Comparison of Australian approaches to PFAS waste management

Prepared for:
Tellus Holdings

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Contents

Acronyms and Abbreviations

2016 Commonwealth guidance	Australian Government Department of the Environment and Energy, *Commonwealth Environmental Management Guidance on Perfluorooctane Sulfonic Acid (PFOS) and Perfluorooctanoic Acid (PFOA)*, Draft, October 2016
AFFF	aqueous film forming foams (containing PFAS, in the context of this report)
Ascend	Ascend Waste and Environment
ASLP	Australian standard leachate procedure
Basel Convention	*The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal*. The Convention puts an onus on exporting countries to ensure that hazardous wastes are managed in an environmentally sound manner in the country of import.
contaminant	chemical contaminant within hazardous waste
DE	destruction efficiency
DEFRA	The United Kingdom Department for Environment Food and Rural Affairs
DRE	destruction removal efficiency
EPA	Environment Protection Authority
ESM	environmentally sound management
EU	European Union
GAC	granular activated carbon
General POP guideline	*General technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with persistent organic pollutants*, UNEP/CHW.14/7/Add.1/Rev.1, June 2019
Halogenated organic compounds	chemical compounds containing a 'halogen' (typically fluorine, chlorine or bromine) in their chemical structure
Hazardous waste	A hazardous waste, as defined in the Australian Government's *National Waste Policy: Less waste, more resources* (2009), is a substance or object that exhibits hazardous characteristics, is no longer fit for its intended use and requires disposal. According to the Hazardous Waste Act, hazardous waste means: (a) waste prescribed by the Hazardous Waste Regulations, where the waste has any of the characteristics mentioned in Annex III to the Basel Convention; or (b) wastes covered by paragraph 1(a) of Article 1 of the Basel Convention; or (c) household waste; or (d) residues arising from the incineration of household waste; but does not include wastes covered by paragraph 4 of Article 1 of the Basel Convention.
Hazardous Waste Act	*Hazardous Waste (Regulation of Exports and Imports) Act 1989*
Hazardous Waste Regulations	*Hazardous Waste (Regulation of Exports and Imports) Regulations 1996*

HEPA	Heads of EPAs (of Australia and New Zealand)
IChEMS	Industrial Chemicals Environmental Management Standard
kW	kilowatt
LOR	limit of reporting
LPCL	low POP content limit
mg/kg	milligram per kilogram
µg/kg	micrograms per kilogram
µg/L	micrograms per litre
ms	milli-second
NEPM	*National Environment Protection (Movement of Controlled Waste between States and Territories) Measure 1998*
NSW	New South Wales
NT	Northern Territory
PCB	polychlorinated biphenyl
PFAS	per- and polyfluoroalkyl substances
PFAS NEMP	PFAS National Environmental Management Plan, version 2.0
PFHxS	perfluorohexanesulfonic acid
PFOA	perfluorooctanoic acid
PFOS	perfluorooctane sulfonate
PFOSF	perfluorooctane sulfonyl fluoride
PIC	product of incomplete combustion
POP	persistent organic pollutant
POP-PFAS guideline	*Technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with perfluorooctane sulfonic acid, its salts and perfluorooctane sulfonyl fluoride*, May 2015
POP-PFASs	PFAS chemicals currently listed in the Stockholm Convention: perfluorooctane sulfonic acid (PFOS), its salts (perfluorooctane sulfonates), perfluorooctane sulfonyl fluoride (PFOSF) and perfluorooctanoic acid (PFOA)
Qld	Queensland
SA	South Australia
Rotterdam Convention	Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade
Stockholm Convention	Stockholm Convention on Persistent Organic Pollutants (POPs)
Tas	Tasmania
Tellus	Tellus Holdings Limited
tpa	tonnes per annum
Tracking system	Jurisdiction-based hazardous waste tracking systems, which are in place in NSW, Qld, SA, WA and Vic. These tracking systems can be either online, paper-based, or a combination of both these mechanisms.
Tracked data	Hazardous waste collected under the arrangements of a tracking system.
Treatment	Treatment of waste is the removal, reduction or immobilisation of a hazardous characteristic to enable the waste to be reused, recycled, sent to an energy-from-waste facility or disposed.
US EPA	United States Environmental Protection Agency
Vic	Victoria
WA	Western Australia
WA DWER	Western Australia Department of Water and Environmental Regulation

Waste arisings	Hazardous waste is said to 'arise' when it causes demand for processing, storage, treatment or disposal infrastructure.
Waste fate	Waste fate refers to the ultimate destination of the waste within the management system. Types of fate may include recycling, energy recovery, long-term storage and disposal. (Treatment, transfer and short-term storage are not fates, but are rather part of the pathway leading to a fate).
Waste generation	The process of creating a waste.
Waste management	For the purposes of this report, 'management' of hazardous waste comprises the activities through which it is dealt with in infrastructure approved to receive it. Management is a broad term that encompasses both waste fates (ultimate destination for a waste) and waste pathways (potentially multiple steps between a waste's generation and fate). Therefore, for hazardous waste, tonnes 'managed' = tonnes sent to pathway infrastructure + tonnes sent to fate infrastructure.
Waste management hierarchy	*Waste should be managed in accordance with the following order of preference, so far as reasonably practicable—* *(a) avoidance;* *(b) reuse;* *(c) recycling;* *(d) recovery of energy;* *(e) containment;* *(f) waste disposal*.

Executive summary

Introduction

Per- and polyfluoroalkyl substances (PFAS) make up a large group of man-made highly fluorinated chemicals that have been used in industrial and consumer applications since the 1950s. PFAS are typically persistent, bioaccumulative and toxic. The environmental and potential human health impacts from exposure to PFAS are of increasing concern worldwide.

Australia is a party to the *Stockholm Convention on Persistent Organic Pollutants* (the Stockholm Convention)[1], an international treaty which aims to protect human health and the environment from the effects of persistent organic pollutants (POPs). Some PFAS compounds are specifically listed on the Stockholm Convention while many other PFAS compounds are likely to exhibit similar characteristics of persistence, bioaccumulation and toxicity that POPs do, but are yet to the listed on the Convention.

Ascend was commissioned by Tellus to conduct a comparative review of the approaches currently commercially available in Australia to manage wastes contaminated in PFAS, in light of the most recent science, policy and regulatory frameworks emerging worldwide.

Legal and policy considerations

A range of state, national and international level legal, policy and guidance frameworks with relevance to PFAS waste management were reviewed to distil down four 'dimensions', within which Australian management options were assessed. This dimensions were:

1. Environmentally sound management (ESM) for wastes above the Stockholm Convention's level of concern, the low POP content limit (LPCL) of 50 mg/kg.
2. US EPA interim guidance's preferred order of priority for destruction and disposal options, based on ranging uncertainty for protection of the environment.
3. Waste hierarchy in a hazardous waste (and specifically PFAS) context.
4. Risk of insurance policy exclusion (and contingent liability) for PFAS-related incidents or issues.

Assessment of management options in Australia

Table ES1 collates each score, per waste type, from the individual management option assessments (Section 5.1). A 'traffic light' assessment of the numerical scores has been adopted, where:

Green	= 9-12 point score – method is best suited for this waste type
Orange	= 6-8 point score – method may be suitable for this waste type
Red	= 0-5 point score – method not suitable for this waste type.

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[1] http://chm.pops.int/TheConvention/Overview/TextoftheConvention/tabid/2232/Default.aspx

Table ES1 Collated assessment scores per management option

PFAS waste type	Assessment score per management option (out of 12 points)									
	1. Thermal desorption and off-gas destruction	2. Biosolids specific gasification	3. Incin./ cement kiln	4. Plasma arc	5. Solid waste landfill	6. Haz waste landfill	7. Geological repository	8. In-situ sorption/ separation/ stabilisation methods	9. In-situ soil 'washing', offsite residues	Highest scoring option
AFFF	2	-	6	6	0	0	10	0	-	Geological repository
GAC	2	-	6	6	0	0	10	0	-	Geological repository
Wastewaters	0	-	6	6	0	0	10	10	-	In-situ sorption/ separation & Geological repository
Soil - high	5	-	6	6	0	0	10	1	5	Geological repository
Soil – intermediate	8	-	7	8	3	8	10	1	8	Geological repository
Soil – low	9	-	8	9	7	8	10	1	8	Geological repository
Soil – co-contaminated	0	-	0	0	3	7	10	0	4	Geological repository
Biosolids	7	9	6	6	5	7	0	1	3	Biosolids-specific gasification

Notes:

1. *AFFF = aqueous film-forming foams; GAC = granular activated carbon; wastewaters include ground, surface, industrial and leachate waters; Soil = contaminated soil*
2. *Co-contaminated soil = soil contaminated with PFAS plus one or more other inorganic contaminants, including asbestos*
3. Green *= 9-12 point score – method is best suited for this waste type*
4. Orange *= 6-8 point score – method may be suitable for this waste type*
5. Red *= 0-5 point score – method not suitable for this waste type*

Findings

A comparative review of the approaches currently commercially available in Australia to manage wastes contaminated in PFAS, in light of the most recent science, policy and regulatory frameworks emerging worldwide, has found that:

- geological repository rated highest overall for management of the following PFAS contaminated wastes:
  - aqueous film forming foam (AFFF)
  - granular activated carbon (GAC)
  - all contamination levels of soil, but particularly highly PFAS-contaminated soil and co-contaminated soil (PFAS plus significant levels of contamination in asbestos or inorganic chemicals such as heavy metals)
- in-situ sorption/ separation (pump and treat) techniques and geological repository both rated highest for management of PFAS wastewaters, although the former may be slightly ahead due to the broader environmental benefits of constraining most of the treatment activity onsite
- biosolids-specific gasification rated highest for managing biosolids contaminated in PFAS.

Breaking down the overall rating further, for intermediate to high concentrations of PFAS wastes in particular, geological repository rated significantly higher than all other management options in three of the four measures (ESM, US EPA preferred priority and its ability to extinguish waste generators' contingent liability), the latter an emerging issue discussed in Box ES1 overleaf.

Geological repository was similar to most other methods in the remaining dimension of waste hierarchy, where options such as cement kiln co-incineration and in-situ soil washing rated slightly higher due to their potential ability to allow a degree of reuse/ recycling of soils in particular, post their treatment.

This assessment is recognised as subjective and the opinion of the author, but its semi-quantitative design through the lens of four key legal and policy dimensions provides a transparent and defensible basis of these opinions.

It is noted that there are other practical considerations to a choice of PFAS waste management, such as overall cost competitiveness, transport cost component (ex-situ management options), local regulatory considerations, levels of contamination of the waste, community concerns and scalability of the solution to the size of the problem. These are not considered here, because this assessment focused on elements of environmentally protective policy.

While this does not change this assessment, a practical qualification is that Tellus' Sandy Ridge facility, the only geological repository in Australia, is not currently licensed to accept PFAS waste above 50 mg/kg, a contradiction discussed in Box ES2.

Box ES1 PFAS liability and Permanent Isolation Certificates

Corporate accounting and financial considerations encompass a company's liabilities. A contingent liability is a liability that may occur depending on the outcome of an uncertain future event. A contingent liability is recorded on the company's accounts if the contingency is likely and the amount of the liability can be reasonably estimated. The liability may be disclosed in a footnote on the financial statements unless both conditions are not met.

If onsite or offsite management of a company's PFAS wastes do not destroy PFAS, or contain it sufficiently to remove all risk of future harm it may cause humans or the environment, then a contingent liability may still exist in the accounts of the PFAS waste producing company, regardless of where or even if a future contamination event occurs.

Australia is likely to follow the trend in the US where communities surrounding defence bases, airports and fire-fighting facilities, have initiated class actions against government to address potential human harm (health) and environmental compensation and finance the clean-up of surrounding lands contaminated by PFAS and hydrocarbons.

The Australian Government has so far paid out compensation of $212 million[2] to communities surrounding three military bases in New South Wales, the Northern Territory and Queensland through similar class actions. This is a fraction of the remaining military bases, airports and fire-fighting facilities that will likely attract scrutiny from the public in the future. The US Government, realising the enormity of the problem, has set aside $10 billion[3] for the clean-up of surrounding contaminated lands.

PFAS and hydrocarbons liability in Australia can be reduced through the use of a Permanent Isolation Certificate[4], supported by international and Australian accounting standards IAS 37 and AASB 137. Tellus Holdings' Sandy Ridge geological repository is currently the only facility in Australia that can issue a Permanent Isolation Certificate, which would reduce all future risk for stockpiles of PFAS contaminated material, including AFFF.

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[2] The Sydney Morning Herald (March 11, 2020), *Landmark legal settlement as government pays $212m to victims of toxic contamination*, available at: https://www.smh.com.au/national/landmark-legal-settlement-as-government-pays-212m-to-victims-of-toxic-contamination-20200311-p548x5.html.

[3] Star Tribune (11 September, 2021), *3M's support for PFAS could cost taxpayers billions of dollars*, available at: https://www.startribune.com/3m-s-support-for-pfas-could-cost-taxpayers-billions-of-dollars/600096094/.

[4] Tellus Holdings, *Hazardous waste liability regime and liability reduction through Tellus Services – Technical Data Sheet*, available at: https://tellusholdings.com/wp-content/uploads/2020/06/Liability-Technical-Data-Sheet_C4.pdf.

Box ES2 Tellus licence anomaly with respect to the Stockholm Convention

Tellus' Sandy Ridge geological repository in Western Australia is licensed by the WA DWER to accept PFAS wastes, including PFAS contaminated soil, up to a limit of 50 mg/kg of PFAS contamination. The basis for this limitation is understood to be the PFAS NEMP, which establishes an interim landfill acceptance criteria of 50 mg/kg (sum of PFOS + PFHxS) or 50 mg/kg as PFOA. The PFAS NEMP itself quotes the Stockholm Convention's 50 mg/kg LPCL[5] as the basis for its choice of this value as a landfill acceptance criteria.

Consequently the licence limit of 50 mg/kg is based on the PFAS NEMP landfill acceptance criteria, which is in turn has been established to mirror the Stockholm Convention's LPCL. The LPCL is set as a threshold floor – above which the POP must be managed via environmentally sound management (ESM), and below which ESM essentially doesn't apply. The concepts of ESM, the LPCL, the PFAS NEMP's landfill acceptance criteria and the subsequent DWER licence limit are all inextricably linked.

Further, the Stockholm Convention's General POP guideline and POP-PFAS guideline describe in intricate detail what management methods qualify as ESM, otherwise referred to in these guidelines as methods for environmentally sound disposal. Geological repository is described specifically (section IV.G.3.(b)) as one of these methods, "when destruction or irreversible transformation does not represent the environmentally preferable option."

To allow geological repository to accept waste below 50 mg/kg PFAS is a 'no-brainer' – landfills beneath ESM standards can accept that level. What is more important is consideration of wastes contaminated above the Stockholm/ NEMP/ 50 mg/kg touchstone, the level at which the Stockholm Convention's ESM requirements become important.

This leaves the licence condition in the seemingly untenable position of having adopted a 50 mg/kg limit, that is obtained from the Stockholm Convention, but remaining ignorant of Stockholm's purpose for this limit – to deem certain types of management (in this case geological repository) 'environmentally sound' for acceptance of waste above 50 mg/kg PFAS.

How is it possible that the licence uses one key aspect of the Stockholm Convention (the LPCL) but ignores the other key aspect for which this metric has been established (to determine the contamination cut-off for requiring ESM)? The core issue may be the lack of legal recognition for a classification of waste management that neatly covers off on geological repository, which has resulted in Sandy Ridge being scheduled for licensing purposes as a landfill[6]. This creates further inconsistency still, with Stockholm, which is very clear in definitionally distinguishing landfill from geological repository.

This geological repository regulatory classification gap is common across Australian jurisdictions and in this case has led to a perverse outcome.

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[5] HEPA, *PFAS National Environmental Management Plan, Version 2.0 – January 2020*, available at: https://www.dcceew.gov.au/sites/default/files/documents/pfas-nemp-2.pdf, page 72.

[6] Prescribed premises categories Category 65: Class IV secure landfill site and Category 66: Class V intractable landfill site.

1 Introduction

Per- and polyfluoroalkyl substances (PFAS) make up a large group of man-made highly fluorinated chemicals that have been used in industrial and consumer applications since the 1950s. PFAS are typically persistent, bioaccumulative and toxic. The environmental and potential human health impacts from exposure to PFAS are of increasing concern worldwide.

Ascend Waste and Environment Pty Ltd ("Ascend") is a waste and environmental consulting company specialising in the regulatory interface governing hazardous waste, environmental chemicals and emissions management in Australia and the Pacific region, from a compliance (private sector) and development (government) perspective. Geoff Latimer, the author of this report, is Director and sole operator of the company.

Tellus Holdings Ltd ("Tellus") operate Australia's first geological repository, a long-term isolation facility that involves:

- mining, processing and the use of its kaolin clay, mostly for onsite use and also for domestic and export markets, and
- long term storage and permanent isolation of mostly hazardous and intractable chemical wastes and a small volume of low level radioactive wastes (such as smoke detectors and sealed radioactive sources) into the void spaces created by the mining.

Ascend was commissioned by Tellus to conduct a comparative review of the approaches currently commercially available in Australia to manage wastes contaminated in PFAS, in light of the most recent science, policy and regulatory frameworks emerging worldwide.

2 Types of PFAS wastes

PFAS containing wastes that arise in the Australian hazardous waste market include:

- PFOS containing aqueous film forming foam (AFFF, or firefighting foam)
- spent granular activated carbon (GAC) or similar absorbents used in extraction/ filtration processes from solids and liquids contaminated by PFAS
- PFAS contaminated soils and
- PFAS contaminated wastewaters.

This list is not exhaustive, as PFAS is increasingly being shown to be a ubiquitous contaminant. PFAS contaminated biosolids are not explicitly managed within the hazardous waste market, but contamination in this stream is a growing concern.

While concentrates like AFFF and spent GAC contain very high concentrations of PFAS, contaminated soil (including concrete rubble), contaminated waters and biosolids have lower levels of contamination. Wastes in the latter category are not necessarily less problematic though, because of the problems they pose to waste management infrastructure due to their sheer volume.

Levels, or concentrations, of PFAS in these wastes, like any other chemical contaminants, determine the extent of hazard posed, and the management options available within the Australian frameworks designed to protect human health and the environment from those hazards. Such concentrations must be measured through laboratory analysis, then compared against numerical criteria (or standards) established in Australian jurisdictions to guide the appropriate management of wastes that exhibit hazardous characteristics.

An important consideration for contaminated soils, the largest waste by tonnage arising into Australian waste management infrastructure, is what the contaminants are that constitute the hazardous characteristic(s) for the soil. More often than not there are multiple contaminants, although some may pose a greater hazard than others. When PFAS is one of those contaminants, but not the only contaminant, this can have ramifications for the acceptability of some types of management. There are two examples of this that are topical to this report:

- soils contaminated in PFAS and inorganic chemical contaminants, such as (most commonly) heavy metals
- soils contaminated in PFAS and asbestos, another particularly ubiquitous contaminant found in the industrial and post-demolition land contexts.

In these two examples of *co-contamination*, some management options alone will not acceptably manage the dual hazards posed. Any thermal process will neither destroy inorganic chemicals or asbestos, despite how successfully it might deal with organic contaminants such as PFAS. In the case of asbestos in particular, thermal treatment is likely to exacerbate the hazard, by distributing fibres into the air, potentially exposing treatment plant workers or their nearby communities.

All of the above types of PFAS wastes, including those co-contaminated with other (typically non-organic) chemical species, are considered in this report with respect to the applicability of management options potentially available to them.

3 Legal and policy considerations

Below are a range of state, national and international level legal, policy and guidance frameworks with relevance to PFAS waste management. These considerations are used as dimensions in which Australian management options are assessed later, in Section 5.

3.1 Stockholm Convention

Australia is a party to the *Stockholm Convention on Persistent Organic Pollutants* (the Stockholm Convention)[7], an international treaty which aims to protect human health and the environment from the effects of persistent organic pollutants (POPs). The Convention listed an original 11 pesticides and industrial chemicals in 2001, and a further 18 have been added since 2009. Australia is currently in the process of deciding whether to ratify the new chemicals added to the Convention since 2009.

POPs are hazardous and environmentally persistent substances which can be transported by the earth's oceans and atmosphere. POPs accumulate in living organisms and many have been found in the fatty tissues of humans and other animals. There is general international agreement that global action is required to reduce their impact on humans and the environment.

PFAS are by their nature also POPs, but only perfluorooctane sulfonic acid (PFOS), its salts (perfluorooctane sulfonates), perfluorooctane sulfonyl fluoride (PFOSF) and the most recent addition, perfluorooctanoic acid (PFOA), are actually included on the Stockholm Convention. These Stockholm POP-PFASs are likely to arise in waste with other PFAS chemicals, such as perfluorohexane sulfonate (PFHxS), which is currently under review for potential listing.

Under the Stockholm Convention domestic treaty making process, Australia must determine whether to ratify the listing of PFOS after considering the costs and benefits of ratification. This decision has not yet been made.

However, governments are working together to establish a national standard for the environmental risk management of industrial chemicals, which will set a nationally consistent environmental management approach for the use and disposal of industrial chemicals, including PFAS. This standard will be known as the Industrial Chemicals Environmental Management Standard (IChEMS). The Australian Government have stated publicly that an IChEMS priority from 2022 is scheduling chemicals listed on the Stockholm Convention that haven’t been ratified by Australia[8].

The Stockholm Convention is perhaps the most important policy driver, at the international level, for the sound management of POPs, including PFAS.

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[7] http://chm.pops.int/TheConvention/Overview/TextoftheConvention/tabid/2232/Default.aspx

[8] The Industrial Chemicals Environmental Management Standard, available at: https://www.dcceew.gov.au/environment/protection/chemicals-management/national-standard#our-scheduling-strategy

3.1.1 Key aspects of the Stockholm Convention

For the purpose of evaluating Australian management options for PFAS wastes, the Stockholm Convention provides the following key policy concepts, drivers and directions:

- *environmentally sound management* (ESM) of POPs
- *low POP content limits* (LPCLs)
- Basel and Stockholm Convention adopted technical guidelines on the *environmentally sound management* of wastes containing POPs and, specifically, PFAS.

3.1.1.1 Environmentally sound management

Environmentally sound management (ESM) is a concept specifically used in the Stockholm Convention, Basel Convention and implementing Australian hazardous waste legislation, and is also referred to as 'environmentally sound disposal' and (managed in an) 'environmentally sound manner'.

Article 6 of the Stockholm Convention deals with 'Measures to reduce or eliminate releases from stockpiles and wastes'. Paragraph 1(d) specifically requires parties to the Convention, with respect to stockpiles and wastes contaminated in listed POPs, to manage them 'in a manner protective of human health and the environment', by:

(i) handling them 'in an environmentally sound manner'

(ii) disposing of them "in such a way that the POP content is destroyed or irreversibly transformed so that they do not exhibit the characteristics of POPs or otherwise disposed of in an environmentally sound manner when destruction or irreversible transformation does not represent the environmentally preferable option."

3.1.1.2 Low POP content limit for PFAS

Low POP content limits (LPCLs) are introduced by the Stockholm Convention as a cut-off for when wastes, stockpiles and end of life articles containing POPs are subject to the Convention's requirements.

For the PFAS chemicals listed on the Convention (POP-PFAS), the Basel/ Stockholm technical guidelines for POP-PFASs (see Section 3.1.1.3) define the provisional low POP content for PFOS, its salts and PFOSF as 50 mg/kg.

3.1.1.3 Technical guidance documents issued by the Stockholm Convention

The Basel and Stockholm Conventions have developed a range of technical guidance documents[9], both for the management of POPs generally and also for specific POPs listed on the Stockholm Convention. Those directly relevant to this report are:

- *General technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with persistent organic pollutants*, UNEP/CHW.14/7/Add.1/Rev.1, June 2019. This is referred to hereafter as the "General POP guideline".
- *Technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with perfluorooctane sulfonic acid, its salts and*

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[9] All Basel/ Stockholm technical guidelines are available at: http://www.basel.int/Implementation/TechnicalMatters/DevelopmentofTechnicalGuidelines/TechnicalGuidelines/tabid/8025/Default.aspx

perfluorooctane sulfonyl fluoride, May 2015. This is referred to hereafter as the “POP-PFAS guideline”.

As their titles indicate, their key purpose is to prescribe *environmentally sound management* methods for wastes containing either general POPs or specifically POP-PFAS (namely PFOS, its salts and PFOSF).

The POP-PFAS guideline brings together ESM and LPCL for PFOS, by detailing further what Article 6 paragraph 1(d) of the Stockholm Convention means:

> “*55. Wastes with a content of PFOS, its salts or PFOSF above 50 mg/kg must be disposed of in such a way that the POP content is destroyed or irreversibly transformed in accordance with the methods described in subsection IV.G.2 or otherwise disposed of in an environmentally sound manner when destruction or irreversible transformation does not represent the environmentally preferable option in accordance with the methods described in subsection IV.G.3.*” (subsection III.A. paragraph 55, page 14).

The full titles and contents of subsections IV.G.2 and IV.G.3 of the POP-PFAS guideline are:

- “*IV. Guidance on environmentally sound management (ESM), G. Environmentally sound disposal, 2. Destruction and irreversible transformation methods:*
  - *103. Hazardous waste incineration is, according to the general technical guidelines, at least one of the destruction and irreversible transformation methods applicable for the environmentally sound disposal of wastes with a content of PFOS, its salts or PFOSF at or above 50 mg/kg*.
  - *104. For further information, see subsection IV.G.2 of the general technical guidelines*.
- *IV. Guidance on environmentally sound management (ESM), G. Environmentally sound disposal, 3. Other disposal methods when neither destruction nor irreversible transformation is the environmentally preferable option:*
  - *105. For information, see subsection IV.G.3 of the general technical guidelines*.”

This specifically identifies ‘hazardous waste incineration’ as a destruction and irreversible transformation methods that qualifies as ESM, and defers to the General POP guideline to define what constitutes both ‘other destruction and irreversible transformation methods’ and ‘other disposal methods when neither destruction nor irreversible transformation is the environmentally preferable option’.

The General POP guideline’s IV.G.2 subsection details, under “*IV. Guidance on environmentally sound management (ESM), G. Environmentally sound* disposal, 2. Destruction and irreversible transformation methods”, the following important points:

- Table 4 of the guidelines lists a range of destruction and irreversible transformation methods, specifically relevant to PFOS. They are:
  - cement kiln co-incineration
  - gas phase chemical reduction (GPCR)
  - hazardous waste incineration

  - supercritical water oxidation (SCWO) and subcritical water oxidation.

- While some of the above methods are not available in Australia, others that are, such as plasma arc and thermal/ metallurgical production of metals, are listed in the table as "not determined", which indicates that "information is not available in the literature referred to in this document to confirm the use of the technology" specifically for PFOS.
- "*161. For assessing the performance of the operations in subsections (a) to (k) below, a minimum DE*[10] *of 99.999 per cent, with 99.9999 per cent of DRE*[11] *as a supplement requirement where applicable, provides practical benchmark parameters for assessing disposal technology performance. Higher demonstrated DEs may be preferred on a case-by-case basis. As neither DE nor DRE take into account the potential transformation of the original POP to an unintentionally produced POP, potential releases of unintentionally produced POPs should be considered when choosing a particular operation*."

The General POP guideline's IV.G.3 subsection ("*IV. Guidance on environmentally sound management (ESM), G. Environmentally sound disposal, 3. Other disposal methods when destruction or irreversible transformation is not the environmentally preferable option*") describes two such methods (for wastes with contamination above the LCPL) as:

- '"(a) Specially engineered landfill", which uses both geological barriers and synthetic liners, landfill gas collection systems, leachate collection systems and leachate onsite treatment systems, such as "physico-chemical and biological treatments or advanced treatment technologies such as active carbon filtration, reverse osmosis and nanofiltration, among others." Waste pre-treatment, in the form of a solidification process, 'should' also be employed to ensure the potential of the POP content to enter the environment is minimised.
- "(b) Permanent storage in underground mines and formations", described as:
  - *"330. Permanent storage in facilities located underground in geohydrologically isolated salt mines and hard rock formations is an option for separating hazardous wastes from the biosphere for geological periods of time."*
  - "332. (b) *Caverns or tunnels … located in geological formations that are well below zones of available groundwater or in formations that are completely isolated by impermeable rock or clay layers from water-bearing zones*."

3.2 Basel Convention

The *Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal*[12] (the "Basel Convention") regulates the movement of hazardous wastes across international boundaries. Australia was a foundation signatory to it in 1992, when it came into force.

Under this Convention, the movement of hazardous wastes across international boundaries requires the prior informed consent of all countries involved in the movement, which can only be granted if it is demonstrated that the hazardous wastes are transported and disposed of

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[10] DE = destruction efficiency
[11] DRE = destruction removal efficiency.
[12] http://www.basel.int/Portals/4/Basel%20Convention/docs/text/BaselConventionText-e.pdf

in an *environmentally sound manner*. One hundred and eighty-seven other countries had ratified the Basel Convention as at July 2021. The Convention aims to:

- minimise generation of hazardous waste
- ensure adequate disposal facilities are available
- control and reduce international movements of hazardous waste
- ensure environmentally sound management of wastes
- prevent and punish illegal traffic.

The Basel Convention and the Stockholm Convention are jointly managed by the Switzerland-based Secretariat of the Stockholm Convention, which also supports the Rotterdam Convention[13].

3.2.1 Key aspects of the Basel Convention

The Basel Convention shares key environmental protection concepts with the Stockholm Convention, such as the application of *environmentally sound management* and *LPCLs* in wastes, for its decision-making about international waste movements. Basel also provides the framework for assessing hazardous characteristics, in line with dangerous goods classification approaches, which is the foundation for Australia's definition, classification and management of hazardous wastes.

3.2.1.1 Australia's Hazardous Waste Act

The Commonwealth Government implements its Basel Convention responsibilities through the *Hazardous Waste (Regulation of Exports and Imports) Act 1989*[14] (the "Hazardous Waste Act"), which regulates (via a permitting system) movement of hazardous wastes in and out of Australia.

The object of the Hazardous Waste Act is to:

> *"… regulate the export, import and transit of hazardous waste to ensure that exported, imported or transited waste is managed in an environmentally sound manner so that human beings and the environment, both within and outside Australia, are protected from the harmful effects of the waste."*

ESM is defined in the Act as:

> "*A reference in this Act to the environmentally sound management of hazardous waste is a reference to taking all practicable steps to ensure that the waste is managed in a manner that will protect human health, and the environment, against the adverse effects that may result from the waste*."

Like the Basel Convention, *protection from harm* and management in an *environmentally sound manner* are key concepts that the Hazardous Waste Act must consider in decisions that relate to it.

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[13] Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade, available at: http://www.pic.int/TheConvention/Overview/TextoftheConvention/tabid/1048/language/en-US/Default.aspx

[14] https://www.environment.gov.au/protection/hazardous-waste/about

3.3 The PFAS National Environmental Management Plan

The Heads of EPAs Australia and New Zealand (HEPA) collaborated to develop the PFAS National Environmental Management Plan (PFAS NEMP)[15] and its 2020 update (PFAS NEMP v2.0[16]), which is designed to achieve a nationally agreed approach to the environmental regulation of PFAS.

The PFAS NEMP essentially acts as minimum guidance for states and territories on the management of PFAS contamination in the environment. This is drawn from the latest scientific knowledge, which is still emerging, hence the iterative approach to its revision, with a third edition underway at the time of writing. It guides the regulation of PFAS contaminated sites, PFAS contaminated materials and, where applicable, PFAS-containing products.

A key aspect of the NEMP, from the perspective of waste management, is its provision of PFAS environmental guideline values such as:

- human health investigation levels for soil
- ecological guideline values for soil and
- landfill acceptance criteria (for contaminated soil and other wastes), drawn from the Stockholm LPCL and leachability values taken as multiples of drinking water standards, using a risk based approach.

The NEMP refers directly to management of POP wastes via the Stockholm Convention's Article 6 paragraph 1(d)(ii), as described in this report's Section 3.1.1.1 – that the POP content is 'destroyed or irreversibly transformed' or 'otherwise disposed of in an environmentally sound manner…'

3.4 Origins of the PFAS NEMP

The PFAS NEMP built on 2016 work by the Australian Government Department of the Environment and Energy, *Commonwealth Environmental Management Guidance on Perfluorooctane Sulfonic Acid (PFOS) and Perfluorooctanoic Acid (PFOA)*[17], referred hereafter as the *2016 Commonwealth guidance*. This document was developed "to provide Commonwealth agencies with a consistent, practical, risk-based framework for the assessment and management of PFOS and PFOA contamination on and potentially originating from Commonwealth sites (including airports subject to the Airports Act, 1996)"[18].

The Department of Defence was a key driver for the establishment of this guidance, due to their experience in assessing PFAS contamination on and from their sites.

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[15] PFAS NEMP January 2018, available at https://www.epa.vic.gov.au/your-environment/land-and-groundwater/pfas-in-victoria/pfas-national-environmental-management-plan.

[16] PFAS NEMP Version 2.0 - January 2020, available at https://www.environment.gov.au/system/files/resources/2fadf1bc-b0b6-44cb-a192-78c522d5ec3f/files/pfas-nemp-2.pdf.

[17] Australian Government Department of the Environment and Energy, *Commonwealth Environmental Management Guidance on Perfluorooctane Sulfonic Acid (PFOS) and Perfluorooctanoic Acid (PFOA)*, Draft, October 2016, available at: https://www.agriculture.gov.au/sites/default/files/env/pages/dfb876c5-581e-48b7-868c-242fe69dad68/files/draft-environmental-mgt-guidance-pfos-pfoa.pdf.

[18] The 2016 Commonwealth guidance, 3. Objective, page 6.

The preface of the document frames the guidance to respond directly to the Stockholm and Basel Conventions, including "disposal of POPs content in accordance with Article 6 of the Stockholm Convention, and application of the low content limit for PFOS (50mg/kg) and other waste management approaches in the Basel POPs Technical Guidelines and PFOS Technical Guidelines".

The 2016 Commonwealth guidance provided investigation levels considered later in the NEMP, but of most significance for this review is its direct reference to Article 6 of the Stockholm Convention and subsequent detailed Convention technical guidance. Box 6 on page 22 of the 2016 Commonwealth guidance states:

> "*When destruction or irreversible transformation does not represent the environmentally preferable option due to environmental or human health impacts, then the PFOS in the contaminated soil or sediment should:*
>
> - *be either immobilised or its mobility substantially reduced, for example, using emerging treatment/immobilisation technologies; or*
> - *be disposed of in highly secure specially engineered landfill or, when commercially available in Australia, permanent storage in underground mines and formations, consistent with Section IV.G.3 of the Basel Convention's General technical guidelines on the environmentally sound management of waste consisting of, containing or contaminated with persistent organic pollutants*."

3.5 The original PFAS NEMP

Building on the 2016 Commonwealth guidance, the 2018 PFAS NEMP development process was led by EPA Victoria, on behalf of HEPA.

The 2017 consultation draft of the original PFAS NEMP[19] retained the contents of Box 6 from the 2016 Commonwealth guidance, as described in Section 3.4, which refers specifically to the alternatives to destruction or irreversible transformation outlined by the Basel/ Stockholm technical guidelines.

The final edition of the original PFAS NEMP, published in February 2018, retained the reference to the Stockholm Convention's Article 6 paragraph 1(d)(ii), but chose to remove the further elicitation of what 'disposed of in an environmentally sound manner' meant, according to the Conventions' technical guidelines, i.e., the following words both from the draft and the preceding 2016 Commonwealth guidance:

> "… *be disposed of in highly secure specially engineered landfill or, when commercially available in Australia, permanent storage in underground mines and formations, consistent with Section IV.G.3 of the Basel Convention's General technical guidelines...*"

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[19] HEPA, *PFAS National Environmental Management Plan, Consultation Draft*, August 2017, available at: https://www.epa.sa.gov.au/files/13061_pfas_mgt_plan_draft_2017.pdf.

3.6 State-based PFAS policies and landfill/ management criteria

The PFAS NEMP is the primary guidance for PFAS waste management settings such as acceptance criteria or other environmental values. However, some jurisdictions have expanded on this minimum benchmark, particularly in relation to regulatory or landfill acceptance limits, as discussed below.

Preceding the NEMP, NSW published its *Addendum to the Waste Classification Guidelines (2014) – Part 1: classifying waste*[20] in October 2016, which added PFOS, PFHxS and PFOA specific contaminant concentration values and toxicity characteristics leaching procedure (TCLP) values for the categorisation of waste as either general solid waste or restricted solid waste.

Also preceding the NEMP, WA published its *Interim Guideline on the Assessment and Management of Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS), Contaminated Sites Guidelines*, in January 2017.

The Qld Information sheet for Regulated Waste, *Overview of regulated waste categorisation*[21] outlines the regulated waste categorisation provisions of Chapter 5, Part 1 and Schedule 9 of the *Environmental Protection Regulation 2019* for waste generators and receivers. This categorisation framework somewhat uniquely views any measurable level of PFAS contamination as constituting Regulated Waste, which is Qld regulatory language for hazardous waste.

All state-based values are documented against PFAS NEMP landfill acceptance criteria in Table 1. States and territories not mentioned below use the NEMP for PFAS waste classification.

A notable observation from Table 1 is that Qld and NSW regulations are significantly stricter than the NEMP with what PFAS wastes they accepts into landfill. Qld's approach is to regulate essentially any detectable level of PFAS as Regulated Waste above limits of reporting (LOR). The PFAS NEMP suggests indicative LORs available at standard commercial laboratory rates are:

- 1-5 μg/kg (or 0.001-0.005 mg/kg) for soil (equivalent to total concentration)
- 0.01-0.05 μg/L for water (equivalent to leachable concentration).

It is noted that Qld's <LOR thresholds do not directly relate to landfill acceptance criteria, but denote such waste as Regulated Waste, meaning it has the highest level of regulatory control in Qld.

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[20] NSW EPA (2016), *Addendum to the Waste Classification Guidelines (2014) – Part 1: classifying waste*, available at: https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/wasteregulation/addendum-1-to-the-waste-classification-guidelines.pdf

[21] Qld Government (2022), Information sheet for Regulated Waste, *Overview of regulated waste categorisation*, available at:https://environment.des.qld.gov.au/__data/assets/pdf_file/0026/89333/era-is-categorising-regulated-waste.pdf.

Table 1: Australian landfill acceptance criteria/ waste classification for PFAS wastes

		Landfill acceptance criteria/ waste classification equivalent for sum of PFOS + PFHxS			
Landfill type	**Criteria type**	**NEMP**	**NSW[22,23]**	**WA[24]**	**Qld[25]**
Unlined	ASLP leachable concentration (µg/L)	0.07	N/A	0.001	-
	Total concentration (mg/kg)	20	N/A	0.02	<LOR[25]
Clay/ single composite lined	ASLP leachable concentration (µg/L)	0.7	0.05	1.3	-
	Total concentration (mg/kg)	50	1.8	5	<LOR[25]
Double composite lined	ASLP leachable concentration (µg/L)	7	0.2	13	-
	Total concentration (mg/kg)	50	7.2	50	<LOR[25]

3.7 Recent USA policy interventions

Destruction has historically been the preferred management of POPs of all kinds, and thermal techniques have been highlighted as the most effective. For example, thermal destruction has typically been recommended by the various Stockholm Convention technical guidelines as a sound choice method for managing POP waste.

However, most of the brominated and fluorinated POPs (as opposed to the originally listed chlorinated POPs) are highly flame-retardant, which is the reason for their past commercial use and successful application. They are very hard to burn.

Questions are beginning to be asked about whether the prevailing understanding of 'traditional POP' destruction applies as well to PFAS, relating to the efficacy of destruction of PFAS chemicals in thermal processes such as incineration. These include:

- If PFAS (and potentially brominated flame retardants) are more resistant to being burnt than chlorinated POPs, do the same residence time/temperature conditions completely combust and therefore destroy PFAS?
- If these conditions are indeed suitable to enable complete combustion of PFAS, are they being required, demonstrated and monitored by thermal plant regulators? In other words, are these plants operating to the specifications required to destroy PFAS?

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[22] NSW EPA 2016, Addendum to the Waste Classification Guidelines (2014) – Part 1: classifying waste, available at: https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/wasteregulation/addendum-1-to-the-waste-classification-guidelines.pdf

[23] 'Unlined' landfills are not applicable in NSW as the minimum standard in that state is a primary barrier system.

[24] WA DER 2017, Government of Western Australia Department of Environment Regulation, *Interim Guideline on the Assessment and Management of Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS), Contaminated Sites Guidelines*, Version 2.1 January 2017, available at: https://www.der.wa.gov.au/images/documents/your-environment/contaminated-sites/guidelines/Guideline_on_Assessment_and_Management_of_PFAS_v2.1.pdf

[25] Thresholds for Regulated Waste in Qld for PFAS are 0 mg/kg, which is defined as less than the level of reporting (LOR) limit.This means any detectable concentration of PFAS deems a waste to be Regulated Waste.

- What is the evidence that products of incomplete combustion (PICs) containing fluorinated species are not produced from incomplete combustion of PFAS or reformation of combustion by-products?
- In trying to solve one environmental problem (destroying AFFF and related PFAS wastes) are we creating a new one in PFAS or related chemical dispersal into the air environment, from thermal (incomplete) combustion?
- What studies or monitoring are being carried out to answer these questions?
- In light of these questions, are traditional thermal treatment facilities fit for purpose for complete PFAS waste destruction, particularly with higher concentration wastes?

3.7.1 US EPA interim guidance regarding PFAS management

In December 2020, the US Environmental Protection Agency (US EPA) published interim guidance on this very subject: *Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances*[26]. The document considers the types of PFAS wastes discussed in this report, and reviews the following types of management for suitability of managing each of these waste types:

- thermal treatment
- landfills
- underground injection (considered for liquid PFAS wastes)
- storage.

The guidance provides ‘the best up-to-date information on potential releases during the destruction and disposal of PFAS and PFAS-containing materials and identifies data gaps to be filled that can inform future EPA guidance.’

Below are the concluding statements from the guidance relevant to Australian agencies tasked with making informed decisions in the evaluation of existing destruction and disposal options, noting the significant uncertainties that apply:

> *“Managers of PFAS materials could consider the following existing destruction and disposal options in the order of lower uncertainty to higher uncertainty while considering the other factors mentioned above to come up with a decision that is as protective of the environment as possible.*
>
> ***1. Interim storage**. While not a destruction or disposal method, interim storage may be an option if the immediate destruction or disposal of PFAS and PFAS-containing materials is not imperative. In general, interim storage (estimated to be anywhere from 2 to 5 years) would be utilized until research reduces the uncertainties associated with other options.*
>
> ***2. Permitted deep well injection** (Class I). Underground injection would be limited to liquid-phase waste streams.*

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[26] US EPA (2020), *Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances*, available at: https://www.regulations.gov/document/EPA-HQ-OLEM-2020-0527-0003.

> ***3. Permitted hazardous waste landfills** (RCRA Subtitle C). These have the most stringent environmental controls in place and higher potential capacity to manage the migration of PFAS into the environment.*
>
> ***4. Solid waste landfills** (RCRA Subtitle D) that have composite liners and leachate collection and treatment systems. These landfills receive non-hazardous waste and tend to have environmental controls commensurate with the waste they receive. These controls can vary from state to state.*
>
> *The following options have higher levels of uncertainties regarding their capacity to manage the migration of PFAS into the environment. In order to reduce the uncertainties, interim storage may be considered for PFAS or PFAS-containing materials before these options are selected…*
>
> ***5. Hazardous waste combustors**. These would include commercial incinerators, cement kilns, and lightweight aggregate kilns, subject to the considerations outlined in this guidance.*
>
> ***6. Other thermal treatment**. This would include carbon reactivation units, sewage sludge incinerators, municipal waste combustors, and thermal oxidizers, subject to the considerations outlined in this guidance."*

The guidance notes that the carbon–fluorine bond is much stronger than the carbon–chlorine bond, and that breaking the carbon–fluorine bond requires 1.5 times more energy and therefore higher temperatures and reaction times. However, it also makes it clear that specific types of thermal treatment are likely to destroy PFAS if these flame conditions are met. The reasons for its caution and uncertainty around thermal destruction technologies can be summarised as:

1. A lack of definitive evidence of complete PFAS destruction in real-world conditions ('few experiments have been conducted under oxidative and temperature conditions representative of different field-scale incineration devices used for PFAS destruction').
2. A poor understanding and evidence base on the potential formation/reformation of products of incomplete combustion (PICs).
3. The current lack of standardised methods to measure PFAS and PFAS-PIC emissions ('lack of validated sampling and measurement methods for the potentially large number of fluorinated and mixed halogenated organic compounds that might be formed').
4. Uncertainty whether air pollution control devices (used at thermal plants) are adequately controlling fluorinated PICs (which EPA recognises to be 'inevitable').
5. Poor field data from existing thermal operations that destroy PFAS wastes, in terms of PFAS/fluorinated PIC emissions characterisations against feed waste concentrations and types.

The guidance describes current research into PFAS thermal treatment conditions and PIC characterisation and behaviour through pollution control processes for various PFAS-containing materials, as well as methods for sampling and analysing PFAS in air emissions and ambient air. Planned areas of future research by US EPA are identified in three broad areas:

1. Research to better characterise PFAS-containing materials targeted for destruction or disposal, so that management methods can be better tailored to which material streams.
2. Research to measure and assess the effectiveness of existing methods for PFAS destruction, improve existing methods, and/or develop new methods for PFAS destruction.
3. Research to measure and assess the effectiveness of existing methods for PFAS disposal, improve existing methods, and/or develop new methods for PFAS disposal.

Concluding the discussion, it seems that destruction of PFAS in thermal plants commonly used in Australia (soil thermal treatment facilities, cement kilns and plasma arc facilities) is likely to destroy the vast majority of PFAS, but significant uncertainty remains:

- Fluorinated PICs may pass through the combustion and air pollution control stages to be released, at some level, in the surrounding air. This uncertainty is enhanced by the unresolved nature of what fluorinated PICs might be formed and how to standardise testing for them.
- There is limited field-based evidence that either PFAS or fluorinated PICs are completely destroyed in operational facilities, and therefore do not migrate to surrounding communities, either by air emission or solid residual waste pathways.

3.7.2 US Department of Defense response

In response to the US EPA's interim PFAS management guidance, the US Department of Defense has momentarily ceased thermal destruction of PFAS containing materials.

In a memo dated 26 April 2022[27], the Defense Department issued a ban on incinerating PFAS-laden items, with particular emphasis on AFFF. Under the *2022 National Defense Authorization Act*, the military was required to prohibit incineration of those materials beginning April 26, with a moratorium now in full enforcement for all Defense contracts, new and existing.

The memo states that the prohibition is in place until the Defense Department "issues guidance implementing the US EPA interim guidance on the destruction and disposal of PFAS", which it indicates is well progressed.

3.7.2.1 Community activism against the Defense Department

Even prior to the emergence of the US EPA's cautionary guidance, questions about the suitability of thermal destruction to PFAS-containing wastes had surfaced there, where incineration is a common existing form of municipal solid waste management. The US Defense Department had contracted several commercial incinerators to destroy stocks of AFFF since 2016. Following a range of reports in the US press questioning the safety of disposing of AFFF by incineration, specifically about the potential for PFAS and related air

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[27] Office of the Assistant Secretary of Defense (26 April 2022), *Temporary Prohibition on Incineration of Materials Containing Per- and Polyfluoroalkyl Substances (PFAS)*, available at: https://media.defense.gov/2022/Apr/28/2002986273/-1/-1/1/TEMPORARY-PROHIBITION-ON-INC[…]NG-PRE-AND-POLYFLUOROALKYL-SUBSTANCES-PFAS-APRIL-26-2022.PDF.

emissions impacting nearby communities, a lawsuit was filed against the Department in February 2020[28].

The lawsuit alleged that the Department of Defense was irresponsible in contracting a number of incineration facilities, violating the *National Defense Authorization Act 2019*, which spelled out guidelines for safely incinerating AFFF. The Act requires the Defense Department to ensure that incineration is conducted at sufficient temperature to ensure the maximum degree of emission reduction. The plaintiffs argue that no specification of operating temperatures was made by Defense, and no due diligence was carried out to demonstrate adherence to these operating conditions as evidence of likely PFAS destruction.

The lawsuit stopped short of claiming actual harm to communities surrounding the incinerators that disposed of Defense's AFFF, but inferred this based on the lack of oversight of the facilities' operations.

3.8 Hazardous waste and the Waste Hierarchy

Decisions about the relative environmental credentials of waste management choices have often been made on the basis of positioning of that management choice on the waste hierarchy. The waste hierarchy is described in many policy documents around the world, including Victoria's very recently amended Environment Protection Act[29]:

> "***18 Principle of waste management hierarchy***
>
> *Waste should be managed in accordance with the following order of preference, so far as reasonably practicable—*
>
> (a) *avoidance;*
>
> (b) *reuse;*
>
> (c) *recycling;*
>
> (d) *recovery of energy;*
>
> (e) *containment;*
>
> (f) *waste disposal*."

However, consideration of two sometimes opposing properties is required in determining the most appropriate environmental management for hazardous wastes. This is because there is a competing tension between hazard protection and resource efficiency (the latter being the aim of circular economy approaches) that is not the case with non-hazardous wastes – which one should outweigh the other in an integrated environmental assessment? This dilemma is represented by Figure 1.

The waste hierarchy promotes recycling and energy recovery above hazard treatment and containment approaches, but is silent on the issue of protection from harm, which makes it limited as a single decision tool for management of hazardous wastes. This limitation is

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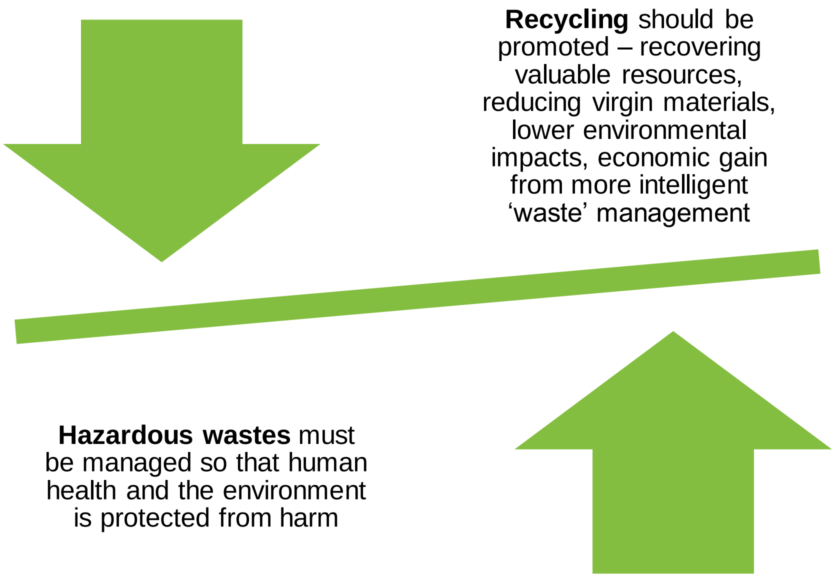
[28] EarthJustice (20 February 2020), *Department of Defense Illegally Burning Stockpiles of Toxic "Forever Chemicals"*, available at: https://earthjustice.org/news/press/2020/department-of-defense-illegally-burning-stockpiles-of-toxic-forever-chemicals.

[29] State Government of Victoria, *Environment Protection Act 2017*, available at: https://www.legislation.vic.gov.au/in-force/acts/environment-protection-act-2017/006

recognised by the Department Environment Food and Rural Affairs (DEFRA) in the UK, through specific guidance on applying the waste hierarchy to hazardous waste[30], which has been written to assist compliance with the *Waste (England and Wales) Regulations 2011*.

Figure 1: The hazardous waste 'recover' versus 'protect' dilemma



DEFRA's advice and the regulations themselves require waste management that "*takes into account the resource value of the hazardous wastes and the need for health and safety to be maintained*", which "*may result in a lower option in the hierarchy being chosen but results in a better overall environmental outcome*." Clause 12(3) of the Regulations also require "*technical feasibility (such as lack of infrastructure availability) and economic viability*" to be considered when applying the hierarchy.

The waste hierarchy is most applicable to non-hazardous waste, where cost and efficiency are the main drivers (and not protection from hazard). As the hazard of a waste goes up, the more important the protection from its hazard becomes, compared to recovering resource value, if both can't be done together. Protection from harm is fundamental to hazardous waste management.

3.9 Liabilities for PFAS damages

PFAS related future damages, costs and liability for harm is becoming increasingly relevant for organisations who could be held responsible for PFAS contamination of land, waters and potentially the air environment. These liabilities could impact in two ways:

- whether insurance policies for a site's operations extend to cover future issues related to PFAS contamination

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[30] DEFRA (2011), *Guidance on applying the waste hierarchy to hazardous waste*: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69457/pb13687-hazardous-waste-hierarchy-111202.pdf

- whether PFAS waste treated on-site, or removed for off-site management, could retain some liability on the producer of that waste in the event of a future contamination issue, regardless where that issue occurs (contingent liability).

3.9.1 Limitations on insurance coverage

PFAS contamination is a growing concern for insurers, where the addition of PFAS pollution exclusions to their polices are becoming more commonplace as a way to limit their own risk. For example, a leading international insurer's commercial insurance policy has been sighted by the author to contain a "PFAS Absolute Exclusion Endorsement", as a form of recent annexure to an existing policy. This exclusion relates solely to PFAS and voids the applicability of the policy in the event of loss, damages, liability, cost or related impact caused directly or indirectly, or in connection with PFAS.

This substantially increases the risks and liabilities associated with managing PFAS containing wastes, where the PFAS is not destroyed.

3.9.2 Contingent liability

Corporate accounting and financial considerations encompass a company's liabilities. A contingent liability is a liability that may occur depending on the outcome of an uncertain future event. A contingent liability is recorded on the company's accounts if the contingency is likely and the amount of the liability can be reasonably estimated. The liability may be disclosed in a footnote on the financial statements unless both conditions are not met.

If onsite or offsite management of a company's PFAS wastes do not destroy PFAS, or contain it sufficiently to remove all risk of future harm it may cause humans or the environment, then a contingent liability may still exist in the accounts of the PFAS waste producing company, regardless of where or even if a future contamination event occurs.

3.9.3 Australian community class actions

Such liability can manifest itself in the form of class actions taken by communities against those responsible for management of PFAS waste. Australia is likely to follow the trend in the US where communities surrounding defence bases, airports and fire-fighting facilities, have initiated class actions against government to address potential human harm (health) and environmental compensation and finance the clean-up of surrounding lands contaminated by PFAS and hydrocarbons.

The Australian Government has so far paid out compensation of $212 million[31] to communities surrounding three military bases in New South Wales, the Northern Territory and Queensland through similar class actions. This is a fraction of the remaining military bases, airports and fire-fighting facilities that will likely attract scrutiny from the public in the future. The US Government, realising the enormity of the problem, has set aside $10 billion[32] for the clean-up of surrounding contaminated lands.

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[31] The Sydney Morning Herald (March 11, 2020), *Landmark legal settlement as government pays $212m to victims of toxic contamination*, available at: https://www.smh.com.au/national/landmark-legal-settlement-as-government-pays-212m-to-victims-of-toxic-contamination-20200311-p548x5.html

[32] Star Tribune (11 September, 2021), *3M's support for PFAS could cost taxpayers billions of dollars*, available at: https://www.startribune.com/3m-s-support-for-pfas-could-cost-taxpayers-billions-of-dollars/600096094/.

3.10 Summary of the key legal and policy considerations

The legal and policy considerations countenanced throughput Section 3, as they most closely relate to evaluating PFAS waste management approaches, can be distilled down to four key dimensions for comparison of Australian management options:

1. Environmentally sound management (ESM) for wastes above the Stockholm Convention's level of concern, the low POP content limit (LPCL) of 50 mg/kg.
2. US EPA interim guidance's preferred order of priority for destruction and disposal options, based on ranging uncertainty for protection of the environment.
3. Waste hierarchy in a hazardous waste (and specifically PFAS) context.
4. Risk of insurance policy exclusion (and contingent liability) for PFAS-related incidents or issues.

3.10.1 ESM for wastes above the LPCL

The concept of environmentally sound management is reinforced as perhaps the most important principle throughout Section 3, from the Stockholm and Basel Conventions at the international level to the Hazardous Waste Act and PFAS NEMP at the national level. Definition and detailed elaboration of what ESM (for wastes with PFAS above the LPCL, or 50 mg/kg) looks like in various contexts is provided by the Conventions' technical guidelines as being:

- destroyed or irreversibly transformed in accordance with the following methods:
  - cement kiln co-incineration
  - gas phase chemical reduction (GPCR)
  - hazardous waste incineration
  - supercritical water oxidation (SCWO) and subcritical water oxidation
  - other methods (such as plasma arc) listed in Table 4 on p.35 of the General POP Guideline, with additional information to confirm their validity with respect to PFAS destruction or irreversible transformation
- or, when destruction or irreversible transformation does not represent the environmentally preferable option:
  - specially engineered landfill (equivalent to hazardous waste landfill in Australia), with a requirement for leachate treatment as a recommendation for immobilisation pre-treatment.
  - permanent storage in underground mines and formations, such as geohydrologically isolated salt mines or hard rock formations for separating hazardous wastes from the biosphere for geological periods of time.

For wastes below the LCPL in PFAS (50 mg/kg), the General POP Guideline infers a preference for any of the management methods identified as ESM in the dot points above, but also allows for disposal "in an environmentally sound manner in accordance with pertinent national legislation and international rules, standards and guidelines, including specific technical guidelines developed under the Basel Convention." This essentially recognises the PFAS NEMP as national guidance, which allows for lower levels of landfill for

PFAS wastes below 50 mg/kg (single lined) and 20 mg/kg (unlined), noting the leachability criteria that accompany these contaminant levels.

3.10.2 US EPA management priority

This dimension follows a diminishing order of preference for existing destruction and disposal options, to be as protective of the environment as possible:

1. interim storage
2. deep well injection (for liquid wastes)
3. hazardous waste landfill
4. solid waste landfill
5. hazardous waste incinerators and cement kilns
6. other thermal treatment.

3.10.3 Waste hierarchy (for hazardous waste)

POPs above the LPCL cannot be recycled or reused according to the Stockholm Convention, other than in specific exempt circumstances, so this falls away as a consideration of PFAS waste in a waste hierarchy context.

A decision of how to manage a waste that is presented is too late for consideration of avoidance, so that leaves a set of considerations remaining:

1. recovery of energy, with demonstrated protection from harm to the environment or human health
2. containment, with demonstrated protection from harm to the environment or human health
3. disposal, with demonstrated protection from harm to the environment or human health.

3.10.4 Insurance policy exclusion/ liability for PFAS contamination

This dimension requires consideration of the risk that an insurance policy, a key operational issue for hazardous waste managers, could refuse to cover, refuse to recognise a claim in relation to PFAS.

Related to this is a waste management facility’s capacity to destroy or isolate PFAS sufficiently, to satisfy the insurance and accounting industry requirements for extinguishing/ reducing future liability. International and Australian Accounting Standards (IAS 37 and AASB 137) require a waste producer to maintain an accounting provision equal to its best estimate of the future cost of properly disposing of that waste – contingent liability. Such a liability may or may not be removed from the waste producer’s business, even if the waste has been removed from site.

The dimension of insurance policy coverage and liability removal is connected to community acceptance as well more specific scientific evidence of potential to create offsite harm.

4 Management options in Australia

PFAS management options in Australia are still evolving, as they are around the world, but given the pressing nature of the problem of PFAS wastes such as contaminated soils, a number of approaches have been adopted over the last five years.

Various key references[33,34,35,36] have been used, along with the author's understanding of Australia's hazardous waste infrastructure, to come up with a list of PFAS management options currently available in Australia or, in the case of the last-listed option, those with at the potential for further development. Those PFAS options considered in this report are:

1. thermal desorption and off-gas destruction
2. biosolids-specific gasification
3. incineration/ cement kiln
4. plasma arc
5. solid waste landfill (unlined landfills 'should be avoided')
6. hazardous waste landfill
7. geological repository
8. in-situ sorption/ separation/ stabilisation methods
9. in-situ soil 'washing'
10. under-developed technologies/ approaches.

We note that there are more technology options possible, as described in the references above, but these are not in development or operation in Australia and may not yet be specifically proven for PFAS destruction/ management.

Table 2 summarises these options, including the facilities within Australia that operate each technology and which PFAS-containing waste materials they may or do target. The subsections following describe each option in greater detail.

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[33] UNEP (2019), *General technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with persistent organic pollutants (General POPs)* [The General POP Guideline], available at: http://www.basel.int/Implementation/TechnicalMatters/DevelopmentofTechnicalGuidelines/TechnicalGuidelines/tabid/8025/Default.aspx

[34] ITRC (2022), Technical resources for addressing environmental releases of per- and polyfluoroalkyl substances (PFAS), available at: https://pfas-1.itrcweb.org

[35] Blue Environment in association with Randell Environmental Consulting and Ascend Waste and Environment (2019), *Assessment of hazardous waste infrastructure needs and capacities in Australia 2018*, prepared for the Department of the Environment and Energy, available at: https://www.dcceew.gov.au/environment/protection/publications/hazwaste-infrastructure-assessment-2018

[36] HEPA, *PFAS National Environmental Management Plan, Consultation Draft*, August 2017, available at: https://www.epa.sa.gov.au/files/13061_pfas_mgt_plan_draft_2017.pdf.

Table 2: Summary of PFAS waste management options in Australia

Option	Description	Target materials	Sites in Australia
1.Thermal desorption and off-gas destruction	Thermal treatment process intended to remove contaminants from solids and drive them into the vapor phase (desorption) where they are destroyed by a higher temperature afterburner, leaving decontaminated heat-treated soil to be used for other purposes or landfilled.	Contam. soil AFFF/ GAC	Four in Vic: Renex Dandenong Sth, EnviroPacific (Solve) Laverton, Veolia Brooklyn and SUEZ-Ventia (EarthSure) at Lyndhurst landfill site
2. Biosolids-specific gasification	Essentially similar to Thermal desorption and off-gas destruction, because gasification burns a syngas at high temperature for energy recovery. Separated as a technique because it is biosolids-specific and not a primary technique for PFAS destruction.	Biosolids	Logan City Council, Qld, operate Australia's first biosolids gasification plant
3. Incineration/ cement kiln	Destruction of chemicals using heat, where very high temperatures are applied directly to the PFAS-contaminated solids or liquids. Cement kiln hazardous waste destruction is known as co-incineration because chemical destruction and cement clinker production occurs simultaneously.	Wastewaters AFFF/ GAC	Cement Australia (Gladstone Qld and Railton Tas). Various clinical waste incinerators (located in Vic, NSW, SA and WA) and other potential thermal infrastructure not licensed to manage PFAS but with potential to, such as new EFW plants, residue derived fuel plants, brickworks and metal smelters.
4. Plasma arc	Destruction technique where liquid or gaseous waste is rapidly heated (up to 3,100°C) in plasma arc causing dissociation elemental ions and atoms. May be used with pre-treatment, such as thermal desorption.	Wastewaters AFFF/ GAC	Cleanaway Narangba Qld
5. Solid waste landfill	Offsite disposal in clay/single composite lined landfills, typically used for non-hazardous waste but may also accept low level hazardous wastes such as tyres, asbestos and low-level contaminated soil (below prescribed contaminant limits).	Contam. soil Co-contam. soil Biosolids	Various single-lined landfills across Aust.
6. Hazardous waste landfill	Offsite disposal in double composite lined landfills fitted with leachate collection, typically used for hazardous solid waste below prescribed contaminant limits.	Contam. soil Co-contam. soil Biosolids	Various double-lined landfills across Aust., including Taylors Road Lyndhurst Vic, Elizabeth Drive Kemps Creek NSW and Ti-tree Bioenergy Willowbank Qld
7. Geological repository	Offsite containment/ disposal in geological and man-made barriers to isolate waste permanently from the biosphere. Often employed with ‘front-end’ mining (kaolin/ salt) as ‘back-end’ waste deposition in the voids created.	Contam. soil Co-contam. soil Wastewaters AFFF/ GAC	Tellus Sandy Ridge WA

Option	Description	Target materials	Sites in Australia
8. In-situ sorption/ separation/ stabilisation methods	In-situ treatments using either sorption media (waters – 'pump and treat') followed by offsite residue media management or direct amendment product application to stabilise (soils).	Contam. soil, waters	Pump and treat using GAC widely adopted onsite in Australia for groundwater clean-up. Soil amendment not routinely used at present.
9. In-situ soil 'washing', offsite residue management	A proprietary wet, physical and chemical 'washing' process employed onsite to remove PFAS from soil fractions. The residual separated PFAS requires management offsite while the 'washed' soil can be re-emplaced, depending on the effectiveness of PFAS removal.	Contam. soil	In-situ treatment offered by Ventia (SourceZone technology)
10. Under-developed technologies/ approaches	Not yet fully proven for PFAS management, but manages other POPs, such as solvated electrons (advanced reduction processes). Other technologies still at trial stage, such as: nano remediation, AECOM's DE-FLUORO (electrochemical oxidation) process, in-situ thermal and foam fractionation.	Contam. soil Wastewaters	Not yet fully developed or implemented commercially in Australia.

4.1 Thermal desorption and off-gas destruction

This is a two-step thermal treatment process intended to remove organic chemical contaminants (such as PFAS) from solids (typically soil) by using moderate heat to drive them into the vapor phase (desorption), where they are collected and destroyed by a high temperature afterburner, leaving decontaminated heat-treated solid material to be recycled for other purposes, or landfilled.

Effectiveness depends on the ability to deliver heat to achieve sufficient and evenly distributed temperature cost-effectively. For highly contaminated soil, treatment may only reduce the contamination to acceptably low levels, cost-effectively, so that the thermally treated material must be landfilled (or used as landfill cover) rather than re-purposed in soil or structural applications. This is particularly true of facilities that co-locate such treatment with landfill, such as the SUEZ-Ventia (EarthSure) facility in Victoria.

An advantage of this approach over mass burn incineration is the ability to separate and reduce/ destroy the hazard while retaining the ability, for intermediate and low concentration contamination, to recycle the thermally treated residual soil material into other uses.

This method is subject to the same US EPA cautions, around destruction efficiency and the potential for residual PFAS air emissions, as all other thermal techniques discussed in this report.

4.2 Biosolids-specific gasification

Essentially similar to *thermal desorption and off-gas destruction*, because there is first a lower temperature process similar to pyrolysis (to retain carbon in the solid biochar residue as much as possible), with the off-gases (which would include PFAS) burnt in a gasification furnace at high temperature where PFAS is presumably destroyed, subject to the same US EPA cautions around PFAS environmental protection as all other thermal techniques discussed in this report.

Australia's first biosolids gasification plant located at Logan, south of Brisbane, opened in April 2022, with the gasification process providing energy from waste to power the facility (energy recovery).

This has been separated in this report’s assessment as a technique from thermal desorption/ off gas destruction because it is biosolids-specific and not a primary technique for PFAS destruction.

4.3 Incineration/ cement kiln

Incineration is destruction of chemicals using heat, where very high temperatures (typically over 1,000 ^{0}C) are applied directly to the PFAS-contaminated solids or liquids.

Cement kiln hazardous waste destruction is known as co-incineration because chemical destruction and cement clinker production occurs simultaneously. Cement kilns in Australia that are used to also destroy hazardous materials use a small portion of carefully formulated ‘alternative fuel’, made from hazardous wastes with degrees of calorific value. This fuel substitution allows a form of energy recovery from the waste, but is carefully limited so as not to interfere with clinker production or its properties.

These processes differ from thermal desorption because all of the waste is directly fed into high temperature furnaces (mass burn), rather employing a lower temperature volatilisation step (for PFAS and other organic pollutants). Temperatures used in cement kilns and incinerators could be as low as 850 ^{0}C, but if the waste contains significant halogenated organic substances (such as PFAS), then a temperature greater than 1,100°C, with a residence time greater than two seconds (under conditions that ensure appropriate mixing)is required by regulators.

This method is subject to the same US EPA cautions, around destruction efficiency and the potential for residual PFAS air emissions, as all other thermal techniques discussed in this report. However, incineration and cement kiln co-incineration have been proven to have high destruction efficiencies for other POPs.

4.4 Plasma arc

This is a destruction technique where liquid or gaseous waste is rapidly heated in a plasma arc causing dissociation of elemental ions and atoms.

In Australia, the PLASCON plasma-arc system was developed by the Commonwealth Scientific Industrial Research Organisation (CSIRO) and commercialised by an Australian company, via their subsidiary. The process develops a high temperature (>10 000 ^{0}C) plasma-arc by ionising argon gas using a 150 kW DC discharge between the cathode and the anode. The waste, as a liquid or gas is injected directly into the plasma and rapidly (<1 ms) heats to about 3,100 ^{0}C and is pyrolysed for about 20 ms in the water-cooled reaction chamber (flight tube). To ensure no formation of soot a controlled amount of oxygen is injected into the plasma to convert any carbon to carbon dioxide. At the end of the flight tube, the gas at about 1,500 ^{0}C is rapidly (<2 ms) quenched to less than 100 ^{0}C in a direct spray condenser using an alkaline spray solution. The gas is further cooled and scrubbed of any remaining acid gases in a packed tower. These off-gases, which contain mainly carbon monoxide and argon are then flared to oxidise the carbon monoxide to carbon dioxide.

Contaminants in solid and bulk wastes are thermally desorbed and condensed and then fed as a liquid to the PLASCON unit for destruction.

This method is subject to the same US EPA cautions, around destruction efficiency and the potential for residual PFAS air emissions, as all other thermal techniques discussed in this report. However, with such extreme temperatures exceedingly high destruction efficiencies proven for other POPs, this technique has excellent promise for thermal destruction of PFAS.

4.5 Solid waste landfill

Solid waste landfills are a common form of offsite disposal which employ clay/single composite liners. They are typically used for non-hazardous waste but may also accept low level hazardous wastes such as tyres, asbestos and low-level contaminated soil (below prescribed contaminant limits).

These landfills offer less protection from leaching of chemical contaminants that hazardous waste landfills.

4.6 Hazardous waste landfill

Hazardous waste landfills are limited to a handful in Australia (or about three depending on how strictly engineering controls are assessed). They involve offsite disposal in double composite liner systems, are fitted with leachate collection and typically used for hazardous solid waste below prescribed contaminant limits.

Australian hazardous waste landfills may fall short of what the Stockholm Convention describes as 'specially engineered landfill' due to requirements that are not yet fully employed here, such as on-site treatment technology to remove PFAS from leachate.

4.7 Geological repository

Geological repository is an excavated, underground facility that is designed, constructed, and operated for safe and secure permanent disposal of high-level hazardous waste. A geological repository uses an engineered barrier system and a portion of the site's natural geology, hydrology, and geochemical systems to permanently isolate the hazard of the waste from the biosphere.

This approach is often employed with 'front-end' mining (kaolin/ salt) supplemented with 'back-end' waste deposition in the voids created. This method has been used in Europe and the USA for hazardous wastes but is also a technique of choice for high-level radioactive waste. The only current Australian facility, Tellus' Sandy Ridge in WA, is a kaolin clay mining/ geological hazardous waste repository (that does not take high-level radioactive waste) and is located in an arid location that has no groundwater.

The Stockholm Convention[37] explicitly describes geological repository as 'permanent storage in underground mines and formations' and further notes that 'geohydrologically isolated salt mines and hard rock formations is an option for separating hazardous wastes from the biosphere for geological periods of time.'

4.8 In-situ sorption/ separation/ stabilisation methods

Sorption is the general term for both absorption and adsorption processes.

Sorption is a pre-treatment method in which solid media is used for removing chemicals from liquids, often called 'pump and treat' technology using granular activated carbon (GAC) or other sorbents. This separation step is usually done in-situ, with residual spent sorbent media removed from site and typically disposed via incineration or similar thermal technique, to destroy the 'filtered' contaminants (such as PFAS). This thermal step is subject to the same US EPA cautions around PFAS environmental protection as all other thermal techniques discussed in this report.

In situ treatments using sorption media are also available for soil, but this is used to 'bind' pollutants to soil, not remove them. 'Amendments' are added to soil to reduce the potential for PFAS to mobilise from it to groundwater and surface water. For sorption purposes, PFAS-adsorbing materials (activated carbon or other materials that may include aluminium hydroxide, kaolin clay and other proprietary additives) can be applied through in situ soil mixing to reduce the leachability of PFAS from contaminated soil through physical and/or chemical bonding.

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[37] General Technical Guidelines, subsection IV.G.3(b), paragraph number 330, p.52.

Amendments stabilise PFAS to reduce their release from soil. This occurs primarily through electrostatic interactions between the negative charge on the PFAS functional group and the positive charges on the sorbent, and hydrophobic interactions between the amendment and the electronegative carbon-fluorine chain on the PFAS.

Carbon and mineral-based sorption/ stabilisation techniques vary in their effectiveness according to site conditions, PFAS types, and mixing approaches.

4.9 In-situ soil ‘washing’, offsite residue management

A proprietary wet, physical and chemical ‘washing’ process employed onsite to remove PFAS from soil fractions. The residual separated PFAS requires management offsite while the ‘washed’ soil can be re-emplaced, depending on the effectiveness of PFAS removal.

The ‘washed’ PFAS is collected in-situ on sorption media like GAC (the same as in-situ sorption with waters) which must be thermally destroyed offsite, so this step is subject to the same US EPA cautions around PFAS environmental protection as all other thermal techniques discussed in this report.

Ventia’s SourceZone technology is the only known application in Australia, which underwent a proof-of-performance trial at RAAF Edinburgh between July 2019 and June 2020.

4.10 Under-developed technologies/ approaches

There are a number of developing technologies at various stages of development and trial around the world for PFAS management, typically for waters/ liquids. These are not assessed in the report as they are not commercially available, but are touched on here for completeness.

Solvated electron technology (advanced reduction processes) involves the combination of activation methods such as ultrasound, ultraviolet, microwaves and electron beam with reducing agents (reductants) such as ferrous iron, sulfide, sulfite, iodide, and dithionite to generate very reactive reducing radicals and the hydrated electrons (e−aq) that mineralise contaminants to less toxic products. The author understands that this method is used for PCB removal/ irreversible transformation (typically from oils) at the Coopers Environmental Waste Recycling in NSW.

Also in Australia, AECOM’s DE-FLUORO (electrochemical oxidation) process has been recently reported in the media[38] as a new approach to PFAS liquid treatment that uses a proprietary electrode.

Nano remediation or nanofiltration is a form of membrane technology that is pressure-driven and shown to be effective in the removal of PFAS from waters and leachates. Nanometre-sized membrane pores are used to remove compounds in a process similar to reverse osmosis, but nanofiltration does not remove smaller ions such as chloride and sodium.

There are many other variants of materials and approaches being developed for removal of PFAS from water streams. In terms of contaminated soil, in-situ thermal processes are

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[38] Australian Water Association (July 22, 2022), *Safer and more energy efficient Australian technology to clean up PFAS contamination*, available at: https://www.awa.asn.au/resources/latest-news/safer-and-more-energy-efficient-australian-technology-to-clean-up-pfas-contamination.

gaining some attention in the literature, particularly using lower temperature desorption type processes.

Finally a number of mature technologies, typically outside of Australia, are being re-investigated specifically for their application to PFAS removal and destruction, such as supercritical water oxidation, alkali metal reduction and a range of new chemical oxidation and reduction technologies.

5 Assessment of management options

This section assesses each nominated management option against the four key legal and policy dimensions distilled from Section 3. These are:

- environmentally sound management (ESM) for wastes above the Stockholm Convention's level of concern, the low POP content limit (LPCL) of 50 mg/kg
- US EPA interim guidance's preferred order of priority for destruction and disposal options, based on ranging uncertainty for protection of the environment
- waste hierarchy in a hazardous waste (and specifically PFAS) context
- risk of insurance policy exclusion (and contingent liability) for PFAS-related incidents or issues.

Any such assessment is subjective and in the opinion of the author, and each dimension has been assessed equally without weighting. Analysis through the lens of each respective dimension is designed to add rigour to the exercise. To make the approach semi-quantitative for easier comparison between options, a scoring system has been implemented as follows:

- a 3 point score signifies that the dimension has been demonstrated
- a 2 point score signifies that the dimension may be demonstrated
- a 1 point score signifies uncertainty - there could be circumstances that could satisfy the dimension
- a 0 point score signifies that the dimension has not been demonstrated.

It is noted that there are other practical considerations to a choice of PFAS waste management, such as overall cost competitiveness, transport cost component (ex-situ management options), local regulatory considerations, levels of contamination of the waste, community concerns and scalability of the solution to the size of the problem. Only the four dimensions are considered here, because this assessment focuses on elements of environmentally protective policy.

This assessment attempts to translate the current body of knowledge to the Australian infrastructure context, suggesting types of management that are likely to be suitable for a particular PFAS waste and, within this, prioritising those that appear best suited to a particular PFAS waste.

5.1 Individual management option assessment tables

Following are detailed assessments of each management option, presented in tabular form against each waste type. Beneath each table is summary text which further explains the outcome of each assessment and the way it was obtained.

Table 3 Assessment of thermal desorption and off-gas destruction

PFAS waste type	Assessment dimension - thermal desorption and off-gas destruction				Score (out of 12 points)
	1. ESM	2. US EPA priority	3. Waste hierarchy/hazwaste	4. Insurance exclusion risk	
AFFF	?	x	x	?	2
GAC	?	x	x	?	2
Wastewaters	x	x	x	x	0
Soil - high	✓	?	?	?	5
Soil – intermediate	✓	?	✓	✓	8
Soil – low	✓	✓	✓	✓	9
Soil – co-contaminated	x	x	x	x	0
Biosolids	?	✓	✓	✓	7
Comment					
While thermal destruction is a primary form of ESM for POPs, a full score of 3 is not given because ESM requires a minimum destruction efficiency of 99.999 per cent[39] and this has not yet been demonstrated for PFAS compounds[34] (as opposed to other POPs) in this process. ESM also requires that “potential releases of unintentionally produced POPs should be considered”[39] and, as the US EPA cautions, this has not been well researched for PFAS.		It is noted that US EPA priority is a very current consideration that may change as the knowledge base grows. Thermal methods are likely to pose lower risks of impact from PFAS emission to the air environment the lower their levels in soil contamination, compared to higher levels of PFAS soil contamination. Scoring above partially reflects this difference, even though the US EPA guidance views thermal treatment of soils (of any contamination) with the same uncertainty (of environment protection).	For a 3-point high score, technique must both sufficiently manage the hazard and place highly on the hierarchy (recycling is the highest in the context of this report). For high-level contamination, thermal desorption may leave residual PFAS in the soil, which would restrict any potential for post-treatment soil to be recycled. In this case the hazard-reduced soil would go to the lowest hierarchy position (disposal), but with significant hazard reduction.	If ESM (destruction) is demonstrated then PFAS liability is likely to be extinguished from the generating site. If ESM is uncertain then some PFAS liability could remain, despite the waste having been excavated and removed from the generating site.	May be suited for low and intermediate level contaminated soils, subject to confirmation of destruction efficiency >99.999%. With modification, may be suitable (subject to mitigation of odour and high-moisture issues) for biosolids.

Notes:

1. *AFFF = aqueous film-forming foams; GAC = granular activated carbon; wastewaters include ground, surface, industrial and leachate waters; Soil = contaminated soil*
2. *Co-contaminated soil = soil contaminated with PFAS plus one or more other inorganic contaminants, including asbestos*
3. ✓ *satisfies dimension for this waste type = 3 point score*
4. ✓ *may satisfy dimension for this waste type = 2 point score*
5. ? *under certain circumstances could meet dimension for this waste type = 1 point score*
6. x *does not meet dimension for this waste type = 0 point score*

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[39] General POP guideline Section IV.G.2 point 161.

Summary of assessment of thermal desorption and off-gas destruction

Primarily a soil treatment technique, thermal desorption and off-gas destruction scores highest for treatment of soil with low to intermediate levels of PFAS, since both of these will fall below the LPCL of 50 mg/kg (PFOS, its salts and PFOSF), where thermal destruction to the level of ESM is not strictly required by the Convention. These sub-LPCL contaminant levels reduces the risk of environmental impacts, even if ESM destruction efficiencies are not met.

As highlighted by the US EPA interim guidance, the lack of demonstrated evidence of high destruction efficiencies for PFAS removal from waste and the lack of assurance that reformation of related fluorinated organics does not occur and result in subsequent air pollution is what holds this technique back from high scores for ESM, US EPA priority and insurance risk. These uncertainties have also resulted in lower scores for highly contaminated soils and other wastes such as AFFF and GAC, because any destruction inefficiency would be expected to have heightened impact at higher levels of contamination.

For high-level PFAS contaminated soils, the author understands that post-treatment thermal residues would still contain a level of contamination that would render them equivalent to low-level contaminated soil, to be landfilled in solid waste landfill or potentially used for landfill cover. This loses score on waste hierarchy grounds, because, unlike lower-level contaminated soils, the post-treatment material can be reused (recycled) for fill or similar purposes.

Co-contaminated (inorganics) soil cannot be treated in this process, because the co-contaminants are not amenable to thermal desorption or destruction.

As with any high-temperature process, this technique is very energy intensive (and therefore relatively high in greenhouse gas emissions), without significant energy recovery, which also slightly lowers waste hierarchy/ hazwaste scores.

With pre-treatment modification, such as purpose-built drying and odour management, this technique could be suitable for PFAS destruction within biosolids, where contamination would be at very low levels.

Table 4 Assessment of biosolids-specific gasification

<table>
<tr><th rowspan="2">PFAS waste type</th><th colspan="4">Assessment dimension - biosolids-specific gasification</th><th rowspan="2">Score (out of 12 points)</th></tr>
<tr><th>1. ESM</th><th>2. US EPA priority</th><th>3. Waste hierarchy/hazwaste</th><th>4. Insurance exclusion risk</th></tr>
<tr><td>Biosolids</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>9</td></tr>
<tr><td colspan="6">Comment</td></tr>
<tr><td colspan="2">While thermal destruction is a primary form of ESM for POPs, a full score of 3 is not given because ESM requires a minimum destruction efficiency of 99.999 per cent[40] and this has not yet been demonstrated for PFAS compounds[34] (as opposed to other POPs) in thermal processes. ESM also requires that “potential releases of unintentionally produced POPs should be considered”[39] and, as the US EPA cautions, this has not been well researched for PFAS.</td><td>It is noted that US EPA priority is a very current consideration that may change as the knowledge base grows. Thermal methods are likely to pose lower risks of impact from PFAS emission to the air environment the lower their levels are in the waste. Biosolids are likely to have very low concentrations of PFAS and other micropollutants.
The 2-point score above reflects the US EPA position of environmentally protective uncertainty associated with any thermal process.</td><td>Gasification of biosolids at the Logan facility provides a recycled bi-product (biochar), recovers energy and is likely to destroy the low level hazard, but certainly reduces it dramatically from what would otherwise occur (land applied untreated for POP contamination).</td><td>If ESM (destruction) is fully demonstrated then PFAS liability is likely to be extinguished from the generating site. Some caution is retained in this score because the biochar will be used as an agricultural amendment, which is a risk if there is incomplete destruction of PFAS.</td><td>Biosolids only method, although not specifically engineered as a POP/ PFAS destruction technique.</td></tr>
</table>

Notes:

1. *AFFF = aqueous film-forming foams; GAC = granular activated carbon; wastewaters include ground, surface, industrial and leachate waters; Soil = contaminated soil*
2. *Co-contaminated soil = soil contaminated with PFAS plus one or more other inorganic contaminants, including asbestos*
3. ✓ *satisfies dimension for this waste type = 3 point score*
4. ✓ *may satisfy dimension for this waste type = 2 point score*
5. ? *under certain circumstances could meet dimension for this waste type = 1 point score*
6. x *does not meet dimension for this waste type = 0 point score*

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[40] General POP guideline Section IV.G.2 point 161.

Summary of assessment of biosolids-specific gasification

The Logan biosolids gasification plant is a biosolids-only method, that has not specifically been engineered as a POP/ PFAS destruction technique. This plant was designed as an environmentally preferred approach to land application of biosolids for agricultural beneficiation, which has inefficiencies of logistics and therefore cost, to get biosolid-product to farms, and potential odour issues, with the matter of destruction of persistent bioaccumulative and toxic micropollutants (like PFAS) a third tier beneficiary of the approach.

The fact that PFAS are likely to be present at low levels reduces the risk of environmental impacts, even if ESM destruction efficiencies are not met. While a LPCL that is biosolids-specific for PFOS/ PFOA or other POPs may yet be introduced by the Stockholm Convention, this would be set as protective for land application, so would be expected to apply to the biochar, not the biosolids undergoing thermal treatment.

Assuming the evidence base for thermal destruction of PFAS can be strengthened, biosolids gasification processes such as this one show plenty of promise as pollutant-destructive but resource efficient (energy and retained nutrient value in the recycled product) at the same time.

Table 5 Assessment of incineration/ cement kiln

PFAS waste type	Assessment dimension - incineration/ cement kiln				Score (out of 12 points)
	1. ESM	2. US EPA priority	3. Waste hierarchy/hazwaste	4. Insurance exclusion risk	
AFFF	✓	x	✓	✓	6
GAC	✓	x	✓	✓	6
Wastewaters	✓	x	✓	✓	6
Soil - high	✓	x	✓	✓	6
Soil – intermediate	✓	?	✓	✓	7
Soil – low	✓	✓	✓	✓	8
Soil – co-contaminated	x	x	x	x	0
Biosolids	?	✓	?	✓	6
Comment					
While thermal destruction is a primary form of ESM for POPs, a full score of 3 is not given because ESM requires a minimum destruction efficiency of 99.999 per cent[41] and this has not yet been demonstrated for PFAS compounds[34] (as opposed to other POPs) in high temperature thermal. ESM also requires that “potential releases of unintentionally produced POPs should be considered”[39] and, as the US EPA cautions, this has not been well researched for PFAS.		It is noted that US EPA priority is a very current consideration that may change as the knowledge base grows. Thermal methods are likely to pose lower risks of impact from PFAS emission to the air environment the lower their levels of contamination, compared to higher levels of PFAS contamination. Scoring above reflects this difference, even though the US EPA guidance views thermal treatment (of any contamination) with the same uncertainty (of environment protection).	For a 3-point high score, technique must both sufficiently manage the hazard and place highly on the hierarchy (recycling is the highest in the context of this report). Cement kiln co-incineration offers at least close to complete hazard reduction and energy recovery in the form of a degree of fuel substitution, while incineration without energy recovery offers only disposal.	If ESM (destruction) is demonstrated then PFAS liability is likely to be extinguished from the generating site.	May be best suited for AFFF and GAC (and waters) rather than soils, since the former have limited or no residues. Small quantities of soil may be suitable, from an operability and residual solid waste standpoint.

Notes:

1. *AFFF = aqueous film-forming foams; GAC = granular activated carbon; wastewaters include ground, surface, industrial and leachate waters; Soil = contaminated soil*
2. *Co-contaminated soil = soil contaminated with PFAS plus one or more other inorganic contaminants, including asbestos*
3. ✓ *satisfies dimension for this waste type = 3 point score*
4. ✓ *may satisfy dimension for this waste type = 2 point score*
5. ? *under certain circumstances could meet dimension for this waste type = 1 point score*
6. x *does not meet dimension for this waste type = 0 point score*

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[41] General POP guideline Section IV.G.2 point 161.

Summary of assessment of incineration/ cement kiln

Thermal destruction or ‘mass burn’ incineration, and its close cousin cement kiln co-incineration, have the potential to retain high temperatures and long flame contact times that could lead to high destruction efficiencies. The evidence base for these destruction efficiencies (and a lack of fluorinated reformation reaction products) must be strengthened before these methods are recommended as protective of the environment by the US EPA, and accepted fully as ESM (thermal destruction) as they are for many other POPs. This is what holds this technique back from higher scores for ESM, US EPA priority and insurance risk.

Since the POPs are not desorbed first from the waste matrix, as they are in thermal desorption, the matrix itself can be a limitation for this method, leading to residues that may have operability or waste management consequences. This means soils are not ideally suited, although low quantities relative to feed of other furnace materials may be acceptable. Conversely, because all of the waste can be fed directly to the high temperature furnace, incineration is preferred over thermal desorption for non-soil wastes, even containing high levels of PFAS contamination/ composition.

This technique is very energy intensive (and therefore relatively high in greenhouse gas emissions), without significant energy recovery, which also results in low waste hierarchy/ hazwaste scores. Cement co-incineration performs better in this regard than incineration, because there is a small circular economy benefit from virgin fuel substitution with ‘alternative fuel’ hazardous waste.

Table 6 Assessment of plasma arc

PFAS waste type	Assessment dimension – plasma arc				Score (out of 12 points)
	1. ESM	2. US EPA priority	3. Waste hierarchy/hazwaste	4. Insurance exclusion risk	
AFFF	✓	?	?	✓	6
GAC	✓	?	?	✓	6
Wastewaters	✓	?	?	✓	6
Soil - high	✓	?	?	✓	6
Soil – intermediate	✓	?	✓	✓	8
Soil – low	✓	✓	✓	✓	9
Soil – co-contaminated	x	x	x	x	0
Biosolids	?	✓	?	✓	6
Comment					
While thermal destruction is a primary form of ESM for POPs, a full score of 3 is not given because ESM requires a minimum destruction efficiency of 99.999 per cent[42] and this has not yet been demonstrated for PFAS compounds[43,44] (as opposed to other POPs) by plasma arc. ESM also requires that "potential releases of unintentionally produced POPs should be considered"[39] and, as the US EPA cautions, this has not been well researched for PFAS for any thermal technique. Soils and biosolids may be acceptable via the pyrolysis/ desorption pre-treatment, but feed quantities are small (0.04 tonnes per hour) compared to soil thermal plants (40 tonnes per hour[45]).		Plasma arc is not mentioned directly in US EPA interim guidance, other than placing it under their highest uncertainty heading of 'other thermal treatment'. The same assessment profile has been assumed as for incineration.	For a 3-point high score, technique must both sufficiently manage the hazard and place highly on the hierarchy (recycling is the highest in the context of this report). Plasma arc offers at least close to complete hazard reduction but climbs no higher on the traditional hierarchy than disposal, since there is no energy recovery, although low-medium soils are probably recovered, since solid wastes are desorbed prior to plasma.	If ESM (destruction) is demonstrated then PFAS liability is likely to be extinguished from the generating site.	Could be a premier technique for destruction, of high concentration/ small volume wastes in particular. Requires more evidence for complete destruction but quoted 99.99% figure is close to ESM.

Notes:

1. *AFFF = aqueous film-forming foams; GAC = granular activated carbon; wastewaters include ground, surface, industrial and leachate waters; Soil = contaminated soil*
2. *Co-contaminated soil = soil contaminated with PFAS plus one or more other inorganic contaminants, including asbestos*
3. ✓ *satisfies dimension for this waste type = 3 point score*
4. ✓ *may satisfy dimension for this waste type = 2 point score*
5. ? *under certain circumstances could meet dimension for this waste type = 1 point score*
6. x *does not meet dimension for this waste type = 0 point score*

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[42] General POP guideline Section IV.G.2 point 161.

[43] General POP guideline Table 4 states that information is not available in the literature to confirm the acceptability plasma arc treatment of PFAS.

[44] Cleanaway's website states that the Narangba Qld Plascon plasma arc technology eliminates 'contaminants' at a rate of 99.99%: https://www.cleanaway.com.au/sustainable-future/what-is-pfas/.

[45] EPA Victoria Licence number 186685, EnviroPacific Services, Condition LIWA2.8.1, available at: https://portal.epa.vic.gov.au/irj/portal/anonymous?NavigationTarget=ROLES://portal_content/epa_content/epa_roles/epa.vic.gov.au.anonrole/epa.vic.gov.au.searchanon&trans_type=Z001

Summary of assessment for plasma arc

Plasma arc destruction has the potential to be a premier method for PFAS destruction, of high concentration/ small volume wastes in particular. Like all thermal destruction methods, plasma arc requires more evidence to justify complete destruction, without reformation/ incomplete combustion by-products, but the only operator in Australia (Cleanaway Narangba Qld) quotes a destruction efficiency of 99.99%, which is close to ESM's minimum requirement of 99.999%.

It scores quite evenly but only moderately across most wastes, on account of limited published destruction efficiency information specific to PFAS chemicals. However it has historically been used for PCB and other POP destruction and due to the plasma arc's unique heat in the plasma gas (> 10,000 ^{0}C), destruction efficiencies of 99.9999% are recorded for other POPs[46]. Plasma arc has the potential to rate highly on ESM, and therefore US EPA priority and insurance liability risk, with sufficient justification that it efficiently and permanently breaks the C-F bonds in PFAS compounds.

This technique is very energy intensive (and therefore relatively high in greenhouse gas emissions, via Scope 2 energy use), without significant energy recovery, which also results in low waste hierarchy/ hazwaste scores. Since solid wastes are managed in a desorption step, lower level PFAS soils could potentially have recycled value in another application, assuming the desorption process removes PFAS to leave the resulting material below environmental thresholds for that reuse.

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[46] Basel Convention, *Plasma Arc (PLASCON) POPs Technology Specification and Data Sheet*, available at: http://www.ihpa.info/docs/library/reports/Pops/June2009/SBCPLASCONSBCLogoDEFCLEANVERSION_190109_.pdf

Table 7 Assessment of solid waste landfill

PFAS waste type	Assessment dimension – solid waste landfill				Score (out of 12 points)
	1. ESM	2. US EPA priority	3. Waste hierarchy/hazwaste	4. Insurance exclusion risk	
AFFF	x	x	x	x	0
GAC	x	x	x	x	0
Wastewaters	x	x	x	x	0
Soil - high	x	x	x	x	0
Soil – intermediate	?	✔	x	x	3
Soil – low	✓	✔	?	?	7
Soil – co-contaminated	?	?	?	x	3
Biosolids	✔	✔	?	x	5
Comment					
Solid waste landfill can accept low level PFAS soils, which is acceptable under the Stockholm Convention if they are below the LPCL of 50 mg/kg. The PFAS NEMP, 'pertinent national legislation' under the Stockholm Convention, places additional requirements on leachability (must be <0.7 µg/L), which is assumed here to correspond loosely with intermediate level PFAS contaminated soil, if breached. Co-contaminated soil would be acceptable under ESM if the co-contaminants were present at only low levels. Any wastes above the LPCL cannot be accepted, therefore are categorically not ESM.		A higher-score assessment profile than thermal treatments has been taken, since the US EPA guidance assesses there to be more certainty over PFAS environmental control from landfills than from thermal processes. In the case of wastes > LPCL, this priority is voided.	Landfill provides a degree of protection from environmental harm for low level wastes but scores at the bottom of the traditional waste hierarchy (disposal).	PFAS liability may not be fully extinguished from the generating site, given the risk of future landfill leakage of PFAS. This risk is reduced with low level contaminated waste.	Solid waste landfill is suitable for only low levels of contamination, typically of soils but potentially low-level biosolids if future regulation precluded other forms of management.

Notes:

1. *AFFF = aqueous film-forming foams; GAC = granular activated carbon; wastewaters include ground, surface, industrial and leachate waters; Soil = contaminated soil*
2. *Co-contaminated soil = soil contaminated with PFAS plus one or more other inorganic contaminants, including asbestos*
3. ✓ *satisfies dimension for this waste type = 3 point score*
4. ✔ *may satisfy dimension for this waste type = 2 point score*
5. ? *under certain circumstances could meet dimension for this waste type = 1 point score*
6. x *does not meet dimension for this waste type = 0 point score*

Summary of assessment for solid waste landfill

Solid waste landfill is suitable for solid wastes only, and only those with low levels of PFAS contamination. This is typically soil but could potentially extend to low-level biosolids if future regulation precluded other forms of management, noting the potential for subsequent methane emissions (potent greenhouse gas) from the latter waste.

Table 8 Assessment of hazardous waste landfill

PFAS waste type	Assessment dimension – hazardous waste landfill				Score (out of 12 points)
	1. ESM	2. US EPA priority	3. Waste hierarchy/hazwaste	4. Insurance exclusion risk	
AFFF	x	x	x	x	0
GAC	x	x	x	x	0
Wastewaters	x	x	x	x	0
Soil - high	x	x	x	x	0
Soil – intermediate	✓	✓	?	✓	8
Soil – low	✓	✓	?	✓	8
Soil – co-contaminated	✓	✓	?	✓	7
Biosolids	✓	✓	?	✓	7
Comment					
Hazardous waste landfill can accept low to intermediate level PFAS soils, which is acceptable under the Stockholm Convention if they are below the LPCL of 50 mg/kg. The PFAS NEMP, 'pertinent national legislation' under the Stockholm Convention, places additional requirements on leachability (must be <7 µg/L), which is assumed here to be the cut-off for high level PFAS contaminated soil, if breached. Co-contaminated soil would be acceptable under ESM if the co-contaminants were present at levels acceptable for hazardous waste landfill. Any wastes above the LPCL cannot be accepted, therefore are categorically not ESM.		A higher-score assessment profile than thermal treatments has been taken, since the US EPA guidance assesses there to be more certainty over PFAS environmental control from landfills than from thermal processes. In the case of wastes > LPCL, this priority is voided.	Landfill provides a degree of protection from environmental harm but scores at the bottom of the traditional waste hierarchy (disposal).	PFAS liability may not be fully extinguished from the generating site, given the risk of future landfill leakage of PFAS, but unlikely to be a major risk for low and intermediate level waste.	Hazardous waste landfill is suitable for low and intermediate levels of contamination, typically of soils but potentially low-level biosolids if future regulation precluded other forms of management.

Notes:

1. *AFFF = aqueous film-forming foams; GAC = granular activated carbon; wastewaters include ground, surface, industrial and leachate waters; Soil = contaminated soil*
2. *Co-contaminated soil = soil contaminated with PFAS plus one or more other inorganic contaminants, including asbestos*
3. ✓ *satisfies dimension for this waste type = 3 point score*
4. ✓ *may satisfy dimension for this waste type = 2 point score*
5. ? *under certain circumstances could meet dimension for this waste type = 1 point score*
6. x *does not meet dimension for this waste type = 0 point score*

Summary of assessment for hazardous waste landfill

Hazardous waste landfill is suitable for solid wastes only, and only those with low to moderate levels of PFAS contamination, which fall within leachability limits outlined in the PFAS NEMP. This is typically soil but could potentially extend to low-level biosolids if future regulation precluded other forms of management, noting the potential for subsequent methane emissions (potent greenhouse gas) from the latter waste.

As with solid waste landfills, no wastes above LPCL levels (50 mg/kg) can be accepted into the hazardous waste landfills as they are currently equipped in Australia, according to the Stockholm Convention. Wastes above 50 mg/kg could potentially be acceptable under Stockholm, with significant upgrade to include solidification pre-treatment, landfill gas collection and control and leachate collection, monitoring and on-site treatment technology to remove PFAS from leachate. The General POP guideline indicates leachate treatment such as “physico-chemical and biological treatments or advanced treatment technologies such as active carbon filtration, reverse osmosis and nanofiltration, among others.”

SUEZ-Ventia’s EarthSure soil treatment facility at Lyndhurst landfill has onsite capability for physico-chemical solidification pre-treatment, but the Lyndhurst landfill is not known to be currently equipped with leachate filtration/ destruction technology for large scale removal of PFAS from its leachate.

In addition, the PFAS NEMP currently precludes wastes above 50 mg/kg from entering landfill in Australia, regardless of Stockholm Convention interpretation.

Table 9 Assessment of geological repository

PFAS waste type	Assessment dimension – hazardous waste landfill				Score (out of 12 points)
	1. ESM	2. US EPA priority	3. Waste hierarchy/hazwaste	4. Insurance exclusion risk	
AFFF	✓	✓	?	✓	10
GAC	✓	✓	?	✓	10
Wastewaters	✓	✓	?	✓	10
Soil - high	✓	✓	?	✓	10
Soil – intermediate	✓	✓	?	✓	10
Soil – low	✓	✓	?	✓	10
Soil – co-contaminated	✓	✓	?	✓	10
Biosolids	x	x	x	x	0
Comment					
Geological repository is directly identified as ESM in the Stockholm Convention[47] “when destruction or irreversible transformation is not the environmentally preferable option”. US EPA’s high uncertainty of environmental protection from thermal PFAS management demonstrates that destruction is not the environmentally preferable option, at least until more evidence regarding thermal treatment of PFAS becomes available. As an ESM method, geological repository can accept all levels of PFAS wastes (above or below the LPCL of 50 mg/kg) except biosolids. Biosolids are not an acceptable waste due to their high organics content, which will liberate methane gas over time, creating worker health and fire risks in enclosed spaces. Co-contaminated soil is acceptable regardless of co-contaminant levels or species.		The US EPA guidance assesses there to be more environmental protective certainty over PFAS Managed in ‘interim storage’ than other methods. Geological repository is long term containment, but separated waste emplacement and record keeping allows for future retrieval of individual wastes if required. This qualifies this method as equivalent to ‘interim storage’.	This method provides the highest level of protection from harm as it is separated from the biosphere for geological time. It scores second from the bottom of the traditional waste hierarchy (containment).	PFAS liability is fully extinguished from the generating site, according to IAS 37 and AASB 137.	Geological repository is suitable for all PFAS wastes other than biosolids. Its strength lies in protection from harm, which makes it attractive for high hazard wastes in particular.

Notes:

1. *AFFF = aqueous film-forming foams; GAC = granular activated carbon; wastewaters include ground, surface, industrial and leachate waters; Soil = contaminated soil*
2. *Co-contaminated soil = soil contaminated with PFAS plus one or more other inorganic contaminants, including asbestos*
3. ✓ *satisfies dimension for this waste type* *= 3 point score*
4. ✓ *may satisfy dimension for this waste type* *= 2 point score*
5. ? *under certain circumstances could meet dimension for this waste type* *= 1 point score*
6. x *does not meet dimension for this waste type* *= 0 point score*

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[47] General POP guideline, section IV.G.3.(b) point 330. Describes geological repository as ‘Permanent storage in facilities located underground in geohydrologically isolated salt mines and hard rock formations’.

Summary of assessment for geological repository

Geological repository builds a strong case for management of all PFAS wastes other than biosolids. Its strength lies in protection from harm; isolating the waste from the biosphere makes it increasingly attractive for progressively higher-hazard or difficult to manage wastes. It segments itself as a technique from landfilling primarily because there is no groundwater intrusion at all. This segmentation is made clear in the Stockholm Convention General POP guideline, which separates geological repository (section IV.G.3.(b)) from 'specially engineered landfill' (section IV.G.3.(a)).

Tellus Holdings' Sandy Ridge site is built on a kaolin ore deposit on average 30m thick, which provides a virtually impermeable natural barrier. The level of safety provided this 'isolation' of waste enables Tellus to be the only company in Australia that can issue waste generators a Permanent Isolation Certificate. A Permanent Isolation Certificate, according to Tellus' website[48], "may be accepted by clients' accountants and auditors as evidence that they no longer have any probable future cost with respect to the disposal of that waste", which derecognises "any liabilities on its balance sheet concerning such waste and remove any note disclosures of contingent liabilities from its financial statements."

In addition to its full score as a method of contingent liability reduction/ removal, the combination of Stockholm's specification of it as a form of ESM and US EPA's current concerns about thermal destruction efficiency of PFAS score it very highly across all dimensions. Geological repository is directly identified as ESM in the Stockholm Convention "when destruction or irreversible transformation is not the environmentally preferable option". Irreversible transformation is not an available option in Australia, and the US EPA interim advice on thermal destruction is clear. This leaves remaining options for PFAS waste management, according to ESM, as specially engineered landfill or geological repository. The former is not available in Australia (as discussed below Table 8) which leaves geological repository as the only commercially available method for PFAS management above the LPCL in Australia that is acceptable to the Stockholm Convention and US EPA interim guidance, until a better understanding of the environmental risks from PFAS thermal approaches become available.

Traditional waste hierarchy placement as 'containment; scores this area down, but a case could be made for a higher score due to its environmentally protective strength in a hazardous waste context and the lack of greenhouse gas emissions (compared to that from thermal 'disposal').

There is a notable disconnection between the Stockholm Convention's clear identification of geological repository as different to landfill and a method of ESM for POP wastes above the 50 mg/kg LCPL (for PFOS, its salts and PFOSF) and the Western Australian Department of Water and Environmental Regulation's (WA DWER) licence for Tellus Holdings[49]. This is explored in the boxed section below.

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[48] Tellus Holdings, *Hazardous waste liability regime and liability reduction through Tellus Services – Technical Data Sheet*, available at: https://tellusholdings.com/wp-content/uploads/2020/06/Liability-Technical-Data-Sheet_C4.pdf.

[49] Tellus Holdings Limited licence L9240/2020/1, available at: https://www.der.wa.gov.au/component/k2/itemlist/filter?fitem_all=L9240%2F2020%2F1&array26%5B%5D=Licence&moduleId=94&Itemid=175

Box 1 Tellus licence anomaly with respect to the Stockholm Convention

Tellus' Sandy Ridge geological repository in Western Australia is licensed by the WA DWER to accept PFAS wastes, including PFAS contaminated soil, up to a limit of 50 mg/kg of PFAS contamination. The basis for this limitation is understood to be the PFAS NEMP, which establishes an interim landfill acceptance criteria of 50 mg/kg (sum of PFOS + PFHxS) or 50 mg/kg as PFOA. The PFAS NEPM itself quotes the Stockholm Convention's 50 mg/kg LPCL[50] as the basis for its choice of this value as a landfill acceptance criteria.

Consequently the licence limit of 50 mg/kg is based on the PFAS NEMP landfill acceptance criteria, which is in turn has been established to mirror the Stockholm Convention's LPCL. The LPCL is set as a threshold floor – above which the POP must be managed via environmentally sound management (ESM), and below which ESM essentially doesn't apply. The concepts of ESM, the LPCL, the PFAS NEMP's landfill acceptance criteria and the subsequent DWER licence limit are all inextricably linked.

Further, the Stockholm Convention's General POP guideline and POP-PFAS guideline describe in intricate detail what management methods qualify as ESM, otherwise referred to in these guidelines as methods for environmentally sound disposal. Geological repository is described specifically (section IV.G.3.(b)) as one of these methods, "when destruction or irreversible transformation does not represent the environmentally preferable option."

To allow geological repository to accept waste below 50 mg/kg PFAS is a 'no-brainer' – landfills beneath ESM standards can accept that level. What is more important is consideration of wastes contaminated above the Stockholm/ NEMP/ 50 mg/kg touchstone, the level at which the Stockholm Convention's ESM requirements become important.

This leaves the licence condition in the seemingly untenable position of having adopted a 50 mg/kg limit, that is obtained from the Stockholm Convention, but remaining ignorant of Stockholm's purpose for this limit – to deem certain types of management (in this case geological repository) 'environmentally sound' for acceptance of waste above 50 mg/kg PFAS.

How is it possible that the licence uses one key aspect of the Stockholm Convention (the LPCL) but ignores the other key aspect for which this metric has been established (to determine the contamination cut-off for requiring ESM)? The core issue may be the lack of legal recognition for a classification of waste management that neatly covers off on geological repository, which has resulted in Sandy Ridge being scheduled for licensing purposes as a landfill[51]. This creates further inconsistency still, with Stockholm, which is very clear in definitionally distinguishing landfill from geological repository.

This geological repository regulatory classification gap is common across Australian jurisdictions and in this case has led to a perverse outcome.

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[50] HEPA, *PFAS National Environmental Management Plan, Version 2.0 – January 2020*, available at: https://www.dcceew.gov.au/sites/default/files/documents/pfas-nemp-2.pdf, page 72.

[51] Prescribed premises categories Category 65: Class IV secure landfill site and Category 66: Class V intractable landfill site.

Table 10 Assessment of in-situ sorption/ separation/ stabilisation methods

PFAS waste type	Assessment dimension - in-situ sorption/ separation/ stabilisation methods				Score (out of 12 points)
	1. ESM	2. US EPA priority	3. Waste hierarchy/hazwaste	4. Insurance exclusion risk	
AFFF	x	x	x	x	0
GAC	x	x	x	x	0
Wastewaters	✓	✓	✓	✓	10
Soil - high	x	x	?	x	1
Soil - intermediate	x	x	?	x	1
Soil - low	x	x	?	x	1
Soil - co-contaminated	x	x	x	x	0
Biosolids	x	x	?	x	1
Comment					
Sorption is a routine field-based technique for clean-up of PFAS in waters, for example groundwater 'pump and treat' using sorption media such as GAC. While field sorption of PFAS contaminated waters is an environmentally sound form of pre-treatment according to Stockholm[52] such media once spent has to be disposed, typically via incineration. This aspect marks it down to be equivalent in an ESM sense to incineration. Field based sorption/ stabilisation of soils, using binding amendments to adsorb and stabilise PFAS release are mentioned but also require solidification to be considered within ESM, and may potentially require removal to further management. This approach is not ESM.		Sorption/ incineration of spent sorbent for waters is assessed above incineration, because although spent sorbent would be relatively high in PFAS, its volume is vastly lower than the original waste water and it is an in-situ method has only limited need for external management. In-situ sorption/ stabilisation of PFAS contaminated soils is not mentioned as a method within US EPA guidance, so is assumed to be a non-preferred method of PFAS waste management, earning a zero point score.	Sorption/ incineration of spent sorbent for waters allows the in-situ water to remain for further environmental value (essentially recycling). The hazard is close to completely reduced but because spent media is relatively high in PFAS to begin with, thermal combustion issues remain. However, because adsorbent media is a very small volume compared to the original treated water, the maximum points have been given. Solids sorption is a form of containment only.	Since remaining in-situ water is treated to remove PFAS to safe levels, this is likely to significantly reduce contingent liability on site. For soil sorption/ stabilisation the PFAS risk remains, and "these technologies have not been implemented for enough time to demonstrate long-term stability of amendments for PFAS"[53].	In-situ sorption is an effective and well-used technique for waters, although the spent media must still managed elsewhere, typically via incineration. It is assessed as not suitable for soils or other solid wastes.

Notes:

1. *AFFF = aqueous film-forming foams; GAC = granular activated carbon; wastewaters include ground, surface, industrial and leachate waters; Soil = contaminated soil*
2. *Co-contaminated soil = soil contaminated with PFAS plus one or more other inorganic contaminants, including asbestos*
3. *✓ satisfies dimension for this waste type = 3 point score*
4. *✓ may satisfy dimension for this waste type = 2 point score*
5. *? under certain circumstances could meet dimension for this waste type = 1 point score*
6. *x does not meet dimension for this waste type = 0 point score*

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[52] General POP guideline, section IV.G.1(a).

[53] ITRC (2022), Technical resources for addressing environmental releases of per- and polyfluoroalkyl substances (PFAS), available at: https://pfas-1.itrcweb.org

Summary of assessment for in-situ sorption/ separation/ stabilisation methods

in-situ sorption/ separation is an effective and well-used clean-up technique for waters such as PFAS contaminated groundwaters, noting that the spent media must still managed elsewhere, typically via incineration. The benefit of ‘pump and treat’ in-situ clean-up is the hazard (PFAS) is removed from the water on site (at that point in time), leaving the remaining water sufficiently free of PFAS for other environmental uses. What stops it from gaining an even higher score (for contaminated waters) is that the clean-up media (or its entrained PFAS) must be disposed of, which results in the same concerns expressed elsewhere in this document about thermal processes, albeit on a much smaller volume of residual waste (adsorbent media).

In-situ sorption/ stabilisation is assessed as not suitable for soils, in the context of this assessment’s dimensions, because they do not remove nor destroy PFAS, and their longevity of stabilisation has not been demonstrated. They have been shown to be effective as a binder to reduce leachability of PFAS from soil[54], which may be the goal in limiting the spread of PFAS throughout the environment. There are a range of potential sorbent materials at different stages of study, trial or commercialisation.

In-situ sorption/ stabilisation is not a relevant technique for application to other solid PFAS wastes.

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[54] Stewart, R., and R. McFarland. 2017. “Immobilization of Per- and Polyfluorinated Alkyl Substances (PFAS) in 14 Soils from Airport Sites across Australia, available at a presentation at: https://pfas-1.itrcweb.org/references/#_ENREF_820.

Table 11 Assessment of in-situ soil 'washing', offsite residue management

PFAS waste type	**Assessment dimension -**				**Score (out of 12 points)**
	1. ESM	**2. US EPA priority**	**3. Waste hierarchy/hazwaste**	**4. Insurance exclusion risk**	
Soil - high	?	?	✓	?	5
Soil - intermediate	?	✓	✓	✓	8
Soil - low	?	✓	✓	✓	8
Soil - co-contaminated	?	x	?	✓	4
Biosolids	?	x	?	?	3
Comment					
In-situ soil washing is a new technique that rates only casual mention as a pre-treatment technique[55] in the General POP guideline. Ventia's SourceZone technology[56], the only known commercialisation of soil washing for PFAS, has been used in trials, most notably at RAAF Edinburgh air base in SA[56]. Adsorbent media is required for clean-up of rinsate from soil washing, and must be sent offsite for thermal destruction. The technology is untested on biosolids, but because of its loose mention in the guideline it has been awarded the minimum alongside other wastes.		In-situ soil washing is not specifically mentioned in EPA interim guidance, but has been rated above the base score because it is an in-situ technique, with only residual disposal (spent media) requirements.	The majority of 'cleaned' soils can be reused onsite and the hazard is removed from site, albeit for likely thermal destruction (of a much reduced volume of spent media). Similar to 'pump and treat' for contaminated waters, the maximum score has been given for low and intermediate levels of contaminated soil.	This risk is hard to assess for such as new technology. The scores reflect some caution but the likelihood is that the hazard is mostly removed offsite, limiting liability.	Promising new technology for in-situ soil treatment in a similar way to 'pump and treat' water treatment – likely limited to low-intermediate levels of contamination.

Notes:

1. *AFFF = aqueous film-forming foams; GAC = granular activated carbon; wastewaters include ground, surface, industrial and leachate waters; Soil = contaminated soil*
2. *Co-contaminated soil = soil contaminated with PFAS plus one or more other inorganic contaminants, including asbestos*
3. ✓ *satisfies dimension for this waste type = 3 point score*
4. ✓ *may satisfy dimension for this waste type = 2 point score*
5. ? *under certain circumstances could meet dimension for this waste type = 1 point score*
6. x *does not meet dimension for this waste type = 0 point score*

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[55] General POP guideline, section IV.G.1(p).

[56] Ventia (2020), Submission - PFAS Subcommittee of the Joint Standing Committee on Foreign Affairs, Defence and Trade, Remediation of PFAS-related impacts – ongoing scrutiny and review.

Summary of assessment for in-situ soil 'washing', offsite residue management

In-situ soil 'washing' is a promising new technology for in-situ soil treatment in a similar way to 'pump and treat' water treatment that is likely to be applicable to low to intermediate levels of contamination, because PFAS removal can vary with soil types and PFAS species – Ventia's Edinburgh trial found "on average 90% PFOS + PFHxS in clay soils and 98% PFOS + PFHxS in sandy soils", while another soil washing field trial reported in the literature reported 73% removal of PFOS[57].

The benefit of in-situ soil 'washing' is the hazard (PFAS) is removed from the soil on site (at that point in time), leaving the remaining soil sufficiently free of PFAS for other environmental uses. What stops it from gaining an even higher score (for low to intermediate soils) is that the clean-up media (or its entrained PFAS) must be disposed of, which results in the same concerns expressed elsewhere in this document about thermal processes, albeit on a much smaller volume of residual waste (adsorbent media).

In-situ soil washing is not a relevant technique for application to other PFAS wastes other than perhaps biosolids, noting that treatment of this waste is untested.

Summary of assessment for under-developed technologies/ approaches

Technologies/ approaches such as solvated electrons (advanced reduction processes), nano remediation, AECOM's DE-FLUORO (electrochemical oxidation) process, in-situ thermal and foam fractionation, just to name a few, are not yet fully developed or implemented commercially in Australia, so have not been assessed in this report.

They are described briefly in Section 4.10 for context, as the whole area of PFAS waste management is a rapidly developing space.

5.2 Summary of the PFAS management options assessment

Table 12 collates each score, per waste type, from the preceding individual assessments. A 'traffic light' assessment of the numerical scores has been adopted, where:

Green = 9-12 point score – method is best suited for this waste type
Orange = 6-8 point score – method may be suitable for this waste type
Red = 0-5 point score – method not suitable for this waste type.

The most prominent observation from this comparison is the evenness of highly-assessed performance for geological repository, with 10 points out of a possible 12 for every waste type except biosolids. Geological repository ranks lowest of all options for biosolids because it cannot accept this waste due the safety risks that would come from subsequent methane generation.

Even with geological repository was in-situ sorption/ separation/ stabilisation methods (10 points for wastewaters), while just below it was thermal desorption/ off gas destruction and plasma arc, both scoring 9 points for low-level contaminated soil and biosolids-specific gasification (9 points for biosolids).

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[57] Ase Høisæter, Hans Peter H. Arp, Gøril Slinde, Heidi Knutsen, Sarah E. Hale, Gijs D. Breedveld, Mona C. Hansen, *Excavated vs novel in situ soil washing as a remediation strategy for sandy soils impacted with per- and polyfluoroalkyl substances from aqueous film forming foams*, Science of The Total Environment, Volume 794, 2021, available at: https://www.sciencedirect.com/science/article/pii/S0048969721038353

Table 12 Collated assessment scores per management option

PFAS waste type	Assessment score per management option (out of 12 points)									
	1. Thermal desorption and off-gas destruction	2. Biosolids specific gasification	3. Incin./ cement kiln	4. Plasma arc	5. Solid waste landfill	6. Haz waste landfill	7. Geological repository	8. In-situ sorption/ separation/ stabilisation methods	9. In-situ soil 'washing', offsite residues	Highest scoring option
AFFF	2	-	6	6	0	0	10	0	-	Geological repository
GAC	2	-	6	6	0	0	10	0	-	Geological repository
Wastewaters	0	-	6	6	0	0	10	10	-	In-situ sorption/ separation & Geological repository
Soil - high	5	-	6	6	0	0	10	1	5	Geological repository
Soil – intermediate	8	-	7	8	3	8	10	1	8	Geological repository
Soil – low	9	-	8	9	7	8	10	1	8	Geological repository
Soil – co-contaminated	0	-	0	0	3	7	10	0	4	Geological repository
Biosolids	7	9	6	6	5	7	0	1	3	Biosolids-specific gasification

Notes:

6. *AFFF = aqueous film-forming foams; GAC = granular activated carbon; wastewaters include ground, surface, industrial and leachate waters; Soil = contaminated soil*
7. *Co-contaminated soil = soil contaminated with PFAS plus one or more other inorganic contaminants, including asbestos*
8. Green *= 9-12 point score – method is best suited for this waste type*
9. Orange *= 6-8 point score – method may be suitable for this waste type*
10. Red *= 0-5 point score – method not suitable for this waste type*

6 Findings

This section presents the management option assessment findings comparatively, using summarised waste type headings:

- high-level PFAS (non-soil) solid wastes, which includes PFAS containing AFFF and PFAS contaminated GAC
- PFAS contaminated soils
- PFAS contaminated wastewaters
- PFAS contaminated biosolids.

6.1 High-level PFAS (non-soil) solid wastes are best managed by geological repository

High concentration PFAS wastes such as AFFF but also spent GAC (or similar adsorbents), are orders of magnitude above the Stockholm LPCL of 50 mg/kg in PFAS. This sharply limits their management to what is allowable under ESM and, for the purposes of this assessment, also brings the US EPA interim guidance on PFAS management significantly into the equation, because the risks of PFAS-related air pollution from thermal treatment increase with high concentration inputs.

From an ESM perspective in particular, the comparative management option assessment found geological repository to be clearly the best-suited management for high-level PFAS (non-soil) solid wastes, with 10 points scored out of a possible 12. The closest alternatives available in Australia, incineration/ cement kiln co-incineration and plasma arc, were scored much further behind (6 points respectively) but in the category of ‘may be suitable’, on account of them not (yet) being demonstrated to meet ESM for PFAS and ranking lowly against the US EPA interim guidance. All other management methods were assessed as not suitable for high-level PFAS wastes.

While this does not change this assessment, a practical qualification is that Tellus’ Sandy Ridge facility, the only geological repository in Australia, is not currently licensed to accept PFAS waste above 50 mg/kg, a contradiction discussed in Box 1, Section 5.1.

6.2 PFAS contaminated soils are best managed by geological repository

Soils with high, intermediate and low levels of contamination in PFAS were assessed as best-suited for management by geological repository, noting the licence contradiction issue raised in Section 6.1 (for the Sandy Ridge site).

Highly PFAS contaminated soil, which is assumed be above 50 mg/kg, was assessed as having limited preferred options for management, outside of geological repository (10 points). The closest alternatives, incineration/ cement kiln co-incineration and plasma arc, were scored much lower (6 points respectively) but in the category of ‘may be suitable’. While ESM was an important determinant in this assessment, another differentiator was waste hierarchy – for example thermal desorption of high concentrations is unlikely to fully remove PFAS, leaving a residual thermally treated material that cannot be reused and must go to (solid waste) landfill. This left thermal desorption and off-gas destruction somewhat surprisingly at only 5 points, a rating of not suitable for high PFAS contaminated soils.

Low to intermediate concentrations of contaminated soil are likely to be beneath the 50 mg/kg Stockholm Convention cut-off that requires environmentally sound disposal. Largely for this reason, but also because lower levels present lower environmental risks, more options were assessed as at least ‘may be suitable’:

- Geological repository was the best suited (10 points for both low and intermediate).
- Thermal desorption/ off-gas destruction and plasma arc were close behind (9 points for low level PFAS soils and 8 points for intermediate level PFAS soils).
- In-situ soil washing, a new technique offered currently by Ventia, came in at 8 points for both low and intermediate levels of PFAS contamination in soils.
- Hazardous waste landfill (8 points) was similar to solid waste landfill (7 points), for low level PFAS soils, but the former (7 points) rated much higher for intermediate level contamination than the former (just 3 points).
- Incineration/ cement kiln co-incineration scored 8 points for low level contamination and 7 points for intermediate level contamination.

Co-contaminated soil (PFAS plus significant levels of contamination in asbestos or inorganic chemicals such as heavy metals) was assessed as having very limited options – only geological repository (10 points) was rated as best suited, with hazardous waste landfill second at 7 points (may be suitable). All other management methods were assessed as not suitable.

An important qualification to this concerns the combined-capability SUEZ-Ventia (EarthSure) facility at the Lyndhurst landfill site in Victoria. This facility is unique in offering a suite of choices: thermal desorption/ off-gas destruction, with stabilisation solidification treatment and also Victoria’s only hazardous waste landfill, all in one location. If this uniquely facetted facility was assessed on its own, it would score 8 points, which would make it suitable for accepting co-contaminated soils.

6.3 PFAS contaminated wastewaters could be managed by either ‘pump and treat’ or geological repository

For PFAS contaminated waters of any kind, in-situ sorption/ separation (pump and treat) and geological repository both scored 10 points, well beyond the next placed incineration/ cement kiln co-incineration and plasma arc, both assessed as 6 points. While not expressly assessed with the four dimensions in this report, the broader benefits of in-situ management (in the main) compared to removal and offsite management, would likely place pump and treat methods slightly ahead of geological repository for wastewaters.

6.4 PFAS contaminated biosolids are best managed by biosolids-specific gasification

Biosolids-specific gasification is only used at one site in Australia at present (Logan City Council’s biosolids gasification plant in Qld), but this method is assessed as best suited for managing biosolids contaminated in PFAS. There is room for an even higher score of sufficient destruction efficiency with respect to PFAS can be proven.

Regardless, the fact that at least significant PFAS destruction would occur through the gasification process, and that sufficient nutrient value is still retained in the biochar residue for agricultural use, positions this approach as a step-wise improvement on the current questionable practice (in micro-pollutant terms) of applying biosolids directly to agricultural land.

Thermal desorption and off-gas destruction and hazardous waste landfill are assessed as may be suitable (7 points each); although the former may require some modification to demonstrate efficacy, it was scored on the basis of its general design similarities to biosolids-specific gasification.

6.5 Conclusion

A comparative review of the approaches currently commercially available in Australia to manage wastes contaminated in PFAS, in light of the most recent science, policy and regulatory frameworks emerging worldwide, has found that:

- geological repository rated highest for management of the following PFAS contaminated wastes:
    - aqueous film forming foam (AFFF)
    - granular activated carbon (GAC)
    - all contamination levels of soil, but particularly highly PFAS-contaminated soil and co-contaminated soil (PFAS plus significant levels of contamination in asbestos or inorganic chemicals such as heavy metals)
- in-situ sorption/ separation (pump and treat) techniques and geological repository both rated highest for management of PFAS wastewaters, although the former may be slightly ahead due to the broader environmental benefits of constraining most of the treatment activity onsite
- biosolids-specific gasification rated highest for managing biosolids contaminated in PFAS.

This assessment is recognised as subjective and in the opinion of the author, but its semi-quantitative design through the lens of four key legal and policy dimensions provides a transparent and defensible basis of these opinions.

It is noted that there are other practical considerations to a choice of PFAS waste management, such as overall cost competitiveness, transport cost component (ex-situ management options), local regulatory considerations, levels of contamination of the waste, community concerns and scalability of the solution to the size of the problem. These are not considered here, because this assessment focused on elements of environmentally protective policy.

While this does not change this assessment, a practical qualification is that Tellus' Sandy Ridge facility, the only geological repository in Australia, is not currently licensed to accept PFAS waste above 50 mg/kg, a contradiction discussed in Box 1, Section 5.1.

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