Assessment, management and remediation for PFOS and PFOA
Part 1: background
Assessment, management and remediation guidance for perfluorooctanesulfonate (PFOS) and perfluorooctanoic acid (PFOA)

Part 1 – background

March 2017
Important note to readers

This guidance is to be regarded as **both draft and interim**, particularly in relation to health based screening values.

The following caveats and limitations apply to this guidance:

- the health based values in this guidance are based on the interim TDI values endorsed by enHealth in 2016 for PFOS (+PFHxS) and PFOA, and
- should revised TDI values be endorsed by enHealth or another major national health based agency in Australia, then the health derived values in this guidance will be updated accordingly, and the guidance re-issued.

It is recognised that there is much on-going research on the impacts of PFOS and PFOA on human health and the environment, the outcomes of which may improve the assessment, remediation and management of PFOS and PFOA. These developments will be monitored and this guidance will be updated, as appropriate.

It is also recognised that PFAS compounds other than PFOS and PFOA may contribute to the impacts of PFAS on human health and the environment. When further research results for other PFAS compounds (or classes thereof) of sufficient robustness to be utilised in the formulation of guidance for those compounds (or classes thereof) become available, then that information will be used to extend the scope of this guidance.

This guidance should therefore be regarded as **both draft and interim**.

March 2017
Preamble

CRC CARE has milestones in its Agreement with the Commonwealth Government relating to the development of guidance for contaminants of emerging concern in collaboration with end users. Priority contaminants were identified for CRC CARE through regulators and end users who met at a forum held in February 2012. These contaminants included perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA), which belong to a large group of compounds called per- and polyfluoroalkyl substances (PFAS). CRC CARE has undertaken the development of human health screening levels (HSLs) and ecological screening levels (ESLs) for PFOS and PFOA. These values provide a collective view of the available science and application of Australian approaches on the development of human health and ecological based screening levels.

The derivation of HSLs and ESLs has followed the methodologies outlined in the National Environment Protection (Assessment of Site Contamination) Measure 1999, as revised in 2013 (NEPM). HSLs and ESLs are subject to the assumptions, uncertainties and limitations outlined in the relevant parts of the guidance – deviations from the assumptions used in their derivation may mean that a site specific assessment would be required. Further, HSLs for some exposures are calculated using a 100% relative source contribution. If more than one of these sources is relevant, use of the screening values would underestimate risks, and in this case, cumulative assessment of all relevant exposures must be made.

The NEPM emphasises the importance of formulating a conceptual site model on which to base the assessment of soil and groundwater contamination, and guidance has been provided on the development of a conceptual site model for PFOS and PFOA.

It is intended that the HSLs and ESLs that have been developed for PFOS and PFOA should be considered similarly to the NEPM HILs/HSLs and EILs/ESLs in forming generic screening levels which, if exceeded, would indicate that further more detailed investigation is required. The HSLs and ESLs and the information used in their derivation can assist in undertaking this more detailed investigation.

It is emphasised that exceedance of the HSLs and ESLs does not necessarily imply that the contamination poses an unacceptable risk, and the HSLs and ESLs should not be used as remediation targets, as this could result in unnecessary remediation.

The following limitations should be noted:

- The assessment and management of PFAS contamination in soil and groundwater is an emerging science in Australia and internationally and significant work continues to be undertaken. It is recommended that when using this guideline, more recent information is considered.
- Uncertainties and limitations in the guidance values and their application are noted in the guidance document, and these should be considered when using the values. Some of the screening levels have assumed the occurrence of bioaccumulation and biomagnification based on international work – there is uncertainty as to the levels that will occur in Australian organisms. Where significant exceedances of HSLs and ESLs occur, consideration should be given to direct monitoring of potentially affected organisms to determine if there are effects that can be
distinguished. Further assessment would be required where bioaccumulation is an issue.

- This review has focussed on PFOS and PFOA. PFAS include a large number of compounds and analytical methods are reporting an increasing number of PFAS compounds. As this guidance document was being finalised, enHealth (2016) has advised that perfluorohexane sulfonate (PFHxS) should be considered to be additive to PFOS, The use of the HSLs and ESLs for PFOS and PFOA should recognise that other PFAS may contribute to potential effects and where present, these will need to be evaluated for potential cumulative risks in accordance with available information.

Because of the evolving nature of the science relating to PFAS, these guidelines are considered to be interim guidance, and it is recommended that a review of this guidance is considered following any change in recommendation by enHealth or FSANZ.

This guidance is intended for a variety of users within the contaminated sites industry, including site owners, proponents of works, contaminated land professionals, and regulators. It is assumed that readers are familiar with the NEPM 2013. While the aim of this guideline is to provide a resource that can be used at PFAS-contaminated sites across Australia, it does not replace specific laws, regulations and guidance provided at a local level.
## Acknowledgements

CRC CARE Project Advisory Group members:

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## Abbreviations

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<td>AFFFs</td>
<td>Aqueous film forming foams</td>
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<td>CSM</td>
<td>Conceptual site model</td>
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<td>CRC CARE</td>
<td>Cooperative Research Centre for Contamination Assessment and Remediation of the Environment</td>
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<td>ESL</td>
<td>Ecological screening levels</td>
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<td>HSL</td>
<td>Health screening levels</td>
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<td>NEPM</td>
<td>National Environment Protection (Assessment of Site Contamination) Measure 1999, as revised in 2013</td>
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<td>NRF</td>
<td>National Remediation Framework</td>
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<td>PFAS</td>
<td>Per- and polyfluoroalkyl substances</td>
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<td>PFHxS</td>
<td>perfluorohexane sulfonate</td>
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<td>PFOA</td>
<td>Perfluorooctanoic acid</td>
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<td>PFOS</td>
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1. Introduction

1.1. Overview

Chemicals perfluorooctanesulfonate (PFOS) and perfluorooctanoic acid (PFOA) have been identified as contaminants of emerging concern in Australia (CRC CARE 2014a, b). They belong to a large group of compounds called per- and polyfluoroalkyl substances (PFAS).

All PFAS are highly persistent, bioaccumulative and potentially toxic to humans and the environment (CONCAWE 2016). They have been found at concentrations of potential concern at a number of sites, particularly where there has been the use of firefighting foams. Industry and public awareness both in Australian and internationally is growing rapidly (Seow 2013). There is frequent reporting of PFOS contamination in the media, with particular concerns being raised regarding the possible health risks to humans who may have been exposed.

In general, there is limited and incomplete information surrounding the occurrence, fate and toxicity of PFAS in the Australian context. At the start of the development of this guideline, there were no recognised screening level in Australia for protecting human health and ecological systems, making it difficult to determine the level of risk that may be posed by contamination. Because of the persistence and difficulty of treating PFAS contamination, there is also considerable uncertainty about how such contamination can be managed and remediated.

1.2. Purpose of the guidance

The purpose of this guidance is to provide a consistent, risk-based approach to the assessment, management and remediation of PFAS contamination in Australia, specifically:

- Human health and ecological screening levels for PFOS and PFOA contamination in soil, groundwater, surface water, fish consumption, and sediment.
- A framework and discussion regarding the application of these screening levels.
- A risk-based approach to the management and remediation of PFOS and PFOA contamination.

It is envisaged the guidance will be used by practitioners, industry, regulators and owners/occupiers of land contaminated with PFAS. It is intended to complement the National Remediation Framework (NRF) currently being developed by CRC CARE, and in the future may be incorporated into the NRF.

The guidance focuses on PFOS and PFOA, which are the most well understood PFAS, being the most commonly encountered PFAS in the environment and wildlife (Giesy et al. 2010). Limited information is available regarding other PFAS, of which there are several hundred known and potentially many more unknown (Buck et al. 2011). Further discussion is provided in section 2.2.
1.3. **Structure of the guidance**

The risk-based guidance for the assessment, management and remediation of PFOS and PFOA comprises five documents.

**Part 1: Background (this document)**
- Background to the guidance document
- An overview of PFAS, in particular PFOS and PFOA
- Physicochemical properties
- Overview of human health and ecological toxicity
- Prevalence and behaviour of PFOS and PFOA in the environment
- Overview of international guidance and screening levels available (at the time of publication)
- Current situation in Australia

**Part 2: Human health screening levels**
- PFOS and PFOA toxicity in humans
- Toxicokinetics of PFOS and PFOA in humans
- Human health screening levels
- Derivation of human health screening levels
- Application of the human health screening levels

**Part 3: Ecological screening levels**
- Ecological receptors and ecotoxicity of PFOS and PFOA
- Factors influencing toxicity such as bioaccumulation and bioaccessibility
- Screening levels for terrestrial and marine aquatic ecosystems
- Derivation of ecological screening levels
- Considerations in the application of screening levels

**Part 4: Application of human health and ecological screening levels**
- Standalone summary of the human health and ecological screening levels and application information
- Provides users with the essential information to apply the human health and ecological screening levels (users can then refer to part 2 and part 3 for the technical detail and derivation process if required)

**Part 5: Risk-based management and remediation**
- Framework for the risk-based management and remediation of PFOS and PFOA contaminated soil, sediment and water, linking back to the human health and ecological screening levels
- Development of a site specific conceptual site model for PFOS and PFOA contaminated sites
- Aspects that should be considered in the management and remediation of PFOS and PFOA-contaminated media
- Available technologies for treatment of PFOS and/or PFOA-contaminated soil, sediment and groundwater, and applications of technologies
2. PFOS and PFOA overview

2.1. Terminology

The terminology used internationally and in Australia to describe various fluorinated substances, including PFOS and PFOA varies widely, and has evolved over time. The terms ‘fluorinated substances’, ‘fluorochemicals’ and ‘fluorinated chemicals’ which refer to compounds containing at least one fluorine atom are frequently used, but these include a very large range of organic and inorganic substances with very different properties (Buck et al. 2011).

The acronym PFC (per-fluorinated compounds) has also been used widely in literature to include PFOS and PFOA, but definitions have varied widely to include both per- and poly-fluorinated compounds, but also to describe perfluorocarbons (a family of greenhouse gases) which have very different properties and do not include compounds such as PFOS and PFOA.

The most widely cited and increasingly common terminology to describe the group of compounds that includes PFOS and PFOA is that described by Buck et al. (2011). Fluorinated substances are defined where the H substituents have been replaced by F atoms, so that they contain the perfluoroalkyl moiety $C_nF_{2n+1}$ – referred to as perfluoroalkyl and polyfluoroalkyl substances (PFAS). This terminology is adopted in this guidance document.

2.2. Why focus on PFOS and PFOA?

The majority of PFAS research internationally and in Australia has been focused on PFOS and PFOA due to their frequent occurrence in the environment, known persistence, and bioaccumulative properties. Additionally, PFOS and PFOA are the breakdown endpoint of many precursor products (Norström et al. 2015). PFOS and PFOA and precursors are the most commonly encountered PFAS in the environment and wildlife (Giesy et al. 2010). Limited information is available regarding other PFAS, of which there are several hundred known, and potentially many more unknown (Buck et al. 2011). There is currently insufficient data available to derive screening level for other PFAS, though it is likely this will change given the substantial focus on PFAS contamination globally.

Since 2002 long chain PFAS such as PFOS and their precursors have been gradually replaced by industry with shorter perfluoroalkyl chains, or with non-fluoroalkyl products (OECD 2013). These alternatives are generally considered to be less toxic and have reduced bioaccumulative properties, though many are just as persistent as PFOS (Norström et al. 2015). Concerns have been raised about the transformation products of these alternative substances becoming ubiquitously present in the global environment, and about the lack of alternatives for PFAS (Scheringer et al. 2014).

So while this guidance focuses on PFOS and PFOA, it is recognised there is the potential that the current introduction of fluorinated alternatives may eventually lead to similar problems as has occurred with PFOS and long-chain perfluorocarboxylic acids (PFCAs). It will be important to review the guidance on a regular basis to determine whether the continued focus on PFOS and PFOA is warranted, and whether there are
other PFAS (or other compounds) with possible environmental or human health impacts.

2.3. Sources of PFOS and PFOA contamination

PFOS and PFOS-related substances have been used globally in a diverse range of products, including aqueous film forming foams (AFFF), semiconductors, hydraulic fluids, photolithography, Scotchgard tape, grease repellents for packaging, surface treatments for rugs and carpets, paper and packaging, coatings and coating additives, industrial and household cleaning products, pesticides and insecticides (UNEP 2006, Seow 2013, OECD 2013, CRC CARE 2014a). PFAS may also be sourced from household products and possibly from foodstuff.

PFOA in the form of its salts is used to make fluoropolymers, which are fire resistant, and oil, stain, grease and water repellent (US EPA 2014). PFOA is contained in trace amounts in Teflon™ (polytetrafluoroethylene) used on non-stick cookware, waterproof and breathable membranes for clothing, and in the aerospace, automotive, building and construction, chemical processing, electronics, semiconductors and textile industries (Seow 2013, CRC CARE 2014a). PFOA is also produced by the breakdown of some fluorotelomers such as 8:2FtS which can be used in stain, grease and water resistant surface treatment products, paints, coatings, cleaning products, fire-fighting foams and engineering coatings and AFFF fire-fighting foams (Seow 2013, Backe, Day & Field 2013).

Disposal of PFAS to sewer can result in the accumulation of PFAS in wastewater effluent as they may not be removed during the standard treatment process (Thomson et al. 2010), and in the biosolids of sewage treatment plants (Gallen et al. 2014, NICNAS 2015). Landfilling of products containing PFAS may have resulted in the generation of PFOS and/or PFOA-contaminated leachate, and contamination of groundwater in the vicinity of the landfills (Gallen et al. 2014, ALS 2015).

Although the use of PFOS and PFOA in Australia has been largely phased out, some stocks remain and are used in firefighting, for example, and historical legacy contamination issues remain due to the persistent nature of the chemicals. It is expected that most of the sources of PFOS and PFOA contamination noted above have existed in Australia, with the use of AFFF (depending on the specific product used) at fire training grounds being the most well understood.

2.4. International recognition

There has been growing international concern about the environmental behaviour and potential toxicity of PFOS and PFOA, driven by the identification of these man-made substances in air, soil, river water, dust and remote polar regions (Shi et al. 2012, Du et al. 2013). Due to its environmental persistence and ability to bioaccumulate, PFOS has been classified as a persistent organic pollutant (POP) and was added to Annex B of the Stockholm Convention in May 2009 (Sharpe et al. 2010, CONCAWE 2016). Australia has not yet ratified the listing of PFOS under the Convention.
The principal global producer of PFOS, 3M, ceased production of PFOS and PFOA by end of 2002 (Seow 2013), although it is noted production of PFOS and PFOA still occurs in some parts of the world. Subsequently, the US EPA launched a global 2010/2015 PFOA Stewardship program to phase out PFOA and related chemicals by 2015. Internationally there has been a gradual increase in regulation of PFOS and PFOA, with key milestones as follows:

- In 2009 PFOS was added to Annex B (for restriction, not elimination) of the Stockholm Conventions for POPs.
- Manufacture and importation of PFOS based surfactants are not permitted in the USA and the fire-fighting industry has fully transitioned to non-PFOS alternatives (Seow 2013).
- In 2008 Canada also began to regulate and prohibit the manufacture, use, sales and import of PFOS into Canada (Seow 2013).
- Germany has banned the importation, use and manufacture of PFOS, and PFOA is not used in German or European fire-fighting foams.
- The United Kingdom has not placed specific ban or restrictions on the use of PFOA containing foams; however, the fluorosurfactants must not enter groundwater.
- Norway has a national goal to eliminate any discharges of PFOA by 2020. Norway banned PFOS in fire-fighting foams and textiles in 2007 and has proposed a ban on PFOA in consumer products with an upper limit of 1 ppm and 1 µg/m² in textiles and coated material.
- Since 27 June 2011, the use of firefighting foams containing more than 0.0001 wt% PFOS has been prohibited in the EU.
- In the EU, PFOS may only be used for the exempted uses under the directive 2006/122/EC as repealed by COM Regulation (EC) No 552/2009 (Norström et al. 2015)
- In 2013 PFOS was included in the EU Water Framework Directive (Directive 2013/39/EU), with environmental quality standards specified for surface water (fresh and marine), and biota (Norström et al. 2015).

2.5. Australian recognition

There is increasing recognition across Australia regarding the potential issues surrounding PFAS and the need to develop formal guidance and management strategies. Some examples of policies and documents available to date are provided in table 1.

Of significance, enHealth (June 2016) have published their interim national guidance on human health reference values for per- and poly-fluoroalkyl substances for use in site investigations in Australia. This document contains recommended toxicity values as well as drinking water and recreational water quality guidelines for PFOS (+PFHxS) and PFOA. These values have been adopted in this guideline and are further discussed in the part 2 document (Human health screening levels).
## Table 1  Key Australian documents that address PFOS and PFOA contamination

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<tr>
<th>Department</th>
<th>Document</th>
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<tr>
<td>QLD Department of Environment &amp; Heritage Protection</td>
<td>Environmental management of firefighting foam, July 2016</td>
<td>Outlines DoEHP’s procedural requirements for handling, transport, storage, use, release, waste treatment, disposal and environment protection measures relevant to the use of firefighting foams. Considers environmental impacts of PFAS C4 to C14, including PFOS and PFOA, and provides guidance on testing requirements.</td>
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<tr>
<td>Department of Environment and Conservation Western Australia (Seow 2013)</td>
<td>Fire fighting foams with perfluorochemicals – environmental review, 7 June 2013</td>
<td>Provides extensive background on AFFFs and PFAS constituents, including sources, international approach to managing the use of PFAS and human health/environmental impacts, and contamination issues.</td>
</tr>
<tr>
<td>WA Department of Environmental Regulation</td>
<td>Interim guideline on the assessment and management of perfluoroalkyl and polyfluoroalkyl substances (PFAS), February 2016</td>
<td>Provides guidance on the assessment and management of PFAS within the legislative framework provided by WA legislation.</td>
</tr>
<tr>
<td>Department of Defence</td>
<td>Environmental guidelines for management of fire fighting aqueous film forming foam (AFFF) products, 2015</td>
<td>Provides guidance for Defence personnel for environmentally sound procurement, management, use and disposal of AFFF products.</td>
</tr>
<tr>
<td>Department of Defence</td>
<td>Defence contamination directive #8 – interim screening criteria, February 2016</td>
<td>Provides interim screening criteria for the assessment of PFOS, PFOA, and 6:2 FtS on Defence sites.</td>
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<tr>
<td>Department of Industry and Regional Development, and Airservices</td>
<td>Managing PFC contamination at airports June 2015, February 2016</td>
<td>Provides interim screening criteria for the assessment of PFOS, PFOA and 6:2 FtS, and guidance on management of contaminated soil and groundwater on airport sites</td>
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<tr>
<td>Department of Environment and Energy</td>
<td>Draft Commonwealth environmental management guidance, 2 December 2016</td>
<td>Provides guidance to Commonwealth agencies on the assessment and management of PFOS and PFOA contamination associated with Commonwealth sites, with a particular emphasis on the requirements for protection of ecological values.</td>
</tr>
<tr>
<td>Fire Protection Association Australia</td>
<td>Information bulletin selection and use of firefighting foams, version 1, June 2014</td>
<td>Aims to increase awareness of the issues surrounding selection and use of firefighting foams, and environmental impacts. Includes firefighting foams containing PFAS.</td>
</tr>
<tr>
<td>CRC CARE</td>
<td><em>Environmental impact of priority contaminants: a literature review, Technical Report no. 29, January 2014</em></td>
<td>Literature review of emerging contaminants of concern, including PFOS and PFOA. Provides information relating to sources, physico-chemical properties, toxicity, bioaccumulation and biomagnification, and international guidance.</td>
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<tr>
<td>CRC CARE</td>
<td><em>Development of guidance for contaminants of emerging concern, Technical Report no. 32, July 2014</em></td>
<td>Identifies the need for, and areas to be addressed in developing guidance for several emerging contaminants of concern in Australia, including PFOS and PFOA.</td>
</tr>
<tr>
<td>enHealth</td>
<td><em>Interim national guidance on human health reference values for per- and poly-fluoroalkyl substances for use in site investigations in Australia, June 2016</em></td>
<td>Provides a review of toxicity reference values and recommended TDI, in addition to interim Australian Drinking Water Quality Guideline and Recreational Water Quality Guideline for PFOS (+PFHxS) and PFOA.</td>
</tr>
</tbody>
</table>
3. Properties of PFOS and PFOA

3.1. PFAS compounds overview

As noted in section 2.1, PFAS refers to a large number of fluorine-containing compounds. This guidance focuses on PFOS and PFOA as these compounds have been the focus of international work. At the time of preparation of this guidance, there was insufficient toxicity information available to allow derivation of guidance values for other PFAS (ATSDR 2015).

3.2. Physical and chemical properties

PFOS is a perfluoroalkane sulfonic acid (PFSA), with a fully fluorinated 8-carbon chain. The term PFOS generally refers to a mixture of linear and branched isomers, the ratio of which depends on the production process (CONCAWE 2016).

PFOA has an 8-chain carbon length, of which 7 carbons are perfluorinated. The most common PFOA derivative is the ammonium salt APFO (ammoniumpentadecafluorooctanoate) (DEPA 2015).

PFOS and PFOA are manufactured chemicals that are chemically and biologically stable and hence are persistent in the environment, resistant to biodegradation, atmospheric photooxidation, direct photolysis, and hydrolysis (US EPA 2014). PFOS and PFOA can also be formed from related substances or precursor compounds by microbial degradation or larger organism metabolism (e.g. rainbow trout transform perfluorinated acids to PFOS) (CRC CARE 2014a). Although the ultimate net contribution to environmental loadings of PFOS from individual PFOS-related substances cannot be easily predicted, potentially any molecule containing the PFOS moiety could be a precursor to PFOS (UNEP 2006). It is possible that as PFAS are gradually phased out, precursor transformation may continue to contribute to the potential for PFAS exposure (CRC CARE 2014a).

The stability of PFOS and PFOA is due to the strength of the carbon-fluorine bonds; each fluorine atom is shielded by three electron pairs, and the carbon atoms are shielded by the fluorine atoms (CRC CARE 2014a). PFOS and PFOA are moderately soluble in water, and are stable to hydrolysis in the environment based on their long half-lives in water (PFOA half-life reported as 92 years; PFOS half-life >41 years on basis that over study length did not identify change in concentration) (DEPA 2015). They are persistent in groundwater and surface waters, though they have been found to partition from the groundwater column into organic matter rich sediments and soil particles due to their propensity to sorb to natural organic matter.

PFOS and PFOA have low volatility; however, they can be transported long distances in air because of their high atmospheric half-lives (114 days and 90 days respectively) (US EPA 2014). Table 2 provides a summary of key physical and chemical properties of PFOS and PFOA.
Table 2 Properties of PFOS and PFOA

<table>
<thead>
<tr>
<th>Property</th>
<th>PFOS</th>
<th>PFOA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular structure</td>
<td><img src="image" alt="PFOS molecule" /></td>
<td><img src="image" alt="PFOA molecule" /></td>
</tr>
<tr>
<td>Appearance at normal temperature and pressure</td>
<td>White powder</td>
<td>White powder/waxy white solid</td>
</tr>
<tr>
<td>Molar weight (g/mol)</td>
<td>538</td>
<td>414</td>
</tr>
<tr>
<td>Vapour pressure</td>
<td>$3.31 \times 10^{-4}$ Pa (20 °C)</td>
<td>$0.1$ kPa (20 °C)</td>
</tr>
<tr>
<td>Water solubility at 25 °C (mg/L)</td>
<td>550 to 570 (purified) 370 (freshwater) 25 (filtered sea water)</td>
<td>$9.5 \times 10^3$ (purified)</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>$&gt;400$</td>
<td>45 – 50</td>
</tr>
<tr>
<td>Octanol-water partition coefficient (log Kow)</td>
<td>Not Measureable</td>
<td>6.30</td>
</tr>
<tr>
<td>Organic-carbon partition coefficient (log Koc)</td>
<td>2.57 – 4.2</td>
<td>2.06 – 3.7</td>
</tr>
<tr>
<td>Henry’s Law constant (atm-m$^3$/mol)</td>
<td>$3.05 \times 10^{-9}$</td>
<td>Not measurable</td>
</tr>
<tr>
<td>Air-water partition coefficient</td>
<td>$&lt;2 \times 10^{-6}$</td>
<td>Not available</td>
</tr>
</tbody>
</table>

Source: (Zareitalabad et al. 2013, USEPA 2014, DEPA 2015)

3.3. Toxicity

3.3.1 Human health

Recent studies have reported that measureable levels have been detected in the environment and in human blood, tissues and breast milk (Du et al. 2013). Humans are primarily exposed to PFAS, such as PFOS, through food consumption, contaminated drinking water, and a positive relationship between levels in human blood and fish consumption has been established (Shi et al. 2012). Consumption of fish and fish products can be one of the primary sources of human exposure to PFOS, with other potential pathways being ingestion of soil, food and water, inhalation of contaminated air or contaminated dust, exposure to carpets treated with perfluoroalkyls (children), or use of commercial products (ATSDR 2015).

Toxicology studies show that PFOS and PFOA are readily absorbed after oral exposure and accumulate primarily in the blood serum, kidney and liver and have a half-life of approximately two to nine years in humans (US EPA 2014). PFOS and PFOA bind to proteins ($\beta$-lipoproteins and liver fatty acid binding protein), preferentially partitioning to liver, blood and kidney tissue, and can interfere with fatty acid metabolism, and deregulate lipid and lipoprotein metabolism. They do not accumulate in fatty tissues because they exhibit both hydrophobic and lipophobic properties.

A number of studies on regions within Australia have been undertaken where human blood serum levels have been measured for PFOS and PFOA. In 2002–03 measurements from a number of rural area reported PFOS levels ranging from 19.1 to 36.1 ng/mL and PFOA ranging from 7 to 14.5 ng/mL (Kärrman et al. 2006). In 2010–11 pooled data from deidentified surplus pathology samples reported PFOS levels ranging...
from 4.4 to 17.4 ng/mL and PFOA ranging from 3.1 to 6.5 ng/mL (Toms et al. 2014). The decrease in concentrations is attributed to the discontinuation in 2002 of industrial production of PFOS and related compounds. For further discussion, refer to Appendix A of Part 2 of the guidance.

The toxic effect on humans from acute exposure is not known, and the long term adverse effects on humans are not yet well understood due to limited information. There is concern that due to the long half-life of PFOS and PFOA, continued exposure could increase body concentrations to levels that could have adverse outcomes (Seow 2013).

Animal studies have demonstrated a moderate acute oral toxicity, with potential adverse effects on the gastrointestinal tract, liver and thyroid levels (CRC CARE 2014a). Potential developmental, reproductive and other systemic effects were identified in rodents through acute- and intermediate-duration oral studies. Exposure of rats to PFOS caused effects on the neuroendocrine system and liver tumours.

Mixed information is available regarding the carcinogenicity of PFOS and PFOA. The US EPA does not currently classify PFOS or PFOA as carcinogenic (US EPA 2016a, b). The Danish EPA (DEPA 2015) considers PFOS and four derivatives to have a harmonised classification as carcinogenic, toxic to reproduction and acutely toxic. DEPA (2015) has also recommended that PFOA be classified for carcinogenicity, target organ toxicity, acute toxicity and eye irritation. PFOA is classified by the IARC Monographs as possibly carcinogenic to humans (Group 2B). Neither PFOS nor PFOA have been found to exhibit mutagenic properties, though high doses may induce carcinogenicity in animals (US EPA 2016a, b).

A detailed discussion of human toxicity is provided in part 2 of this guidance.

### 3.3.2 Ecological

A detailed discussion of ecological toxicity is provided in the part 3 of this guidance. The following provides a brief overview of ecological toxicity.

#### Aquatic organisms

PFAS are extremely thermally, biologically and chemically stable, and they exhibit hydrophobic and lipophilic characteristics (Konwick et al. 2008). The carbon-fluorine bond in PFAS is the strongest halogen-carbon bond, and shields the carbon chain bonds from reactive species, therefore the fluorinated surfactants are persistent in the environment (Boudreau et al. 2003a, 2003b, Hazelton et al. 2012). PFOS and PFOA have been shown to be metabolically and chemically inert, resisting both biotic and chemical degradation (Boudreau et al. 2003a, 2003b). Also PFAS are known to bioaccumulate and biomagnify in food webs as evidenced by PFOS detection in humans and wildlife (Konwick et al. 2008). PFOS and PFOA have also been found to bioaccumulate in edible aquatic species such has molluscs, crustaceans and fish (Yang et al. 2014).

The toxicological effects of exposure of aquatic organisms to PFOS and PFOA are reasonably well understood. Exposure of aquatic organisms to PFOS and PFOA can result in adverse effects to reproduction, immunology and development in exposed organisms as determined in many studies (refer to part 3: Ecological screening levels). Waterborne PFOS exposure can result in developmental toxicity in oviparous and
viviparous freshwater fish from multiple pathways involved in embryo and larval development, reproduction and stress response (Oakes et al. 2005, Wang et al. 2011). Chronic PFOS exposure has been found to result in decreased body length and weight, altered sex ratio and impaired gamete function in exposed adult zebrafish (Wang et al. 2011). Decreased reproduction and growth of individuals was observed in an intertidal copepod exposed to PFOS of concentrations up to 1 mg/L (Han et al. 2015).

Fewer studies have been undertaken on the effects of PFOS and PFOA exposure to marine organisms, compared to freshwater systems. As salinity can influence the fate and transport of PFOS and PFOA in the environment (Jeon et al. 2010) toxicity of marine organisms must be considered separately to freshwater ecosystems, as they are not necessarily directly comparable, though PFOS appears to have a similar mode of action in freshwater and marine fish. Changes to gene expressions have been observed in green mussels exposed to PFOA and PFOS (Liu et al. 2014) and a small marine teleost fish (Huang et al. 2011).

**Terrestrial ecosystems**

There is limited information on the impacts of PFOS and PFOA exposure on terrestrial organisms. Exposure of earthworms to PFOS may result in decreased growth and DNA damage (Xu et al. 2013, Mayilswami et al. 2014). Earthworms can bioaccumulate PFOS and PFOA through exposure to pore water and ingestion of soil through the gut (Zhao et al. 2014, Zareitalabad et al. 2013).
4. PFOS and PFOA in the environment

4.1. PFOS and PFOA in Australia

PFOS and PFOA have been detected widely in the Australian environment, with the majority of available information sourced from firefighting training grounds (Seow 2013). It is likely that these facilities represent worst case scenarios for PFOS and PFOA contamination, and to date the organisations involved with these installations have been leading the way in assessing and managing PFOS and PFOA contamination. It is recognised that there are other sources of PFOS and PFOA contamination, such as at combustible and flammable liquid storage facilities, electroplating, landfills, sewage treatment facilities, and where there are fire suppression systems installed, but little information is readily available regarding these other sources or the extent of PFAS contamination across the broader environment in Australia. It is expected that information will become available regarding these other potential sources as awareness of PFAS issues grow.

Table 3 shows typical ranges of PFOS and PFOA detected in soil, groundwater, surface water, sediment, and landfills (leachate and biosolids) across Australia. This is based on a limited data set, and may not be representative of the concentrations and extent that will be found in different environments, but it does provide a snapshot of the ranges of concentrations that might be encountered. The data in table 3 indicates:

- Fire training grounds appear to have higher concentrations of PFOS and PFOA compared with other sources. It is expected that fire training grounds and areas where AFFF was stored or used (such as petroleum storage/handling facilities) over many years will continue to be of interest.
- Concentrations of PFOS in soil, surface water and groundwater in the various case examples identified are substantially higher than the concentrations of PFOA. An exception to this was observed in the case of particular landfill leachate samples, where PFOA was found higher than PFOS. This may be the result of the formulation of products present in the landfills, and breakdown of precursor PFAS to PFOA.
- In the case of contamination of receiving waters where fishing and the consumption of fish may occur, the reported groundwater and surface water concentrations for both PFOS and PFOA are potentially of concern with respect to PFAS accumulating in fish and exceeding acceptable levels for human consumption (refer to part 2 of this guidance).
### Table 3 Example contamination concentration ranges of PFOS and PFOA in Australia in a range of matrices

<table>
<thead>
<tr>
<th>Site/location</th>
<th>Soil/sediment/biosolids (mg/kg)</th>
<th>Waters (µg/L)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fire training grounds (groundwater)</td>
<td>Soil: &lt;0.01 – 460</td>
<td>Soil: &lt;LOR – 3.2</td>
<td>Groundwater: 0.07 – 2100 Groundwater: &lt;LOR – 160 Sites included active and former fire training grounds.</td>
</tr>
<tr>
<td>Landfills (leachates/evaporation/aeration pond)</td>
<td>NA</td>
<td>NA</td>
<td>&gt;LOR = 1.87 &gt;LOR – 0.88 PFOS and PFOA were detected in every sample. 6:2: FTS and 8:2FTS detected in 10 of 15 samples. Other PFAS also detected. (ALS 2015)</td>
</tr>
<tr>
<td>Untreated landfill leachate (six states/territories)</td>
<td>NA</td>
<td>NA</td>
<td>Median 0.446 Median 0.306 PFOS and PFOA most frequently detected and abundant PFAS (Gallen et al. 2014).</td>
</tr>
<tr>
<td>Brisbane: Moreton Bay and four influent rivers (background regional data following flood event)</td>
<td>NA</td>
<td>NA</td>
<td>Surface water: 0.00018 – 0.015 (mean) Surface water: 0.00013 – 0.0062 (mean) Sampling conducted post-significant flood event in 2011. PFOS concentrations dominated out of a range of PFAS (Gallen et al. 2014).</td>
</tr>
<tr>
<td>Sydney Harbour: Homebush Bay (regional data)</td>
<td>Sediment: 0.0008 – 0.0062</td>
<td>Sediment: &lt;LOR – 0.00016</td>
<td>Surface water: 0.0075 – 21 Surface water: 0.0042 – 0.0064 PFOS concentrations were highest of a range of PFAS analysed (Thompson et al. 2011).</td>
</tr>
<tr>
<td>Sewage treatment plants (leachate and biosolids)</td>
<td>Biosolids: &lt;LOR – 0.19</td>
<td>Biosolids: &lt;LOR – 0.016</td>
<td>Leachate: &lt;LOR – 1.10 Leachate: 0.016 – 2.1 PFOA in leachate typically exceeded PFOS concentrations (Gallen et al. 2014).</td>
</tr>
</tbody>
</table>

**NOTES:**
**Bold:** indicates concentration can exceed international screening levels (table 4, section 5).

No international screening levels available for biosolids or leachate.
4.2. Fate and transport in the environment

4.2.1 Transport

PFOS and PFOA are widely distributed in the environment, and are detected in soil, sediment, surface waters and groundwater both near point sources and in remote locations. Their persistence in the environment and moderate solubility means they can be transported long distances and transfer between different media. PFOS and PFOA can be transported to surface waters and subsurface waters (i.e. groundwater) as a result of runoff and leaching. Atmospheric transport of precursor compounds and long range transport via ocean currents may also occur, as demonstrated by the detection of PFOS in remote regions of the Arctic caps (US EPA 2014).

PFOS and PFOA have also been shown to be persistent in the aquatic environment with potential to adsorb to particulate matter and bioaccumulate in aquatic organisms (OECD 2002, Hazelton et al. 2012). PFOS has a very low Henry’s Law Constant which indicates that volatilization from water to air is unlikely, and aquatic environments may be a significant potential sink for PFOS (US EPA 2002), particularly marine systems because of the lower solubility of PFOS and PFOA in seawater (Ahrens et al. 2009). This is supported by the detection of PFOS in groundwater and surface water systems near PFOS production plants and firefighting training facilities in the USA (Boudreau et al. 2003a, Konwick et al. 2008). Further, particulate matter will ultimately be deposited in sediments, forming a sink for PFOS. However, Environment Canada (2013) suggests that sediments, while a sink for PFOS, are unlikely to be a sink for PFOA as aqueous concentrations of PFOA are higher than that of PFOS, and PFOA is less strongly adsorbed than PFOS.

Mobility of PFAS in water is partially influenced by the degree of sorption to sediments or soils during transport. Sorption can remove a portion of the PFAS from aqueous solution, and hence reduce the total contaminant mass migration velocity relative to water velocity (CONCAWE 2016).

PFAS also enter the environment through wastewater treatment plants, with discharges both to aquatic and terrestrial environments (Bossi et al. 2008, Hu et al. 2011). Concentrations of PFOS and PFOA may increase in wastewater treatment plant effluent as a result of the wastewater treatment process, possibly through the transformation of precursor products (Chen et al. 2012, Becker et al. 2008). PFOS and PFOA readily adsorb to sludge in wastewater treatment plants and become concentrated in biosolids due to the high organic content (Zareitalabad et al. 2013). PFOS is thought to sorb more readily to biosolids than PFOA (Becker et al. 2008, Guo et al. 2010, Chen et al. 2012). Precursor products present in biosolids can also act as long-term sources of PFOS and PFOA into the environment (Venkatesan & Halden 2014). Further information is provided in part 3 of this guidance.

4.2.2 Exposure pathways

Human exposure to PFOS and PFOA primarily occurs through oral ingestion of contaminated soil, food (including biomagnification through the food chain) and water, and through inhalation (US EPA 2014, ATSDR 2015). Uptake via dermal exposure generally appears to be less of a concern, though information is limited (ATSDR 2015, Kudo & Kawashima 2003). Infants may be exposed through breast milk, and young children through hand-to-mouth activities from treated carpets (ATSDR 2015). PFOS
has been widely detected in human blood serum, though a decreasing trend in concentrations has been observed since 2002 (refer to part 2 of this guidance).

4.2.3 Soil, sediment and water partitioning

The partitioning of PFOS and PFOA between water, soils and sediments is complex, with various factors influencing partitioning such as the strength of bonds, solubility (PFOS solubility decreases in seawater), solution ionic composition, organic content, pH and presence of other contaminants such as hydrocarbons (Lasier 2011). Detailed discussions are provided in part 2 of this guidance.

4.2.4 Bioaccumulation

PFOS and PFOA are known to bioaccumulate and biomagnify in food webs, as evidenced by PFOS detection in humans and wildlife (Konwick et al. 2008, Sharpe et al. 2010, Hazelton et al. 2012). However, detection of PFAS at higher trophic levels does not necessary indicate that biomagnification in the food chain has occurred (Martin et al. 2004). Further, PFOS and PFOA have been shown to be metabolically and chemically inert, resisting both biotic and chemical degradation (Boudreau et al. 2003a, 2003b). However, PFOS and PFOA may have different bioaccumulation trends in the marine food chain, with PFOS having the potential to biomagnify along the food chain and PFOA to a lesser extent (Yang et al. 2012). PFOS and PFOA have been detected in higher trophic animals such as fish, dolphins, seals, polar bears and birds, though PFOS has a higher tendency to bioaccumulate than PFOA (Butt et al. 2008, Thompson et al. 2011a, Fair et al. 2013, Greaves et al. 2013, Leat et al. 2013, Lucia et al. 2015).

Edible plants can uptake PFOS and PFOA from soil, irrigation water and the atmosphere, such as in the vegetative (e.g. leaves, roots, leaf buds and stems) portions of carrots, cucumbers, maize, wheat, potato and oats, with higher concentrations of PFOA observed than PFOS (Stahl et al. 2008, Lechner & Knapp 2011, Zhang et al. 2015).

4.2.5 Bioavailability

There is limited information regarding the effects of aging and soil properties on bioavailability, with toxicity studies focusing on exposure of organisms to fresh PFOS and PFOA. The binding affinity and hence bioavailability of PFOS in soils and sediments are determined by the composition and properties of the soil/sediment matrix (Chen et al. 2012, Das et al. 2013). Determining these could provide some indication of the bioavailability of PFOS. PFOA does not show the same binding affinity to soils and soil composition may not influence the bioavailability and toxicity of PFOA to the same degree. In the absence of sufficient information to allow bioavailability of PFOS and PFOA to be established, it is typically assumed that the contamination is 100% bioavailable. The effect of soil and sediment on bioavailability is discussed in greater detail in part 3, section 2.7.

4.3 Conceptual site model

Understanding the behaviour of PFOS and PFOA in the environment is essential in evaluating risks posed to potential receptors. Because of their persistence and ability to bioaccumulate, the effects of PFOS and PFOA released into the environment can be
far reaching. Developing a conceptual site model (CSM) is an important step in understanding the potential receptors (human or ecological) that might be exposed, and whether complete exposure pathways to receptors exist. Development of a site-specific CSM is discussed in greater detail in part 5 of this guidance.

Because of the potential for bioaccumulation, a site-specific CSM will need to consider the possibility of many exposure pathways, such as:

- Leaching from soil to groundwater (and surface water)
- Groundwater discharge into surface water bodies
- Adsorption to sediments
- Bioaccumulation in seafood
- Accumulation in the biosolids of a sewage treatment plant, and discharge in the effluent of a sewage treatment plant to surface water body
- Uptake by plants and accumulation in soil from irrigation of contaminated water
- Uptake in plants and bioaccumulation in livestock that consume the plant material and soil
- Human exposure to meat and animal products (e.g. milk and eggs)
- Infant exposure to human breast milk and animal milk, and
- Ecological impacts to flora and fauna.

Figure 1 illustrates some of the complexity that is associated with PFOS and PFOA in the environment. This is a simplistic view and does not attempt to cover all exposure pathways or receptors. It is limited to scenarios where there is existing soil and groundwater contamination, and does not consider scenarios whereby site workers may be directly exposed to PFAS products (e.g. fire fighters, electroplaters).
Figure 1 Example CSM for PFAS-contaminated media
5. International Guidelines

A range of human health and ecological investigation levels have been proposed internationally, with new information being released on a regular basis. The investigation levels vary considerably in magnitude. Table 4 provides a summary of some well recognised international PFOS and PFOA screening levels from a range of jurisdictions. It is not intended to capture all available screening levels, but rather to provide a snapshot of the ranges of concentrations considered acceptable internationally. The focus is generally on PFOS and PFOA, though some countries have provided screening levels for other PFAS, including taking a summation approach to certain PFAS, such as in Denmark.

Guidelines and supporting information are available for potable water, groundwater and aquatic ecosystems in some international jurisdictions. Little information was identified regarding acceptable levels for the protection of terrestrial ecosystems – this may be because it is generally of lesser priority, and perhaps not being considered to be a limiting exposure pathway. There is also an absence of accepted screening levels for sewer and landfill disposal – this may be due to the system-specific nature and complexity of establishing acceptance screening levels for PFOS and PFOA in such systems.

Screening levels for the protection of human health, terrestrial and aquatic ecosystems are developed in this guidance document, and discussion is provided regarding how the screening levels compare with available international guideline values.
Table 4 Example international screening levels for PFOS and PFOA

<table>
<thead>
<tr>
<th>Region</th>
<th>Human health (µg/L)</th>
<th>Ecological (µg/L)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Drinking water</td>
<td>Soil (mg/kg)</td>
<td>Fish consumption (ng/L)</td>
</tr>
<tr>
<td></td>
<td>PFOS</td>
<td>PFOA</td>
<td>PFOS</td>
</tr>
<tr>
<td>Denmark</td>
<td>0.1  b</td>
<td>0.4  b</td>
<td>0.1</td>
</tr>
<tr>
<td>Germany</td>
<td>0.3/0.1  b.c</td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>Sweden</td>
<td>0.09  b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UK</td>
<td>0.3</td>
<td>0.3</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Minnesota</td>
<td>0.3</td>
<td>0.3</td>
<td>1.1</td>
</tr>
<tr>
<td>New Jersey</td>
<td>-</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>US EPA</td>
<td>0.2</td>
<td>0.4</td>
<td>6</td>
</tr>
<tr>
<td>(former)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>US EPA</td>
<td>0.07  b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(revised)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canada d</td>
<td>0.6</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Netherlands</td>
<td>0.53</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

NOTES:
- Res/rec – residential / recreational land use
- Com/ind – commercial / industrial land use
- Draft revised SRVs released June 2015 (www.pca.state.mn.us/waste/risk-based-site-evaluation-guidance)
- Guideline value applies to sum of PFAS and derivatives
- German water quality guideline present value of 0.3 µg/L as strict health based value and also a value of 0.1 µg/L as precautionary value (long term quality goal)
- Health Canada also publish drinking water criteria for other PFAS and precursors.
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