbents used include activated carbon, modified clays, minerals, resins.	Low operational cost. Reduces the mobility of PFAS in soil. Range of commercial products available. Treated soil may be suitable for re-use.	PFAS are not destroyed. Limited effectiveness for immobilising short chain PFAS. May require a large quantity of adsorbent which can impact on the suitability of the soil for re-uses. Uncertainties about long-term stability. May not be suitable for clayey soils.
Capping, containment and landfill (physical separation)	Use of physical, engineered barriers to contain PFAS impact. Prevents mobilisation and exposure. Typically involves impermeable or low-permeability engineered clays or geosynthetic materials as capping and liners for containment cells.	Containment engineering is a well-known and widely-used treatment approach for contaminated soil. May be able to apply in-situ, if only capping is required. Removes transport and exposure pathways for human and ecological receptors.	PFAS are not destroyed. Will typically require bulk excavation of soil. Uncertainties around the effectiveness of liner materials for long-term containment of PFAS. Leachates may be generated, which requires management/treatment.

1. Based on information in: CRC CARE (2018), Bolan et al. (2021), Deeb et al. (2021), Shahsavari et al. (2021), ITRC (2022).

Appendix C: Sampling and analysis considerations

This appendix provides an overview of key sampling and analysis considerations relevant to PFAS soil treatment. This includes sampling and analysis for:

- waste classification in accordance with the Environment Protection Act and Environment Protection Regulations
- treatability studies (laboratory/bench & pilot scales)
- full-scale treatment (input and output verification).

The following key documents should be referred to for detailed guidance on sampling and analysis:

- Sampling and analysis of waters, wastewaters, soils and wastes (EPA publication IWRG701).
- Soil sampling (EPA publication IWRG702).
- National Environment Protection (Assessment of Site Contamination) Measure (NEPM) (NEPC 2013).
- PFAS National Environmental Management Plan (NEMP) (HEPA 2020).

C.1 Sampling frequency

The sampling frequency (i.e. number of samples to be collected) should be determined in the context of the purpose of the sampling and the overall sampling and analysis plan.

Table C-1 details sampling frequency considerations for different sampling purposes relevant to treatment of contaminated soil.

Table C-1. Sampling frequency considerations

Purpose of sampling	Sampling frequency considerations
Waste classification and categorisation (treatment inputs and outputs)	Sampling of soils/waste to related to inputs and output of soil treatment to enable the waste classification to be determined is to be completed per: • Guide to classifying industrial waste (EPA publication 1968.1) • Soil sampling (EPA publication IWRG702) • Waste disposal categories- characteristics and thresholds (EPA publication 1828.2) • Waste codes (EPA publication IWRG822.4) Details on the minimum number of samples to be collected (based on the volume of soil being assessed for waste classification) is provided in Soil sampling (Publication IWRG702).

Table C-1 continued

Purpose of sampling	Sampling frequency considerations
Treatability study – Laboratory/bench-scale	Laboratory/bench-scale treatability studies typically use representative bulk samples for the different treatment groups to be tested. The mass/volume of these bulk samples will generally be relatively small (i.e. grams to kilograms). These bulk samples are generally representative field-collected soils or artificially-spiked soils, which have been homogenised prior to treatment. Sampling of the bulk soils is required both pre- and post-treatment to enable the effectiveness of the treatment to be evaluated. The required pre- and post-treatment soil sampling frequencies for laboratory/bench-scale treatability studies should be determined on a case-by-case basis and be sufficient to: • evaluate the variability within bulk samples • enable sufficiently powerful statistical analysis of the treatability study data (i.e. to determine statistical differences between treatment groups).
Treatability study – Pilot-scale	Pilot-scale treatability studies typically use representative bulk samples for the different treatment groups to be tested. The mass/volume of these bulk samples will generally be significantly higher than for a bench stud, and in range of kilograms to tonnes. This is dependent on the specific size of the treatment system/process being used for the pilot-scale study. These bulk samples are generally representative of the actual soils anticipated to be subjected to full-scale treatment. The bulk samples for pilot-scale studies will typically be sourced from representative contaminated areas/sites. As such the soils are likely to have already been subjected to sampling for waste classification purposes. Sampling of the bulk soils is required both pre- and post-treatment to enable the effectiveness of the treatment to be evaluated. The required pre- and post-treatment soil sampling frequencies for laboratory/bench scale treatability studies should be determined on a case-by-case basis and be sufficient to: • confirm the contamination status from any previous waste classification/contaminant characterisation sampling • verify the pre-treatment baseline status of the soil • evaluate the variability within bulk samples • enable sufficiently powerful statistical analysis of the treatability study data (i.e.to determine statistical differences between treatment groups).

Table C-1 continued

Purpose of sampling	Sampling frequency considerations
Full-scale – input verification	Waste soils received at a treatment facility should have already been subjected to detailed sampling and analysis for waste classification purposes. Similarly, for on-site treatment, the contaminant status of soils should have already been well characterised prior to treatment. The purpose of input sampling for full-scale treatment is to verify the previously-determined contaminant status of the soil prior to treatment. This is to confirm the baseline soil contamination status/condition prior to treatment. Representative input verification samples should be collected from each batch of soil received at a facility or inputted into a treatment system. The number of representative verification samples should be determined on a case-by-case basis, based on the variability in the source material and level of confidence in the previous sampling and analysis data. As a minimum, one verification check-sample should be collected for each source. If the confidence in the existing sampling and analysis data is low, detailed sampling may be required (i.e. per the requirements for waste classification).
Full-scale – output verification and waste classification	Output material (i.e. treated soil) from full-scale treatment should be subject to sampling to: • verify the treatment effectiveness • confirm that the treated soil meets the required criteria/specifications for the identified end-uses of the treated soil. The number of representative output samples should be determined on a case-by-case basis, to consider the variability in the treated material, treatment objectives and intended end-uses of the treated soils. Where treated soils are to be moved off-site, the sampling frequency should be sufficient to enable the waste classification to be determined.

C.2 Analysis

This section provides and overview of analytical considerations. In relation to PFAS, the available analytical methods are evolving rapidly. As such, advances in analytical methods and best practice analytical approaches should be considered based on the current state of knowledge.

C.2.1 Laboratories

Sample analysis should be performed at National Association of Testing Authorities (NATA) accredited laboratories and using NATA-accredited analytical methods.

If analysis is not NATA-accredited, then sufficient information should be documented to demonstrate that the analysis has been undertaken using appropriate methods and quality assurance/quality control procedures.

Refer to the following documents for information on analytical laboratory requirements:

- Sampling and analysis of waters, wastewaters, soils and wastes (EPA publication IWRG701)
- National Environment Protection (Assessment of Site Contamination) Measure, Schedules B2 and B3 (NEPC 2013)
- PFAS National Environmental Management Plan (HEPA 2020).

The analytical methods used should be able to achieve a laboratory limit of reporting (LOR) low enough to enable comparison to the adopted numerical assessment and/or treatment criteria.

C.2.2 Contaminants/parameters for analysis

The contaminants/parameters for analysis should be determined in the context of the purpose of the sampling and the overall sampling and analysis plan.

To assist in determining which contaminants to analyse for in relation to the classification of industrial waste, see Guide to classifying industrial waste (EPA publication 1968.1)

C.2.3 Total contaminant analysis

Analysis of soil/waste must determine total concentrations of contaminants of concern (i.e. total solids concentration).

National Environment Protection (Assessment of Site Contamination) Measure, Schedules B3 (NEPC 2013) provides details on acceptable analytical methods for a range of contaminants and parameters.

The PFAS NEMP (HEPA 2020) provides details on standard analytical methods for total PFAS analysis. This includes methods suitable for different suites and matrices.

C.2.4 Leachability analysis

Analysis of soil/waste will typically require sample analysis to determine the leachable fraction of the contaminant in the soil. This is particularly important for PFAS as it is highly mobile. Further, the environmental and waste classification criteria are based on both total and leachable concentrations. Further information on leachability analytical methods for PFAS is provided in:

- PFAS NEMP (HEPA 2020)
- ITRC (2022)
- Rayner et al. (2022).

The most common laboratory-based soil leachability methods are summarised in **Table C-2**. This includes methods for assessing both short-term and long-term leachability of contaminants.

Laboratory leachability methods are based around simulating leaching conditions relevant to purpose of the leachability assessment. This will generally involve simulating worst-case and/or typical leachability conditions.

For most contaminants, leachability generally increases with decreasing pH. However, in relation to PFAS, leachability generally increases with pH.

Table C-2. Laboratory based leachability methods (adapted from information in PFAS NEMP (HEPA 2020), ITRC (2022), Rayner et al. (2022)

Method	Description	Examples
Batch test	Solid material subjected to an aliquot of leaching solution over a specified time (equilibrium test)	Australian Soil Leaching Procedure (ASLP) [1] Toxicity Characteristic Leaching Procedure (TCLP) [2] Synthetic Precipitation Leaching Procedure (SPLP) [3] Leaching Environmental Assessment Framework (LEAF) 1313 [4] LEAF 1316 5
Multi-batch tests	Solid material subjected to multiple aliquots of leaching solution over a specified time (mass-transfer test)	Multiple Extraction Procedure (MEP) [6] Modified multi-batch extractions
Column tests	Solid material packed into a column. Leaching fluid percolated through the column at a constant flow rate	LEAF 1314 [7]
Semi-dynamic leaching tests	Submergence of solid material or ponding of leaching fluid on solid materials with potential periodic renewal of leaching fluid	LEAF 1315 [8] Ponding experiments

1. ASLP: Australian Standard Leaching Procedure. Australian Standards 2019. AS4439.3.
2. TCLP: Toxicity Characteristic Leaching Procedure. US EPA 1992, Method 1311.
3. SPLP: Synthetic Precipitation Leaching Procedure. US EPA 1994, Method 1312.
4. LEAF 1313: Leaching Environmental Assessment Framework. US EPA 2017. Method 1313: SW-846, Liquid-solid partitioning as a function of extract pH using a parallel batch extraction procedure.
5. LEAF 1316: Leaching Environmental Assessment Framework. US EPA 2017. Method 1316: SW-846, Liquid-solid partitioning as a function of liquid-to-solid ratio in solid materials using a parallel batch procedure.
6. MEP: Multiple extraction procedure. US EPA 1992. Method 1320: SW-846, test methods for evaluating solid waste, physical/chemical methods.
7. LEAF 1314: Leaching Environmental Assessment Framework. US EPA 2017. Method 1314: SW-846, Liquid-solid partitioning as a function of liquid-solid ratio for constituents in solid materials using an up-flow percolation column procedure.
8. LEAF 1315: Leaching Environmental Assessment Framework. US EPA 2017. Method 1315: SW-846, Mass transfer rates of constituents in monolithic or compacted granular materials using a semi-dynamic tank leaching procedure.

C.2.5 Non-standard PFAS analysis

There a several non-standard methods developed for PFAS analysis. This are designed to measure concentrations of PFAS-related analytes to help characterise the total PFAS mass, transformation products (e.g. related to precursors), and/or degradation products.

The most common non-standard PFAS analytical methods are summarised in **Table C-3**.

Table C-3. Non-standard PFAS analytical methods

Method	Description
Total oxidisable precursor (TOP) assay [1]	Method for indirectly measuring the total PFAS precursor concentration. The TOP assay considers PFAS with perfluorinated carbon chain lengths from C4 to C14.
Total organic fluorine (TOF) assay [1]	Method for indirectly measuring the total PFAS precursor concentration. The TOF assay considers the total mass of organic fluorine.
Hydrogen fluoride (HF) measurement [2]	Measurement of HF is undertaken for thermal PFAS treatment techniques. HF is the most stable product from the combustion of fluorocarbon compounds. HF measurement is undertaken to evaluate control efficiency of HF at emission outlets. HF measurement is not suited to mass-balance assessments to evaluate PFAS destruction efficiency.[2]

1. Based on information in PFAS NEMP (HEPA 2020).
2. Based on information in US EPA (2020) Interim guidance on the destruction and disposal of perfluoroalkyl and polyfluoroalkyl substances and materials containing perfluoroalkyl and polyfluoroalkyl substances.

Appendix D: Example treatment efficiency calculations

Table D-1 provides examples of treatment efficiency equations for selected treatment technologies. These treatment efficiency equations may be used for treatability studies and/or full-scale validation. The treatment efficiency equations are provided as examples only. The specific approach for calculating treatment efficiency should be determined on a case-by-case basis.

Table D.1. Example treatment efficiency equations

Technology	Example treatment efficiency/effectiveness equation	Reference
Immobilisation	Treatment effectiveness can be calculated based on the percentage of leached PFAS using the following equations. Equation 1: $$\%\ of\ leachate\ PFAS = \frac{C_w}{C_{total}} \times 100$$ Where: C_{total} = Total concentration of an individual PFAS in untreated soil (mg/kg) prior to leaching C_w = Concentration of an individual PFAS in leachate (µg/g = mg/kg) calculated according to Equation 2. Equation 2: $$Cw = \frac{C\ \times V}{m}$$ Where: C = Concentration of an individual PFAS in leachate (µg/L) V = Volume of leachate (L) m = Weight of untreated or treated soil used in each leaching experiment (g) Equation 3: Treatment efficacy reported as a percentage reduction in leaching (%) from treated soils relative to untreated soil according to: $$\%Reduction = 1 - \left(\frac{C_{w,teated\ soil}}{C_{w,untreated\ soil}}\right) x\ 100$$ Where: $C_{w,\ treated\ soil}$ = Concentration of an individual PFAS in leachate of treated soil (µg/L) $C_{w,\ untreated\ soil}$ = Concentration of individual PFAS in leachate of untreated soil (µg/L)	Navarro et al. (2023)
Soil washing	Treatment effectiveness can be calculated by comparing the concentration of PFAS in treated soil to the concentration in the untreated soil. This can be expressed as percentage removal efficiency (RE) for: • soil • leachate • PFAS concentrations • PFAS mass. RE can be calculated according to the following equation: $$RE\% = 100 - \left(\frac{C_{treated}}{C_{untreated}} \times 100\right)$$ Where: RE% = Percentage removal efficiency $C_{treated}$ = Concentration (or mass) in treated soil $C_{untreated}$ = Concentration (or mass) in untreated soil	Quinan et al. (2022)

Table D-1 continued

Technology	Example treatment efficiency/effectiveness equation	Reference
Thermal	Treatment effectiveness can be calculated as both destruction and removal efficiency (DRE) and overall removal efficiency (RE). The DRE should be undertaken as a PFAS mass-balance calculation. Below is an example of the fluorine mass-balance calculation to determine the DRE of the thermal oxidiser: $$Organic\ Flourine\ DRE\ (\%) = [F_{EG}(F_{FS} - F_{TS})] \times 100$$ Where: DRE = Destruction removal efficiency F_{EG} = mass inorganic fluorine in thermal oxidiser (TO) exhaust gas F_{FS} = mass of organic fluorine in feed soil F_{TS} = mass of organic fluorine in treated soil The DRE can be calculated for the individual treatment processes in the system. It should also be expressed in the context of all combined environmental media outputs from the system, such as: • treated solids • carbon bed • bag house dust • effluent • cyclone dust • boiler discharges • flue gases. An example equation is below: $$DRE\ (\%) = \frac{Mass_{in} - Mass_{out\ all\ media}}{Mass_{in}} \times 100$$ Where: DRE = Destruction removal efficiency $Mass_{in}$ = Mass in feed soil $Mass_{out\ all\ media}$ = Mass in all output media from the treatment (i.e. treated solids, carbon bed, bag house dust, effluent, cyclone dust, boiler discharges, flue gases) The overall removal efficiency (RE) for the soil can also be calculated according to the equation below. This can be calculated based on PFAS concentrations or as a PFAS mass basis. $$RE(\%) = \frac{C_{in} - C_{out}}{C_{in}} \times 100$$ Where: RE = Removal efficiency C_{in} = Concentration (or mass) in feed soil C_{out} = Concentration (or mass) in treated solid material	Based on equations in Barranco et al. (2020)

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