Annex 15 Restriction Report
Proposal for a restriction

Per and polyfluoroalkyl substances (PFAS) in firefighting foams

- EC Number: N/A
- CAS Number: N/A

August 2025

DISCLAIMER

With reference to the use of the information and data contained within this document, the Health and Safety Executive (HSE), as the Agency for UK REACH, makes the following disclaimer:

- The conclusions of this document have been compiled using information available at the time of writing. Additional or new information or assessment may require conclusions to be altered.
- Any statements, analyses or data within the document are without prejudice to future regulatory work which may need to be undertaken later by HSE (in conjunction with the Environment Agency under Article 2B of UK REACH).
- HSE is not in any way liable for the use of the information and data contained in this document by any third party.
- Any use of information and data in this document remains the responsibility of the user.

Summary

The restriction proposed in this report aims to reduce risks to health and the environment from the use of per- and polyfluoroalkyl substances (PFAS) in firefighting foams.

PFAS are a broad class of synthetic, fluorinated organic chemicals. They have attracted regulatory attention globally owing to their pervasiveness and persistence in the environment which make them difficult to remove using current remediation methods.

Firefighting foams that contain PFAS are a source of direct emissions of these substances into the environment. Therefore, the Secretary of State for the Department for Environment, Food and Rural Affairs (Defra), with the agreement of the Scottish Government and the Welsh Government, requested that HSE as the Agency for UK REACH prepare an Annex 15 report under UK REACH in respect of a possible restriction on the use of PFAS in firefighting foams.

The following report provides an assessment of the human health and environmental risks associated with the use of PFAS in firefighting foams (including liquid firefighting foam concentrates and ready-to-use foams). It assesses the alternatives to PFAS, along with the effectiveness, practicality, monitorability and economic impacts of potential risk management measures.

The main function of PFAS in firefighting foams is to act as a surfactant, forming a film over the surface of a burning liquid. This prevents flammable gases being released from fires and helps to prevent fires from reigniting. Therefore, PFAS-containing firefighting foams are used to extinguish fires that involve flammable liquids ("class B" fires). This report considers the use of such foams by the fire and rescue services in GB and specific applications in the (petro)chemicals industry, at offshore installations, in ready-to-use products (including hand-held extinguishers), on board boats, at civilian/commercial airports and for defence (military) purposes. Most of the PFAS-containing firefighting foam placed on the GB market is used in the (petro)chemical industry, which accounts for approximately 60% of the total GB sales volume.

Emissions of PFAS to the environment have been demonstrated from all uses of PFAS-containing firefighting foam in GB. The Agency estimates that approximately 48 tonnes of PFAS are emitted to the GB environment from use in such firefighting foams per year.

Once PFAS enter the environment, transformation processes eventually lead to the formation of highly stable fluorinated substances, referred to as terminal degradation products. The Agency concludes that the terminal degradation products that arise

from PFAS contained in firefighting foams are very persistent. These terminal degradation products are also sufficiently mobile to reach environmental compartments of concern, including those remote from sources. In particular, their mobility in water means that they can contaminate water sources, including drinking water. Following exposure of people to PFAS, these substances can remain in the human body for a long time, and continued exposure is expected to lead to increasing body burdens. Some terminal degradation products and other PFAS are suspected carcinogens, cause harm to the developing child and can cause effects in organs such as the liver or in the immune system.

Because of the extreme persistence in the environment, it is reasonable to conclude that with continued emission, any threshold of effect that could be established would be breached over time. Therefore, the Agency considers it appropriate to adopt the same approach to risk assessment that would be taken for non-threshold substances. When a non-threshold approach to environmental risk assessment is taken, any emissions to the environment are considered to be a proxy for environmental and health risks.

As environmental emissions occur from all uses of PFAS-containing firefighting foam in GB, with surface and ground water identified as compartments of particular concern, the Agency considers that the use of PFAS-containing firefighting foam is associated with a risk to the environment and human health via the environment.

Existing measures to control PFAS, such as guidelines for concentrations of certain PFAS in drinking water and requirements for capture and containment of waste, are in place in GB. However, these measures do not control emissions of PFAS into the environment following the use of firefighting foams. Owing to their persistence and resistance to environmental remediation measures, continuing emissions of these substances from their use in firefighting foams are expected to lead to progressively increasing concentrations of PFAS in the environment over time and contribute to PFAS exposures at the population level.

Therefore, the Agency concludes that the use of PFAS in FFF presents a risk to the environment, and human health via the environment, that is not adequately controlled by measures already in place.

Consequently, a restriction on the placing on the market and use of PFAS in firefighting foams was assessed as a potential measure to address this risk.

The exact composition of the PFAS contained in firefighting foams is largely unknown because of the proprietary nature of the products and because PFAS manufacturing processes can result in complex mixtures of structurally-related PFAS. It is also possible that PFAS not currently used in FFF could be developed as alternatives or for new applications. Therefore, a restriction that encompasses the whole PFAS class reduces the potential for regrettable substitution with other PFAS that have the same risks as those already identified.

Significant effort has been made to develop and transition to fluorine-free firefighting foams. However, the sectors in which PFAS-containing foams are used present some challenges for transition; including the cost, compatibility with all scenarios in which firefighting foams need to be used and their efficacy compared with PFAS-containing foams. For the latter, this includes ensuring that alternative foams are sufficiently able to extinguish a fire in time to ensure there is no increased risk to life. There are only a small number of robust reports of alternative foams being used in real fire incidents, but there are fluorine-free foam formulations that meet the established performance standards in controlled firefighting test scenarios. Further, examples of successful transitions exist in each of the sectors analysed by the Agency.

Given that alternatives are broadly available to replace PFAS in firefighting foams across sectors, the Agency suggests that a restriction on the placing on the market and use of PFAS-containing firefighting foams is appropriate. The proposed restriction includes sector-/use-specific transition periods (as defined in Tables 1 and 2 below) to support an orderly transition, and ensure that users can adapt to suitable alternatives without jeopardising safety. These transition periods have been determined using those derived in the EU restriction on PFAS in firefighting foams as a basis, and supplemented with GB-specific information gathered during the development of this report.

The Agency also concludes that a restriction on the placing on the market and use of firefighting foam does not appear disproportionate relative to other chemicals' restriction interventions, though it has not been possible to undertake a fully quantified cost benefit assessment at this stage.

The Agency therefore proposes that a restriction under UK REACH is appropriate to address the identified risks. Within 12 months of the publication of this report, the Agency will formulate its opinion on the suggested restriction.

Suggested restriction:

A restriction on the **placing on the market and use** of PFAS as a constituent in firefighting foam, where PFAS will be defined as **"any substance that contains at least one fully fluorinated methyl (CF_3) or methylene (CF_2) carbon atom without any hydrogen, chlorine, bromine, or iodine atom attached to it."**

Table 1: Transitional periods for placing on the market.

	Sector/use	Transitional period from the entry into force
1	Portable fire-extinguishers (defined by BS EN3-7, BS EN-1866 and BS EN-16856)	6 months
2	Sectors with specific transition periods for use defined in Table 2	Until the end of the transitional period for uses defined in Table 2
3	All other uses[#]	5 years

[#] There may be other uses that are not covered by the sector specific transition periods in Table 2. For such cases, the Agency suggests a 5 year transition period for placing on the market which is in line with the requirements for most sectors. Other uses could, for example, include chemical manufacturing facilities not classed as COMAH sites.

Table 2: Transitional periods for use

	Sector/use	Transitional period from the entry into force
1	Portable fire extinguishers (defined by BS EN3-7, BS EN-1866 and BS EN-16856)	5 years
2	COMAH sites; except for those already covered by the arrangements for aviation (see point 6)	10 years
3	Training and testing[#]; except testing of firefighting systems for their function.	18 months

	Sector/use	Transitional period from the entry into force
4	Fire and rescue services; except for those also responsible for attending industrial fires for establishments covered by COMAH, where the 10 year transition period will apply for **use at these establishments only** (see point 2).	18 months
5	On board civilian boats	5 years
6	Civilian aviation sites	5 years
7	Defence*; except for military vessels where a 10 year transition period will be applicable	5 years
8	Offshore oil and gas installations	10 years
9	All other uses$	5 years

[#] A separate transition period is considered appropriate for training with FFF compared to their use during live incidents. Given that most training takes place under controlled conditions and measures are already in place to use PFAS-free foams for such purposes, a relatively short transition period is considered appropriate. Likewise for testing (e.g., testing foams to establish suitability), a shorter transition period is considered appropriate. An exception should be made for the testing of fixed firefighting systems to ensure they can continue to comply with required safety standards until the end of the sector-specific transition periods.

*Defence is considered to include sites on land either owned by the Ministry of Defence (MoD), or where the MoD has rights to the land or assets owned by or operated on behalf of the MoD. An exception should be made for use on military vessels, where a longer transition period is considered appropriate to account for specific defence requirements and to allow for any refitting.

[$] There may be other uses that are not covered by the sector specific transition periods in points 1 to 8. For such cases, the Agency suggests a 5 year transition period which is in line with the requirements for most sectors. Other uses could, for example, include chemical manufacturing facilities not classed as COMAH sites.

To ensure levels of PFAS in FFF are reduced to as low as reasonably practicable and for the restriction to be effective and practical (including enforceable), it is necessary to include a concentration limit for the amount of PFAS permitted within foam concentrate. The Agency considers that the restriction for **placing on the market** should apply where the concentration of total PFAS is **greater than 1 mg/L** in the foam concentrate. This limit is sufficiently low to prevent intentional addition of PFAS to such foams, noting the lowest concentration considered as providing any functionality is 1000 mg/L. In addition, the Agency understands that the available analytical methods (Annex B) are able to quantify total PFAS at this level.

Further consideration will be given to establishing a concentration limit for use, noting that such a limit would need to account for residual release from existing systems (i.e., rebound, refer to Section 3.1.7) and the costs associated with decontamination or replacement of such systems (Section 6.4.2.11). The Agency notes that ECHA's restriction of PFAS in FFF proposed a limit of 1 mg/L but the draft Commission regulation (European Commission, 2025) considered a limit of 50 mg/L appropriate for "the total of all PFAS in firefighting foams and concentrates originating from and present in such equipment which contained PFAS-containing firefighting foams and that has undergone cleaning".

Analysis for the EU restriction suggests that a limit of 50 mg/L would represent a reduction in concentration and emissions of 99.8%, whilst a limit of 1 mg/L would result in a 99.99% reduction. Taking this and the economic analysis conducted by the Agency into account (Section 6.4.2.11), the Agency considers that the restriction for **use** should apply where the concentration of total PFAS is greater than **50 mg/L**, However, the Agency will seek further information to understand the costs of decontamination and the impact of a higher concentration on emissions during the opinion development.

During opinion development, the Agency will also consider whether the restriction could include additional complementary measures during any transitional periods to minimise emissions, so far as is reasonably practicable. Such measures may include, for example:

- A requirement for users of firefighting foam products, which contained total PFAS at greater than 1 mg/L when placed on the market, to document and maintain a management plan addressing how they:
    - use PFAS-containing firefighting foam, including an assessment of the technical and economic feasibility of alternatives,
    - seek to minimise PFAS release to the environment from the use of such foams.

  Such a plan would be kept up-to-date and available for inspection by the relevant enforcing body on request.
- Labelling requirements that apply to the packaging of firefighting foam containing total PFAS at greater than 1 mg/L when placed on the market. Such a label would alert users to the presence of PFAS and support proper handling of these materials during the transition periods.

Abbreviations

ADME	Absorption, distribution, metabolism and excretion
ADONA	Ammonium 4,8,-dioxa-3H-perfluorononanoate
AFFF	Aqueous Film-Forming Foam
APFO	Ammonium Pentadecafluorooctanoate
AR-AFFF	Alcohol resistant aqueous film-forming foam
AR-FFFP	Alcohol resistant film-forming fluoroprotein
AR-SFFF	Alcohol resistant synthetic fluorine-free foam
ATSDR	Agency for Toxic Substances and Diseases Registry
B	Bioaccumulative
BOD	Biochemical oxygen demand
CAA	Civil Aviation Authority
CBA	Cost-benefit analysis
CER	Cost-effectiveness ratio
CHP	Catalysed hydrogen peroxide propagation
CIA	Chemical Industries Association
CLP	Regulation on the Classification, Labelling and Packaging of Substances and Mixtures
Cl-PFESA	Chlorinated polyfluorinated ether sulfonic acid
CMR	Carcinogenic, mutagenic and toxic to reproduction
NOOC	China National Offshore Oil Corporation
COD	Chemical oxygen demand
COMAH	Control of Major Accident Hazards
DGHAR	Dangerous Goods in Harbour Areas Regulation
DoD	US Department of Defence
DSEAR	Dangerous Substances and Explosive Atmosphere Regulations
DWI	Drinking Water Inspectorate
EBR	Eastern Balancing Reservoir
EC50	median effective concentration
ECHA	European Chemicals Agency
EUSES	European Union System for the Evaluation of Substances
FAA	Federal Aviation Administration
FBSA	Perfluorobutyl sulfonamide
FDPSO	floating drilling production storage and offloading
F-DIOX	2,2-difluoro-2[[2,2,4,5-tetrafluoro-5-(trifluoromethoxy)-1,3-dioxolan-4-yl]oxy] acetic acid
FFF	Firefighting Foam
FFFP	Film forming fluoro-protein
FHxSA	Perfluorohexane sulfonamide
FIA	Fire Industry Association

FOI	Freedom of information
FOSA	Perfluorooctane sulfonamide
FOSAA	Perfluorooctane sulfonamido acetic acid
FP	Fluoroprotein foam
FPSO	floating production storage and offloading
FRS	Fire and Rescue Service
FSO	floating storage and offloading
FSRU	floating storage regasification unit
FTOH	Fluorotelomer alcohol
FTCA	Fluorotelomer carboxylic acids
FTUCA	Fluorotelomer unsaturated carboxylic acids
F3	Fluorine-free foams
HAL	Heathrow Airport Ltd
HBGV	Health-based guidance values
HCL	Henry’s Law Constant
HWI	Hazardous waste incineration
ICAO	International Civil Aviation Organization
ICER	Incremental cost-effectiveness ratio
IC50	Median inhibitory concentration
IMO	International Maritime Organization
IM50	Median maturation concentration
IPEN	International Pollutants Elimination Network
JOIFF	International Organisation for Industrial Emergency Services
K_d	Adsorption coefficient
K_{OC}	Organic carbon normalised adsorption coefficient
L-FABP	Liver fatty acid binding protein
LC-MS	Liquid chromatography mass spectrometry
LC50	median lethal concentration
LNG	Liquified natural gas
LOD	Limit of detection
LOEC	Lowest observed effect concentration
LRTP	Long Range Transport Potential
M	Mobile
MAPP	Major Accident Prevention Policy
MBRs	Membrane bioreactors
MCA	Maritime Coastguard Agency
MCL	Mandatory classification and labelling
MDL	Method detection limit
MoD	Ministry of Defence
NATO	North Atlantic Treaty Organization
NASEM	US National Academies of Science, Engineering and Medicine
NFCC	National Fire Chiefs Council
NFPA	National Fire Protection Agency
NGO	Non-governmental organisation

N-MeFOSA	Heptadecafluoro-N-methyl octane sulfonamide
OECD	Organisation for Economic Co-operation and Development
ORR	Office for Rail and Road
P	Persistent
PAP	Polyfluoroalkyl phosphate esters
PASF	Perfluoroalkyl sulphonyl fluoride
PBT	Persistent, bioaccumulative and toxic
PFAA	Perfluoroalkyl acids
PFAS	Per- and polyfluoroalkyl substances
PFASaAM	Perfluoroalky sulphonamido amine
PFASaAmA	Perfluoroalkyl sulphonamide amino carboxylate
PFBA	Perfluorobutanoic acid
PFBS	Perfluorobutane sulfonic acid
PFCA	Perfluoroalkyl carboxylic acid
PFDA	Perfluorodecanoic acid
PFDoDA	Perfluorododecanoic acid
PFDoDS	Perfluorododecanesulfonic acid
PFDS	Perfluorodecane sulfonic acid
PFECA	Perfluoroalkylether carboxylic acid
PFESA	Perfluoroalkylether sulfonic acid
PFEtS	Perfluoroethane sulfonic acid
PFHpA	Perfluoroheptanoic acid
PFHpS	Perfluoroheptane sulfonic acid
PFHxA	Perfluorohexanoic acid
PFHxDA	Perfluorohexadecanoic acid
PFHxS	Perfluorohexane sulfonic acid
PFNA	Perfluorononanoic acid
PFNS	Perfluorononane sulfonic acid
PFOA	Perfluorooctanoic acid
PFODA	Perfluorooctadecanoic acid
PFOS	Perfluorooctane sulfonic acid
PFPA	Perfluoroalkyl phosphonic acid
PFPeA	Perfluoropentanoic acid
PFPeS	Perfluoropentane sulfonic acid
PFPiA	Perfluoroalkyl phosphinic acid
PFPrA	Perfluoropropanoic acid
PFPrS	Perfluoropropane sulfonic acid
PFSA	Perfluoroalkyl sulfonic acid
PFTeDA	Perfluorotetradecanoic acid
PFTrDA	Perfluorotridecanoic acid
PFTrDS	Perfluorotridecane sulfonic acid
PFUnDA	Perfluoroundecanoic acid
PFUnDS	Perfluoroundecane sulfonic acid
PIC	Products of incomplete combustion

PMT	Persistent, mobile and toxic
POPs	Persistent Organic Pollutants
PPARα	Peroxisome proliferator-activated receptor alpha
PPE	Personal protective equipment
PV	Present Value
QSPR	Quantitative structure/property relationship
RAC	Committee for Risk Assessment
RMO	Risk management options
RMOA	Regulatory management options analysis
RO	Restriction option
RPS	Regulatory position statement
SDS	Safety data sheets
SEAC	Committee for Socio-Economic Analysis
SEM	Systematic evidence map
SFFF	Synthetic fluorine-free foam
SPMP	Site Protection and Monitoring Programme
STOT RE	Specific target organ toxicity, repeated exposure
STOT SE	Specific target organ toxicity, single exposure
SVHC	Substance of very high concern
TFA	Trifluoroacetic acid
TFMS	Trifluoromethane sulfonic acid
UL	Underwriters Laboratory
UN	United Nations
UTC	Unintentional trace contaminants
vB	very Bioaccumulative
vM	very Mobile
vP	very Persistent
WIMS	Environment Agency Water Information Management System
WoE	Weight of evidence
WwTP	Wastewater treatment plants

PFAS grouping and chain length

Table 3: PFAS grouping and carbon chain length.

The following table includes the PFAS sub-group and carbon chain length for PFAS cited in this report.

PFAS group	PFAS sub-group	Perfluorinated Cn (total Cn)	PFAS abbr.	Substance name	CAS RN
PFAAs	**Ultra short-chain PFCAs (C2-C3)**	1 (2)	TFA	Trifluoroacetic acid	76-05-1
		2 (3)	PFPrA	Perfluoropropanoic acid	422-64-0
	Short-chain PFCAs (C4-C7)	3 (4)	PFBA	Perfluorobutanoic acid	375-22-4
		4 (5)	PFPeA	Perfluoropentanoic acid	2706-90-3
		5 (6)	PFHxA	Perfluorohexanoic acid	307-24-4
		6 (7)	PFHpA	Perfluoroheptanoic acid	375-85-9
	Long-chain PFCAs (≥C8)	7 (8)	PFOA	Perfluorooctanoic acid	335-67-1
		7 (8)	APFO	Ammonium perfluorooctanoate	3825-26-1
		8 (9)	PFNA	Perfluorononanoic acid	375-95-1
		9 (10)	PFDA	Perfluorodecanoic acid	335-76-2
		10 (11)	PFUnDA	Perfluoroundecanoic acid	2058-94-8
		11 (12)	PFDoDA	Perfluorododecanoic acid	307-55-1
		12 (13)	PFTrDA	Perfluorotridecanoic acid	72629-94-8
		13 (14)	PFTeDA	Perfluorotetradecanoic acid	376-06-7
		14 (15)	PFPeDA	Perfluoropentadecanoic acid	141074-63-7
		15 (16)	PFHxDA	Perfluorohexadecanoic acid	67905-19-5
		16 (17)	PFHpDA	Perfluoroheptadecanoic acid	57475-95-3
		17 (18)	PFODA	Perfluorooctadecanoic acid	16517-11-6

PFAS group	PFAS sub-group	Perfluorinated Cn (total Cn)	PFAS abbr.	Substance name	CAS RN
	Ultra short-chain PFSAs (C1-C2)	1 (1)	TFMS	Trifluoromethane sulfonic acid	1493-13-6
		2 (2)	PFEtS	Perfluoroethane sulfonic acid	354-88-1
	Short-chain PFSAs (C3-C5)	3 (3)	PFPrS	Perfluoropropane sulfonic acid	423-41-6
		4 (4)	PFBS	Perfluorobutane sulfonic acid	375-73-5
		5 (5)	PFPeS	Perfluoropentane sulfonic acid	2706-91-4
	Long-chain PFSAs (≥C6)	6 (6)	PFHxS	Perfluorohexane sulfonic acid	355-46-4
		7 (7)	PFHpS	Perfluoroheptane sulfonic acid	375-92-8
		8 (8)	PFOS	Perfluorooctane sulfonic acid	1763-23-1
		9 (9)	PFNS	Perfluorononane sulfonic acid	474511-07-4
		10 (10)	PFDS	Perfluorododecane sulfonic acid	335-77-3
		11 (11)	PFUnDS	Perfluoroundecane sulfonic acid	749786-16-1
		12 (12)	PFDoDS	Perfluorododecane sulfonic acid	79780-39-5
		13 (13)	PFTrDS	Perfluorotridecane sulfonic acid	791563-89-8
	PFPAs	6 (6)	C6 PFPA	Perfluorohexyl phosphonic acid	40143-76-8
		8 (8)	C8 PFPA	Perfluorooctyl phosphonic acid	40143-78-0
	PFECAs & PFESAs	4 (6)	HFPO-DA	2,3,3,3-tetrafluoro-2-(1,1,2,2,3,3,3-heptafluoropropoxy)propanoic acid	13252-13-6
		5 (7)	ADONA	Ammonium 4,8-dioxa-3Hperfluorononanoate	958445-44-8
		6	EEA-NH4	Ammonium difluoro[1,1,2,2-tetrafluoro-2-(pentafluoroethoxy)ethoxy]acetate	908020-52-0
		6 (3)	F-DIOX	2,2-difluoro-2-[[2,2,4,5-tetrafluoro-5-(trifluoromethoxy)-1,3-dioxolan-4-yl]oxy] acetic acid	1190931-41-9
		7 (8)	6:2 Cl-PFESA	6:2 Chlorinated polyfluorinated ether sulfonic acid	73606-19-6
		9 (10)	8:2 Cl-PFESA	8:2 Chlorinated polyfluorinated ether sulfonic acid	763051-92-9
		8 (8)	9Cl-PF3ONS	Perfluoro(2-((6-chlorohexyl)oxy)ethanesulfonic acid	756426-58-1
	PASF-based substances	6 (6)	FHxSA	Perfluorohexane sulfonamide	41997-13-1

PFAS group	PFAS sub-group	Perfluorinated Cn (total Cn)	PFAS abbr.	Substance name	CAS RN
PFAA Precursor		8 (8)	FOSAA	Perfluorooctane sulfonamido acetic acid	2806-24-8
		8 (8)	PFOSA (FOSA)	Perfluorooctane sulfonamide	754-91-6
		8 (12)	N-EtFOSE	N-ethyl perfluorooctane sulfonamide ethanol	1691-99-2
		8 (9)	N-MeFOSA	Heptadecafluoro-N-methyloctanesulfonamide	31506-32-8
		8 (11)	N-MeFOSAA MeFOSAA Me-PFOSA-AcOH2	2-(N-Methylperfluorooctanesulfonamido)acetic acid	2355-31-9
		8 (12)	N-EtFOSAA EtFOSAA Et-PFOSA-AcOH	2-(N-Ethylperfluorooctanesulfonamido) acetic acid	2991-50-6
	FT-based substances	5 (8)	5:3 FTCA	5:3 fluorotelomer carboxylic acid	914637-49-3
		4 (6)	4:2 FTS	4:2 Fluorotelomer sulfonic acid	757124-72-4
		6 (8)	6:2 FTS	6:2 Fluorotelomer sulfonic acid	27619-97-2
		8 (10)	8:2 FTS	8:2 Fluorotelomer sulfonic acid	39108-34-4
		6 (8)	6:2 FTOH	6:2 Fluorotelomer alcohol	647-42-7
		8 (10)	8:2 FTOH	8:2 Fluorotelomer alcohol	678-39-7

1 Introduction

1.1 Problem Statement

On the 05 March 2024, the Secretary of State for the Department for Environment, Food and Rural Affairs (Defra), with the agreement of the Scottish Government and the Welsh Government, asked the Agency to prepare an Annex 15 report in respect of a possible restriction on per- and polyfluoroalkyl substances (PFAS) in firefighting foams (FFFs).

Reproduced request:

> I am writing to issue a formal request under Article 69(1) of UK REACH to the Health & Safety Executive (HSE), in their role as the UK REACH Agency, to prepare a dossier conforming to the requirements of Annex 15 of UK REACH in respect of a possible restriction on poly- and perfluoroalkyl substances (PFAS) in fire-fighting foams (FFFs).
>
> The Regulatory Management Options Analysis (RMOA), conducted by HSE and the Environment Agency and published in April 2023, concluded that PFAS as a group have a number of properties that together pose a concern to the environment and human health, in particular:
>
> - Persistence of substances or their degradation products in the environment, as the carbon-fluorine bonds which characterise PFAS are extremely strong.
> - Potential for a high level of mobility in the environment, leading to widespread dispersal and risk of contamination including to the water environment.
> - Uncertainties over long-term adverse impacts to the environment and human health.
>
> Based on the likely effectiveness and efficiency of the risk management options reviewed, the RMOA recommended that it would be appropriate to consider the preparation of restriction dossiers to support potential UK REACH restrictions to address further accumulation of PFAS in the environment. The RMOA recommended that a dossier relating to the use of FFFs should be prioritised due to the evidence and information available, and due to their likely direct emissions into the environment.
>
> The RMOA recommended that, in order to avoid regrettable substitution, a group approach should be used. For the purpose of the Annex 15 dossier, HSE may use a definition of PFAS as they may reasonably consider appropriate to assess and manage the risks identified in their role as the UK REACH Agency.
>
> For the reasons set out above, the Secretary of State considers that the use of PFAS-containing FFFs poses a reasonably foreseeable risk to the environment that is not adequately controlled and needs to be addressed. The Secretary of State is therefore issuing a formal request to the HSE to prepare a restriction dossier conforming to the requirements of Annex 15 of UK REACH in respect of the manufacture, placing on the market, and use of these substances. This dossier should include information on hazard and risk, and available information on alternative substances and techniques. This dossier

should also consider whether action is necessary beyond any measures already in place to manage risk throughout the lifecycle of these substances.

End of reproduced text.

1.2 Restriction Scope

As noted above, the Agency received a request under Article 69(1) of UK REACH to prepare an Annex 15 restriction report on PFAS in firefighting foams (FFFs). It is therefore necessary to define what is meant by both these terms within this report.

1.2.1 Firefighting foams (FFFs)

Firefighting foams are produced by mixing liquid foam concentrate, water and air at the point of use. Foam concentrates which contain PFAS are therefore the target of this restriction report. Alternative forms of fire suppression system (e.g. gaseous suppression systems), even if they contain PFAS, are not in scope.

The scope of this restriction is limited to liquid firefighting foam products.

1.2.2 Per- and polyfluoroalkyl substances (PFAS)

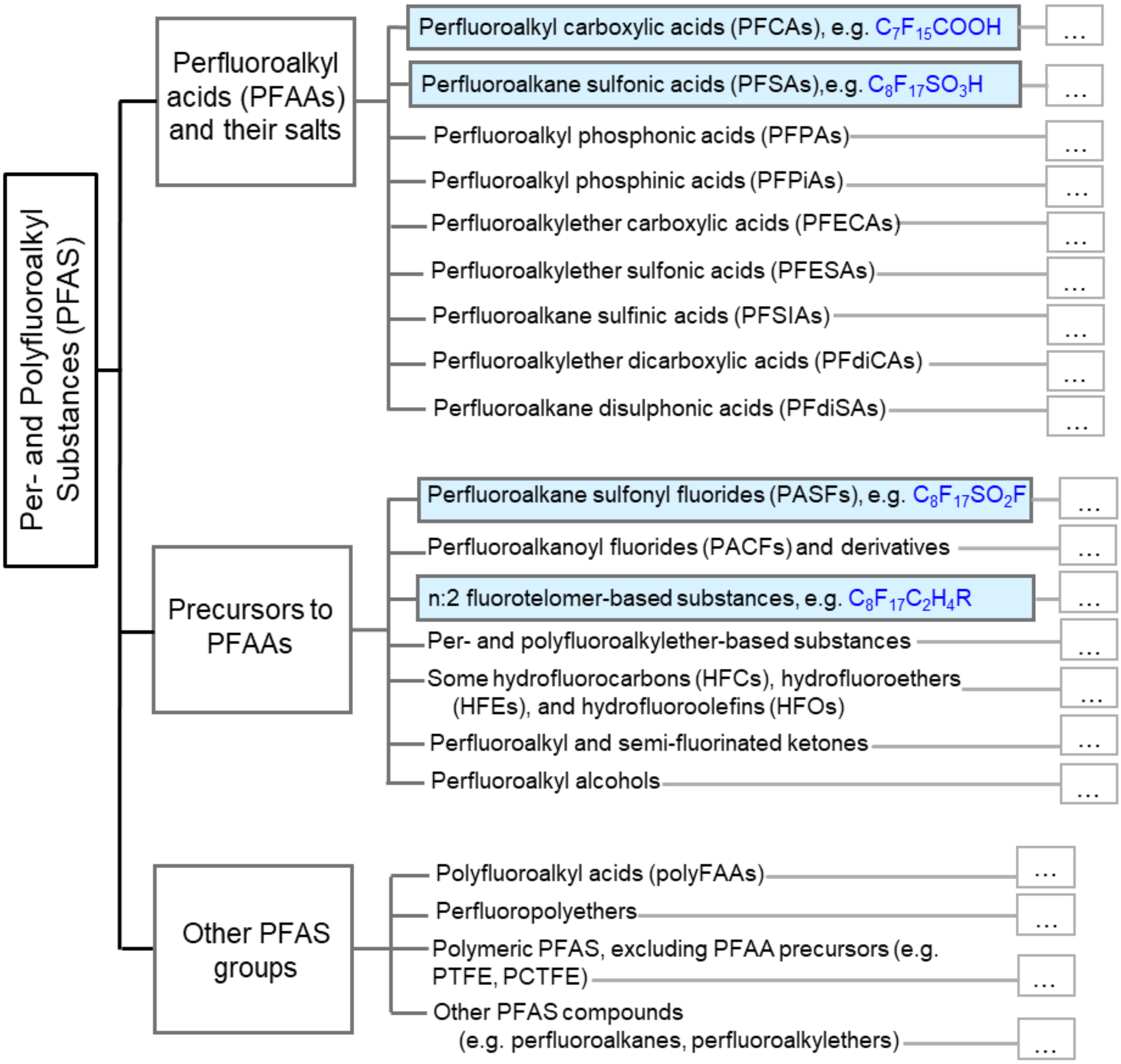
Per- and polyfluoroalkyl substances (PFAS) are a broad chemical class of synthetic chemicals that contains thousands of individual substances (OECD, 2021b). Perfluoroalkyl substances have fully fluorinated carbon chains, i.e., they have all C-H bonds replaced by C-F, while polyfluoroalkyl substances have at least one C-H bond remaining. There is no single, agreed definition for PFAS in the context of human health or environmental protection. Consequently, regulatory bodies have implemented different PFAS definitions to suit their specific objectives.

In 2021, the OECD provided a definition of PFAS based on chemical structure, refining the earlier work of Buck *et al*. (2011), with the intention of providing a consistent and coherent terminology. OECD (2021b) defines PFAS as “fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any hydrogen, chlorine, bromine, or iodine atom attached to it) i.e., with a few noted exceptions, any chemical with at least a perfluorinated methyl group ($-CF_3$) or a perfluorinated methylene group ($-CF_2$) is a PFAS”.

This definition is based on the chemical structure and does not indicate hazards or effects of these substances, nor does it imply that all PFAS have identical properties. This is a very broad and encompassing definition, so substances meeting this will have diverse molecular structures. Consequently, they exhibit diverse physical, chemical, and biological properties; being solids, liquids or gases, involatile or volatile, water-soluble or water-insoluble, reactive or inert, and bioaccumulative or non-bioaccumulative (OECD, 2021). Approximately 15,000 substances on the US EPA CompTox Dashboard meet the OECD definition of PFAS (CompTox Chemicals Dashboard (epa.gov) [accessed 05 September 2024]).

The wide range of different chemicals that fall within the OECD definition of PFAS can be grouped in different ways. In an attempt to reconcile the different terminologies used and to provide consistency, OECD (2021) also included a comprehensive overview of PFAS groups (Figure 1.1). This terminology will be used in this restriction proposal.

Figure 1.1: PFAS groups as defined by OECD (2021), with PFAS identified as present in FFF highlighted in blue.



OECD (2021b) notes that this definition serves as a foundational framework for understanding the broader PFAS category and that to address specific needs, the definition may be refined for particular activities by incorporating additional criteria, such as specific properties or areas of use.

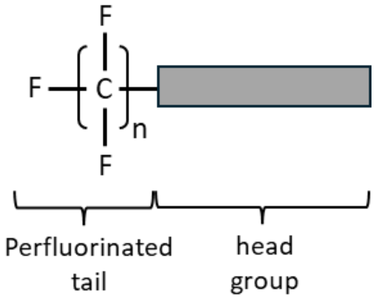
1.2.3 Function of PFAS in FFFs

FFFs work to suppress fires by the combination of two actions. Firstly, the addition of water cools the fire. Secondly, the foam forms a layer that suppresses the combustible fuel vapours, preventing reignition. The addition of PFAS to the foam aids this second action owing to their surfactant properties. The fluorinated surfactant drains from the foam and forms an immiscible film that travels across the surface of the fuel, suppressing fuel vapours and resealing when the foam blanket breaks or is disturbed. Even after the foam blanket breaks down, PFAS surfactant will continue to suppress combustible fuel vapours, preventing reignition.

1.2.4 Identification of PFAS in FFFs

The PFAS used in FFFs are often listed as proprietary fluorinated surfactants in safety data sheets (SDS), without specific details, which makes it difficult to establish the identity of the individual substances present. However, to provide the required surfactant properties, the PFAS used in FFFs will have a chemical structure that consists of a per- or polyfluoroalkyl tail and a head group (Figure 1.2) and will all be liquids at environmentally relevant temperatures.

Figure 1.2: Generic structure of PFAS found in FFFs.



PFAS used in FFFs are either produced by electrochemical fluorination or fluorotelomerisation (including: Backe *et al.*, 2013; Barzen-Hanson *et al.*, 2017; D'Agostino and Mabury, 2014; Liu *et al.*, 2024b; Place and Field, 2012; Ruyle *et al.*, 2023; Wood, 2020). Differences in manufacturing processes dictate which PFAS groups are the most abundant. Both methods produce perfluorinated compounds, though some polyfluorinated compounds may be present as low-level impurities. Electrochemical fluorination results in the formation of linear and branched compounds, but the perfluoroalkyl chains do not break during telomerisation and therefore branching does not occur with that method. However, both methods produce complex mixtures of structurally related PFAS, the composition of which cannot be exactly predetermined (Barzen-Hanson *et al.*, 2017; Liu *et al.*, 2024b). Further details on these manufacturing methods are presented in Annex A.

Changes in formulations have occurred as a result of regulatory action, such as nomination to the Stockholm Convention of PFOS and PFOA (C8 chemistry). This resulted in an increase in FFFs using C6 chemistry and a shift away from electrochemical fluorination to fluorotelomerisation (D'Agostino and Mabury, 2014; Houtz *et al.*, 2013; Liu *et al.*, 2024b; Seow, 2013).

1.2.5 PFAS definition for this restriction

The Agency considers that the most appropriate definition of PFAS to use in this restriction report is the OECD (2021) definition i.e., **any substance with at least a perfluorinated methyl group (-CF_3) or a perfluorinated methylene group (-CF_2-) (without any hydrogen, chlorine, bromine, or iodine atom attached to it)**.

Information on the technical function that the PFAS perform in FFF (i.e., as a surfactant) and the classes of PFAS typically identified as being present is available (Sections 1.2.3, 1.2.4 and 2.1.1). However, the Agency has incomplete knowledge of the specific PFAS used in FFF owing to their proprietary nature. It is also possible that PFAS not currently used in FFF could be developed as alternatives or for new applications. Therefore, encompassing the widest range of PFAS in the scope of the restriction reduces the potential for regrettable substitution with other PFAS that have the same risks as those already identified.

It is also noted that targeted analysis, which focuses on identifying specific PFAS compounds, will not be able to fully characterise the PFAS present in FFF, contaminated fire suppression equipment or exposed environmental compartments given the number of potential PFAS present and lack of available analytical standards (e.g. Aro *et al.*, 2021; Houtz *et al.*, 2016; Liu *et al.*, 2024b; Murakami *et al.*, 2009). A broader definition would have practical benefits and aid monitorability as non-targeted analytical approaches that do not differentiate between specific PFAS could be used. Further detail on analytical approaches and the balance between selectivity and sensitivity is presented in Annex B.

Further benefits of using an internationally agreed definition include consistency with the approach to the risk management of FFF being taken in other jurisdictions i.e., the EU (ECHA, 2023c). Noting that PFAS presents a global concern and given that PFAS-containing FFF products are imported into and exported from GB, a common definition would reduce the burden and aid compliance with any regulatory risk management actions.

2 Hazard Assessment

2.1 General approach to hazard assessment

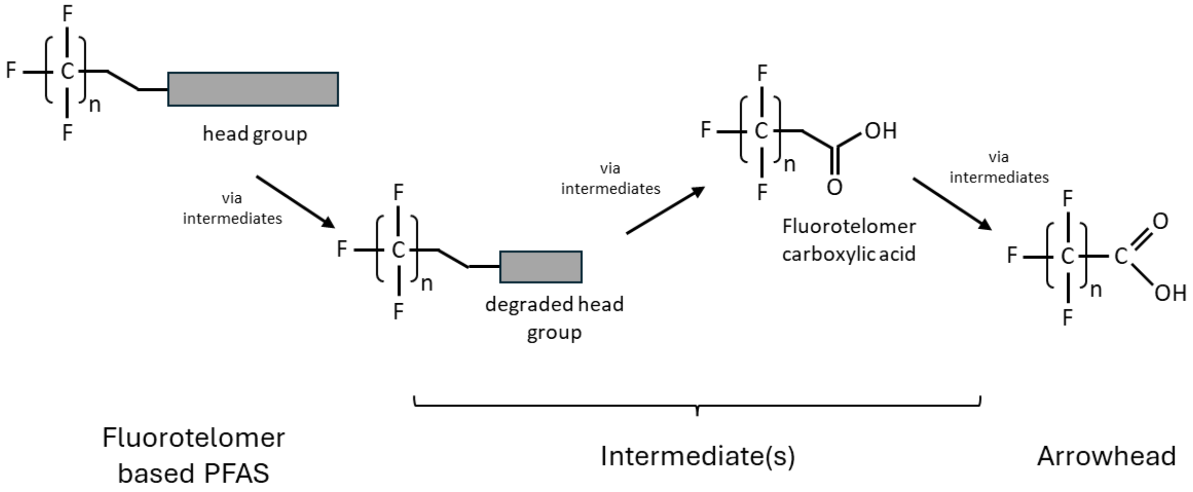
PFAS that meet the OECD (2021b) definition are in scope of this report (Section 1.2.5). However, given the thousands of PFAS that meet this definition, together with a lack of information on the hazards of most of them, it is not feasible to undertake a comprehensive hazard assessment of all substances in scope. Moreover, as explained in Section 1.2.4 and Annex A, the manufacturing processes of PFAS used in FFF can result in complex mixtures of structurally related PFAS, and the exact identification of individual PFAS in FFF, present either intentionally or unintentionally as impurities, is usually unknown. Therefore, a more focused approach has been taken to this hazard assessment, as explained below and in the separate human health and environmental sections.

This section covers hazards to human health and the environment. The focus of the human health section is to assess toxicity in relation to the criterion in UK REACH Annex 13, which is used to inform the environmental assessment.

2.1.1 Substances assessed – general approach

Once a PFAS enters the environment or an organism, transformation processes might occur, typically starting on the non-fluorinated part of the molecule. Rates may be slow, but these processes will eventually lead, via intermediates, to highly stable fluorinated substances, sometimes referred to as terminal degradation products or arrowheads. Figure 2.1 shows the representation of a degradation pathway from a fluorotelomer-based precursor to a perfluoroalkyl carboxylic acid (PFCA) arrowhead. PFAS that transform to PFAAs are called PFAA precursors. PFAAs are characterised by a carbon chain where all hydrogen atoms are replaced with fluorine atoms and with an acidic functional group (e.g., $-COOH$, $-SO_3H$) at one end.

Figure 2.1: Pathway of degradation from precursor to PFAA arrowhead



A large proportion of all PFAS are PFAA precursors. For example, an OECD report categorised approximately 88% of 4,730 PFAS on the global market as PFAA precursors (PFAS considered in the report had identified CAS numbers and either a perfluoroalkyl moiety with three or more carbons or a perfluoroalkylether moiety with two or more carbons) (OECD, 2018). The remaining 12% were substances categorised as PFAS without reactive functional groups, such as perfluorinated alkanes, or were already PFAAs. This indicates that more than 88% of the PFAS identified in OECD (2018) were either PFAAs or PFAA precursors.

Whilst the exact composition of individual FFF products is rarely known, the available information indicates that PFAS present in FFFs are either PFAAs (primarily PFCAs or PFSAs), or PFAA-precursors (Wood *et al.*, 2020).

The PFCAs and PFSAs are sub-divided into long-, short-, and ultra-short chain lengths, where the chain length is the number of carbon atoms associated with the tail of the molecule:

- Long chain PFCAs have ≥ 8 total carbons i.e., perfluorooctanoic acid (PFOA; C8) and longer carbon chain lengths;
- Short chain PFCAs have 4 to 7 total carbons (i.e., perfluorobutanoic acid (PFBA; C4) to perfluoroheptanoic acid (PFHpA; C7));
- Ultra-short chain PFCAs have 2 or 3 total carbons (i.e., trifluoroacetic acid (TFA; C2) and perfluoropropanoic acid (PFPrA; C3));
- Long chain PFSAs have ≥ 6 total carbons (i.e., perfluorohexane sulfonic acid (PFHxS; C6) and longer carbon chain lengths);
- Short chain PFSAs have 3 to 5 total carbons (i.e., perfluoropropane sulfonic acid (PFPrS; C3) to perfluoropentane sulfonic acid (PFPeS; C5)); and

- Ultra-short chain PFSAs have 1 or 2 total carbons (i.e., trifluoromethane sulfonic acid (TFMS; C1) and perfluoroethane sulfonic acid (PFEtS; C2)).

Fluorotelomers can be sub-divided into long-chain lengths, with > 6 fully fluorinated carbons (e.g., 8:2 FTOH), and short-chain lengths, with ≤ 6 fully fluorinated carbons (e.g., 6:2 FTOH), reflecting the carbon chain length of their corresponding final PFAA degradation product.

See the PFAS grouping and chain length table (Table 3) PFAS grouping and chain length for a list of PFAS cited in the current document.

2.2 Human health hazard assessment

2.2.1 Approach

The information landscape on the health effects of PFAS are fragmented at best, with most available data concentrated on only a limited number of substances. In 2022, the US EPA compiled a systematic evidence map (SEM) of epidemiological evidence for 150 PFAS (Radke *et al.*, 2022; US EPA, 2022a). This was later expanded to a total of 345 PFAS and integrated into a comprehensive dashboard that provided an overview of the human health-related information available at the time (Shirke *et al.*, 2024; US EPA, 2024c). The general conclusion was that for most of the substances there were little to no data from humans to inform the evaluation of potential health effects. ECCC and Health Canada (2024), in its draft PFAS report, indicated that there were fewer than 50 PFAS in total for which there were sufficiently robust toxicological data to inform on potential human health effects (ECCC and Health Canada, 2024). Data availability according to sub-group and potential health effect as tabulated by Health Canada is presented in Annex D.2.1, Table D.3. To date, no specific biomarkers of effect for PFAS have been identified (ATSDR, 2021).

This section provides an overview of the reported toxicological findings in experimental systems, the human health effects of PFAS of relevance to FFF and classifications in accordance with GB CLP. The section illustrates the extent to which toxicological information is available and how this informs on the toxicity status of those substances in relation to PMT properties. It does not constitute a critical assessment of observed effects nor a systematic review of the available hazard data for individual PFAS or PFAS groups.

In accordance with UK REACH Annex 13, a substance fulfils the toxicity criterion if:

- it meets the criteria for classification as carcinogenic Category 1, germ cell mutagenic Category 1, or reproductive toxicity Category 1 or 2; and/or

- there is other evidence of chronic toxicity, as identified by the substance meeting the criteria for classification for specific target organ toxicity after repeated exposure (STOT RE) Category 1 or 2.

The primary information sources were the GB CLP mandatory classification and labelling (MCL) list and authoritative assessments and reviews, with inclusion of some relevant published articles. ECHA's Classification and Labelling (C&L) Inventory was also consulted to identify supplier notified self-classifications; it is acknowledged that this source does not contain information on the rationale for the self-classification or the underlying data, nor have the self-classifications undergone regulatory assessment.

2.3 Substances assessed – human health

The PFAAs that have been used in FFFs comprise PFCAs and PFSAs. As noted above, PASFs and fluorotelomers can also be present in FFFs and are PFAA precursors. For example, the fluorotelomer alcohols 8:2 FTOH and 6:2 FTOH transform through various intermediates to PFCAs in mammals (see Section 2.3.1.3), whilst PASFs can transform to PFSAs (see Annex C.1.3 and HSE (2023)). Therefore, human exposure can occur either indirectly via the environment, or occupationally to precursors, intermediates and PFAAs. Firefighters could be directly exposed to intermediates and PFAAs if they are present in FFF, or indirectly following metabolism of precursors to intermediates and PFAAs. Consequently, this assessment considers PFCAs, PFSAs and relevant intermediates and precursors, where information on their toxicokinetics and toxicity is available.

The perfluoroalkylether acid PFAAs, PFECAs and PFESAs, are currently not thought to be present in FFF, but as noted in Annex C.2 products based on similar chemistry could feasibly be developed. Therefore, they are also included in the scope of the human health hazard assessment.

2.3.1 Toxicokinetics

The absorption, distribution, metabolism and excretion (ADME) of most PFAS remain largely uncharacterised. Current knowledge is derived from studies with variable focus and quality, and much of this information is concentrated on specific PFAS groups, such as perfluoroalkyl carboxylic acids (PFCAs), perfluoroalkyl sulfonic acids (PFSAs), ether-PFAS, and certain perfluoroalkyl acid (PFAA) precursors (ATSDR, 2021; ECHA, 2023a; EFSA *et al.*, 2020a; Fenton *et al.*, 2021; Pizzurro *et al.*, 2019). Existing evidence on a limited subset of PFAS, mainly PFAAs, indicates notable inter-species differences in toxicokinetics, particularly in tissue distribution and elimination rates. These differences could substantially influence the bioactivity and toxicity of these substances in different species (including humans) and so need careful consideration when interpreting experimental toxicological findings from animal studies and extrapolating them to potential health effects in humans (Dawson *et al.*, 2023; Pizzurro *et al.*, 2019).

2.3.1.1 Absorption

Both studies in animals and with humans indicate that PFAS are readily absorbed via the oral, inhalation and dermal routes (ATSDR, 2021; ECHA, 2023a; EFSA *et al.*, 2020a). Mostly, data are available for PFAAs. Quantitative information was available primarily for the oral route (ATSDR, 2021).

For example, ATSDR (2021) reported data on oral absorption in rats, mice and monkeys for ten PFCAs (ranging from carbon chain length of C4 to C14), three PFSAs (C4 to C8) and two PFECAs (HFPO-DA, ADONA). Quantitative estimates for oral absorption in animals ranged from > 50% for PFHxS (a long-chain PFSA) to > 95% for PFBA (a short-chain PFCA), PFOA, PFBA, PFNA, PFDA, PFUnDA and PFDoDA (all long-chain PFCAs) (ATSDR, 2021). ECHA (2023a) noted that even high molecular-weight compounds such as C6/C12 PFPiA and C8/C10 PFPiA (not expected to be present in FFF, but illustrative of the potential for oral absorption across sub-groups) were absorbed into the bloodstream of rats. EFSA *et al.* (2020a) reported that 27-57% of an orally administered dose of the fluorotelomer alcohol 8:2 FTOH (a PFCA precursor) was absorbed in rats. Oral absorption of PFOA, PFHxA, PFOS and the PFESAs 6:2 Cl-PFESA and 8:2 Cl-PFESA has also been indicated in humans (ECHA, 2023a).

There is evidence of absorption of PFOA in rats via the inhalation route (ATSDR, 2021). Absorption via inhalation in humans can be inferred from available observational studies (ECHA, 2023a) of occupational exposures to PFOS, PFHxS, PFOA and a range of other PFCAs.

Absorption by the dermal route has been demonstrated for PFBA, PFOA and PFOS in rabbits and rodents (ATSDR, 2021). In an *in vitro* human skin model with short- and long-chain PFCAs and PFSAs, there was an inverse correlation between dermal absorption and carbon chain length (Ragnarsdottir *et al.* (2024)).

2.3.1.2 Distribution

EFSA *et al.* (2020a) and ATSDR (2021) concluded that PFCAs and PFSAs are widely distributed in the body. This was supported by studies in laboratory animals and humans. Owing to their polar hydrophobicity, PFCAs and PFSAs preferentially adhere to proteins; consequently, they distribute to and accumulate in biological tissues and organs with high protein content, including the kidney, liver, blood, brain and testes (ATSDR, 2021; ECHA, 2023a; EFSA *et al.*, 2020a; Liu *et al.*, 2024a). As these substances do not undergo metabolism in humans or experimental animals (see below), their distribution is not expected to be affected by the route of exposure (ATSDR, 2021).

Slight differences in distribution have been observed for PFCAs and PFSAs of different chain length. For example, C8 PFOA and PFOS preferentially distribute to the liver in most species, while shorter-length PFBA and PFHxS tend to preferentially distribute to the serum and only to a lesser extent to the liver in animals (Ebert *et al.*, 2020; ECHA, 2023a). ADONA (a PFESA) showed a similar distribution pattern in animals to the studied PFCAs and PFSAs (ATSDR, 2021; EFSA *et al.*, 2020a). The fluorotelomer sulfonic acid 6:2 FTSA (a PFSA precursor) was also detected at high levels in serum and liver, whereas 6:2 Cl-PFESA distributed to serum, gut and liver. However, the distribution pattern of the fluorotelomer alcohol 8:2 FTOH was somewhat different, with the highest levels in fat, liver, thyroid and adrenals (ECHA, 2023a; EFSA *et al.*, 2020a).

PFCAs and PFSAs can cross the placenta and be transferred to the foetus during pregnancy and to infants via breast milk (ATSDR, 2021; ECHA, 2023a; EFSA *et al.*, 2020a).

Several short- and long-chain PFAS (including PFHxA, PFOA, PFNA, PFDA, PFOS, FOSA and 6:2 Cl-PFESA) have been shown to cross the blood-brain barrier and accumulate in human brain in both infants and adults (Xie *et al.*, 2024). Supporting this observation, PFOA, PFNA, PFDA, PFHxS, PFOS and 6:2 Cl-PFESA have been detected in the cerebrospinal fluid in humans, albeit at lower concentrations than detected in the serum (ECHA, 2023a).

Substances including PFDoDA, PFHxS, Cl-PFESAs and PFECAs have been reported to cross the blood-follicle barrier and accumulate in the follicular fluid, indicating exposure of the maturing oocyte developing within the follicle (reviewed in: ECHA, 2023a). ECHA (2023a) stated that there were strong correlations between PFAS concentrations in follicular fluid and those in serum / plasma.

2.3.1.3 Metabolism

The available information from animal experiments and humans indicates that the PFAAs of relevance to this assessment are not metabolised and do not undergo chemical reaction in mammals, irrespective of their perfluorinated carbon chain length. PFCAs, PFSAs, PFESAs (6:2 Cl-PFESA) and PFECAs (including ADONA, HFPO-DA, EEA-NH4) have been shown to be metabolically inert and stable to biotransformation (ATSDR, 2021; ECHA, 2023a).

In contrast, studied members of PFAA precursor groups fluorotelomer alcohols, polyfluoroalkyl phosphate esters (PAPs, precursors to PFCAs) and perfluoroalkyl sulfonamides (PASFs, precursors to PFSAs) undergo biotransformation in experimental animals and humans into arrowhead PFCAs and PFSAs (ECHA, 2023a; EFSA *et al.*, 2020b). They can thus contribute to the overall load of these substances (ECHA, 2023a).

For example, the fluorotelomer alcohols 6:2 FTOH and 8:2 FTOH undergo rapid biotransformation in rats into a range of intermediate products, and finally into PFCAs, releasing fluoride during the process. 6:2 FTOH is metabolised in rats to the stable metabolite 5:3 fluorotelomer carboxylic acid (5:3 FTCA) and to PFCAs including PFBA, PFPeA, PFHxA and PFHpA (reported in: ECHA, 2023a). Also in rats, 8:2 FTOH is metabolised to intermediates and PFOA, PFNA, PFHpA and PFHxA (EFSA *et al.*, 2020a) . The yield of PFOA and PFNA from 8:2 FTOH was generally low but increased in a time- and dose-dependent manner, consistent with their long half-lives in mammals (Butt *et al.*, 2014). In humans, 8:2 FTOH has been shown to be transformed to fluorotelomer carboxylic acids (FTCAs) and fluorotelomer unsaturated carboxylic acids (FTUCAs) and further to the long-chain PFCAs PFOA and PFNA (reviewed in: ECHA, 2023a). ECHA (2023a) reported that sulfonamide precursors were transformed in mice to C6 and C7 PFSAs.

2.3.1.4 Excretion

PFCAs and PFSAs are excreted via both urine and faeces, with additional excretion possible through menstruation and breastfeeding (ATSDR, 2021; ECHA, 2023a; EFSA *et al.*, 2020a).

PFCAs and PFSAs are primarily excreted into the urine (especially PFCAs with carbon chain length <10; EFSA *et al.*, 2020a), with smaller amounts eliminated in the faeces. For the studied PFCAs with carbon chain length ≥ 11 (PFUnDA, PFDoDA, PFTrDA and PFTeDA), faecal excretion was the predominant route of excretion EFSA *et al.* (2020a). Enterohepatic recirculation in humans can be extensive, for example for PFOA and PFOS, potentially contributing to the long elimination half-lives and bioaccumulation potential of these substances in humans.

Elimination half-lives in humans, depending on the type of PFAS, can range from days to years. For example, estimates for PFOA are 2.1-8.5 years, for PFOS 3.1-7.4 years and for PFHxS 4.7–15.5 years (EFSA *et al.* (2020a); Annex D.2, Table D.5). For PFCAs (C5 to C13) and PFSAs (C4 to C8), the longer the chain length, the slower the elimination from the body. In humans, C8 to C11 PFCAs, C6 to C8 PFSAs, and 6:2 Cl-PFESA have the longest half-life values (years to decades) (Annex D.2, Table D.4).There are significant differences in the rates of elimination between species (see Annex D.2, Table D.4) (ECCC and Health Canada, 2024). Modelling has indicated that elimination half-lives increase proportionally with body weight (Dawson *et al.*, 2023).

IARC (2016) reported that, uniquely to humans, PFOA is highly efficiently reabsorbed in the kidneys compared with other studied animals, which leads to much longer retention in the human body. Consequently, the body burden of PFOA in humans is much greater than in experimental animals.

Elimination of both PFCAs and PFSAs is slower in male rats than in female rats, primarily attributed to differences in renal clearance, which is regulated by sex hormones, especially testosterone (Kudo and Kawashima, 2003). In humans, there is no significant sex difference in elimination half-life of PFOA (Kennedy *et al.*, 2004; Kudo and Kawashima, 2003), but differences in elimination between sexes still occur owing to additional elimination pathways in women, i.e., menstruation and breastfeeding (see Section 3.2).

The long half-life observed with some substances, exceeding rates of excretion, indicate high likelihood of bioaccumulation.

2.3.1.5 Key conclusions

- Oral absorption of all investigated PFAS, across sub-groups and chain lengths, is rapid and extensive in laboratory animals. Limited information indicates the same applies to oral absorption in humans, although quantitative information is not available.

- There is experimental evidence of inhalation absorption of PFOA in rats, and absorption via this route can be inferred in humans.

- Dermal absorption of PFCAs and PFSAs has been demonstrated in animals and human skin models. There is an inverse correlation between dermal absorption and carbon chain length.

- PFCAs and PFSAs are widely distributed in the body. They preferentially adhere to proteins and thus distribute to and accumulate in the blood and well-perfused, protein-rich tissues such as the liver and kidneys.

- Information on the distribution of other PFAS is limited. The studied substances mostly show a similar pattern to the investigated PFCAs and PFSAs, although the distribution patterns of the fluorotelomer alcohol 8:2 FTOH (a PFCA precursor) was somewhat different.

- PFCAs and PFSAs can be transferred to developing foetuses via the placenta and to infants via breast milk. It has been shown that several PFAAs (PFCAs, PFSAs, PFESAs) cross the blood-brain barrier and the blood-follicle barrier.

- The investigated PFCAs, PFSAs, PFECAs and PFESAs are metabolically inert and stable to biotransformation in mammals. In contrast, precursors to these PFAAs undergo biotransformation into a range of intermediates and ultimately to their relevant PFAAs.

- The rate of elimination is determined to some extent by fluorinated-carbon chain length: increases in chain length of PFCAs (C4 to C12) and PFSAs (C4 to C8) are associated with slower elimination. Elimination half-lives in humans can range from days to years.

- Serum protein binding, enterohepatic recirculation and reabsorption in the kidneys contribute to elimination half-lives, which are typically longer in humans than in experimental animals.

2.3.2 Acute toxicity, irritation, sensitisation

Most of the substances listed in Annex D.1, Table D.1 (long-chain PFCAs and long-chain PFSAs) have mandatory classifications for acute oral and inhalation toxicity and eye damage. Some further substances assessed in the PFAS RMOA (HSE, 2023) also showed acute toxicity and irritation / corrosivity to the skin and/or eyes. Skin sensitisation was not generally highlighted as a property of the substances assessed (HSE, 2023).

2.3.3 Repeated-dose toxicity

All but one of the substances listed in Annex D.1, Table D.1 has received a mandatory classification for specific target-organ effects following repeated exposure (STOT RE). The target organs following repeated exposure of experimental animals are typically the liver and kidney. Altered thyroid hormone levels have been reported with exposure to some substances (COT, 2022). PFOS and PFOA have been reported to cause immunotoxicity in animals.

2.3.3.1 Liver effects

In experimental animals, liver effects have been reported for most PFAS for which data are available (ATSDR, 2021; ECHA, 2023a; EFSA *et al.*, 2020a).

The liver findings with individual members of PFAS sub-groups are summarised in Annex B.5 by ECHA (2023a). Amongst the investigated non-polymeric PFAS, the most consistent effects comprised increases in liver weight, hepatocellular hypertrophy and liver-enzyme induction in rodents exposed to PFCAs, PFSAs, TFA, PFECAs, PFESAs and fluorotelomers, amongst others. Hepatic effects observed in repeated-dose PFOA studies were generally reversible once dosing ceased (reported in: ATSDR, 2021). The more severe effect of hepatocellular necrosis was reported after repeated exposure to most PFCAs and PFSAs (but not the short-chain PFSA PFBS or the long-chain (C16) PFCA PFHxDA), several PFECAs, PFESAs and fluorotelomers (short- and long-chain fluorotelomer alcohols), and a long-chain FTSA (PFSA precursor).

ECHA (2023b) cited a review by Fenton *et al.* (2021) that indicated how the nature and extent of liver effects in experimental animals appeared to be, at least in part, dependent on carbon-chain length, with toxicity increasing for PFCAs with $C \geq 8$ and PFSAs with $C \geq 6$. ATSDR (2021) noted that the effects on liver weight and parameters of fatty acid beta-oxidation were more severely affected as the carbon chain length of perfluoroalkyls increased up to about C10, after which the effects started to decline. Additionally, ATSDR (2021) noted that significant peroxisome activity (thought to be at least partially responsible for disrupted fatty acid metabolism) appeared to require $C > 7$, but increases over baseline were observed with $C \geq 4$. The impact of carbon chain length on liver toxicity and potency is consistent with the more prolonged half-lives of the longer molecules (ATSDR, 2021); for different groups (PFCA, PFSAs, PFECAs) it is kinetics (serum half-lives) that determine potency of liver effects (ECHA, 2023a). ATSDR hypothesised that the decline in peroxisome activation and fatty acid beta-oxidation in molecules of $C > 10$ was because longer-chain substances assume helical conformation, preventing them from being bioactive.

Hepatotoxicity in animals appears to be (at least in part) mediated by activation of peroxisome proliferator-activated receptor alpha (PPARα) (ATSDR, 2021; ECHA, 2023a; EFSA *et al.*, 2020a; Fenton *et al.*, 2021). PPARα is a more responsive, and therefore relevant, mechanism of hepatotoxicity in rodents than in humans. However, importantly, ATSDR (2021) concluded that PFAA (evidence primarily from PFOA and PFOS) hepatotoxicity in rodents was likely a result of both PPARα-dependent and independent mechanisms (ATSDR, 2021; ECHA, 2023a).

ATSDR (2021) concluded that whilst liver-weight increases and hepatocellular hypertrophy observed in rodent studies were species-specific adaptive responses without human relevance, other liver effects, including biliary effects and hepatocellular necrosis, were relevant to humans. However, although a range of potential human hepatic outcomes have been highlighted in epidemiological studies, the COT noted that the associations between exposure to the studied PFAS (PFOA, PFOS, PFHxS, PFNA) and liver function/disease in humans were uncertain, inconsistent or only modest (COT, 2022). US National Academies of Science, Engineering and Medicine considered that the evidence for liver-enzyme effects in humans was ‘limited or suggestive’, whilst the evidence of other hepatic effects in humans was inadequate or insufficient (NASEM, 2022).

2.3.3.2 Kidney effects

Kidney effects are less consistently observed in animal studies than liver effects. A list of individual PFAS with evidence of kidney alterations is provided in Annex B.5 of ECHA (2023a).

The most common finding in the kidney of rodents (most studies conducted in rats) was increased organ weight relative to body weight. This has been reported for PFCAs (short-chain to C12 long-chain), the short-chain PFSA PFBS, PFECAs and the short-chain fluorotelomer alcohol 6:2 FTOH, amongst others. In some cases, kidney-weight changes were accompanied by minor histopathology changes or necrotic effects, the latter being reported for PFHxA (short-chain (C6) PFCA) and four PFECAs, amongst others. Animal studies with some other PFAS did not indicate morphological or functional changes in the kidney (ATSDR, 2021; ECHA, 2023a); these were listed by ECHA (2023a) as the short-chain PFCAs (PFBA, C4), some long-chain PFCAs (PFOA, PFDA, PFUnDA, PFDoDA, spanning C8 to C12) and some long-chain PFSAs (PFOS, PFHxS, spanning C6 to C8).

NASEM (2022) considered that the evidence that PFAS caused renal disease in humans was inadequate or insufficient. ECCC and Health Canada (2024) concluded that exposure to PFBA (short-chain PFCA), PFOA (long-chain PFCA) or the long-chain PFSAs PFHxS and PFOS was associated with an increased risk of chronic kidney disease and/or gout in humans. However, Health Canada noted these associations possibly suffered from reverse causation, where impaired kidney function could be responsible for inducing the PFAS toxicity, because competent kidney function is critical for efficient removal of PFAS from the body.

2.3.3.3 Thyroid effects

PFAS effects on the thyroid of experimental animals include alterations in thyroid gland weight, follicular hypertrophy and decreases in serum thyroid-hormone levels. Substances that induced all three of these effects in rats included short-chain PFCAs (PFBA, C4), long-chain PFCAs (PFOA, PFNA, PFHxDA, spanning C8 to C16) and a long-chain PFSA (PFHxS, C6) (ECCC and Health Canada, 2024; ECHA, 2023a). The thyroid findings from animal studies with individual members of PFAS sub-groups are summarised in Annex B.5 by ECHA (2023a).

(EFSA *et al.*, 2020a) reviewed available epidemiological studies and concluded that there was insufficient support for associations between the studied long-chain PFAAs (PFOA, PFNA, PFOS, PFHxS) and thyroid disease or thyroid hormone alterations (EFSA *et al.*, 2020a). Similarly, ATSDR (2021) concluded that there was some evidence of associations between serum levels of some PFAS (the four long-chain PFAAs above plus the long-chain PFCAs PFDA and PFUnDA, spanning C10 to C11) and levels of thyroid hormones or thyroid disease, but these results were inconsistent and more studies had not found any associations (ATSDR, 2021). NASEM (2022) considered there was limited or suggestive evidence of PFAS exposure and thyroid disease and dysfunction in adults.

ECHA (2023a) noted that PFAS can interfere with the thyroid on several levels, including thyroid hormone biogenesis, distribution and receptor binding (ECHA, 2023a; EFSA *et al.*, 2020a).

2.3.3.4 Immune effects

Functional assays investigating immune effects of PFAS in experimental animals provide strong evidence that several PFAS have the ability to modify the immune response, with inhibition / suppression (decreased antibody response) reported as the most consistently observed effect (reviewed in (ECHA, 2023a; Ehrlich *et al.*, 2023)). Most information is available for PFOA and PFOS, but other substances that have shown effects on the immune system in animal studies include the ultra-short-chain PFCA TFA (C2), the short-chain PFCA PFHxA (C6), the long-chain PFCA PFDoDA (C12) and the ether PFAS HFPO-DA (C6). ECHA (2023a) reported that most immunotoxicity effects in experimental animals occurred at doses that resulted in general toxicity, but reductions in T-cell-dependent antibody response were observed in mice at doses of PFOA and PFOS that did not cause generalised toxicity.

Reductions in T-cell-dependent antibody response in animals has been reported to be predictive of immunotoxicity in humans, with the analogous human impact being on antibody generation following vaccination (Ehrlich *et al.*, 2023). PFOA (C8) and PFOS (C8) in humans have both been associated with reduced antibody response to vaccination in humans (EFSA *et al.*, 2020a), although COT noted that there were inconsistencies in the data and the pathological consequences of the reduced vaccine responses were unknown (COT, 2022). In addition to these two long-chain PFAAs, NASEM (2022) concluded there was sufficient evidence for the long-chain substances PFDA (C10) and PFHxS (C6) being associated with decreases in antibody response to vaccines. For the long-chain PFCAs PFNA (C9), PFDA (C10), PFUnDA (C11) and PFDoDA (C12) there was only limited information available and no conclusions could be drawn (NASEM, 2022; Shirke *et al.*, 2024).

2.3.3.5 Other repeated-dose effects

The EFSA CONTAM Panel (EFSA *et al.*, 2020a) concluded there was insufficient information to suggest that PFAS adversely affected neurobehavioural, neuropsychiatric and cognitive outcomes in humans, or that they were associated with allergy and asthma. The Panel also reviewed papers that looked at PFOS, PFOA and other PFAS in relation to endocrine effects in humans (thyroid function and disease, male fertility and puberty, female fertility, menstrual cycle and puberty) and concluded that the available evidence was insufficient to suggest that the PFAS exposures were associated with effects on these endpoints (COT, 2022).

Some PFAS are structurally similar to fatty acids that activate peroxisome proliferator-activated receptors (PPARs), which have a role in regulation of lipid and glucose metabolism. ECCC and Health Canada (2024) proposed that this could explain a potential impact of PFAS on serum lipids, body weight regulation and development of diabetes. EFSA *et al.* (2020a) noted that there did appear to be associations between the long-chain PFCA PFNA (C9) and raised serum cholesterol levels. Conversely, EFSA *et al.* (2020a) noted that the associations between serum PFOS and/or PFOA levels and increases in serum cholesterol levels included considerable uncertainty regarding causality (EFSA *et al.*, 2020a). Reviews by ECCC and Health Canada (2024) and others (ECHA, 2023a; Guo *et al.*, 2022; Ho *et al.*, 2022; Wu *et al.*, 2025) found some consistency in gestational diabetes (but not other forms), alterations in lipid profiles and indications of cholestasis (in animals) but mixed or inconsistent responses in the evidence for animal body-weight changes / obesity in humans and different responses in serum cholesterol levels between animals and humans. The evidence was largely from PFOA and other PFCAs (short- and long-chain), PFOS and other PFSAs (short- and long-chain), the PFAA precursors FOSAA and N-MeFOSA, and ether-PFAS. NASEM (2022) found sufficient evidence linking exposure to PFAS (predominantly PFOA and PFOS) and dyslipidaemia (elevation of serum cholesterol and triglycerides) in adults and children but concluded that there was inadequate or insufficient evidence of an association for other cardiovascular effects.

Epidemiology studies in firefighters in Australia and the USA that were reviewed by ECHA (2023e) are reported in Annex D.2, Table D.6. These studies attempted to identify associations between PFAS concentrations and non-specific biomarkers of effect (for example, cholesterol, lipoproteins, triglycerides, insulin). ECHA concluded that, overall, the studies did not show statistically significant associations between PFAS concentrations and biomarkers of effect or increased risks of disease, although the limitations in terms of study quality and number were noted.

2.3.3.6 Key conclusions

- The most consistent finding in animal studies comprises liver effects. The nature and extent of liver effects appear to increase with increasing carbon-chain length and thus serum half-lives; PFCAs of $C \geq 8$ and PFSAs of $C \geq 6$ up to about C10 exhibit the greatest severity.
- Liver toxicity in laboratory rodent species appears to be at least partially mediated by PPARα, although additional mechanisms are possible. Humans are less responsive to the activation of PPARα than rodents. Associations between PFAS (PFOA, PFOS, PFHxA, PFNA) exposure and liver function or disease in humans are uncertain, inconsistent or modest at best, but in general epidemiological information is sparse.
- Findings of kidney and thyroid toxicity are less consistent in animal studies than liver effects, and there does not appear to be a clear pattern across sub-groups or carbon chain lengths. Clear associations between PFAS exposure and kidney or thyroid effects in humans have not been reported.
- Immune effects have been reported in experimental animal studies following exposure to PFOA, PFOS and some other PFAS, consistent with reduced antibody responses to vaccination in humans. Some authoritative bodies have concluded there is sufficient evidence for reduced antibody response to vaccination in humans for two long-chain PFCAs (PFOA, PFDA) and two long-chain PFSAs (PFOS, PFHxS), although others considered there were some inconsistencies in the evidence and the functional consequences of these effects were unknown.
- Some authoritative bodies have concluded there is an association between exposure to PFOA and PFOS and dyslipidaemia in adults and children, whilst others have noted uncertainty regarding causality; and between PFNA (long-chain PFCA) exposure and increased serum cholesterol levels in humans; there was inadequate or insufficient evidence for other cardiovascular effects in humans.

Table 2.1: Repeated-dose toxicity - data availability, target tissues in laboratory animals and classifications

PFAS sub-group	Perfluorinated Cn (total Cn)	PFAS abbr.	Target organs, tissues, systems	Classification*
Ultra short-chain PFCAs (C2-C3)	1 (2)	TFA	Liver, immune system	
	2 (3)	PFPrA		
Short-chain PFCAs (C4-C7)	3 (4)	PFBA	Liver	
	4 (5)	PFPeA		
	5 (6)	PFHxA	Liver, metabolic, kidney, thyroid	
	6 (7)	PFHpA	Liver	STOT RE 1
Long-chain PFCAs (≥C8)	7 (8)	PFOA	Liver	STOT RE 1
	7 (8)	APFO	Liver	STOT RE 1
	8 (9)	PFNA	Liver, thymus, spleen	STOT RE 1
	9 (10)	PFDA	Liver, metabolic, kidney, immune system	
	10 (11)	PFUnDA	Liver	
	11 (12)	PFDoDA	Liver, kidney, metabolic, immune system	
	12 (13)	PFTrDA	Liver	Notified to ECHA C&L inventory STOT RE 1
	13 (14)	PFTeDA	Liver	Notified to ECHA C&L inventory STOT RE 1
	14 (15)	PFPeDA		
	15 (16)	PFHxDA	Liver, thyroid	
	16 (17)	PFHpDA		
	17 (18)	PFODA	Liver, kidney, metabolic	
Ultra short-chain PFSAs (C1-C2)	1 (1)	TFMS		
	2 (2)	PFEtS		
Short-chain PFSAs (C3-C5)	3 (3)	PFPrS		
	4 (4)	PFBS	Liver, metabolic, kidney, thyroid	
	5 (5)	PFPeS		
	6 (6)	PFHxS	Liver, metabolic, immune system	
	7 (7)	PFHpS		

PFAS sub-group	Perfluorinated Cn (total Cn)	PFAS abbr.	Target organs, tissues, systems	Classification*
Long-chain PFSAs (≥C6)	8 (8)	PFOS	Liver, thyroid, metabolic, immune system	STOT RE 1
	9 (9)	PFNS		
	10 (10)	PFDS		
	11 (11)	PFUnDS		
	12 (12)	PFDoDS		
	13 (13)	PFTrDS		
PASF-based substances	4 (4)	FBSA		
	6 (6)	FHxSA		
	8 (8)	FOSAA		
	8 (8)	PFOSA (FOSA)		
	8 (12)	N-EtFOSE	Liver	
	8 (9)	N-MeFOSA		
	8 (11)	N-MeFOSAA MeFOSAA Me-PFOSA-AcOH2		Notified to ECHA C&L inventory STOT RE 2
	8 (12)	N-EtFOSAA EtFOSAA Et-PFOSA-AcOH		Notified to ECHA C&L inventory STOT RE 2
FT-based substances	5 (8)	5:3 FTCA		
	4 (6)	4:2 FTS		
	6 (8)	6:2 FTS	Kidney	Notified to ECHA C&L inventory STOT RE 2
	8 (10)	8:2 FTS		Notified to ECHA C&L inventory STOT RE 2
	6 (8)	6:2 FTOH	Teeth, bones	STOT RE 2 proposed under GB CLP
	8 (10)	8:2 FTOH	Liver	Notified to ECHA C&L inventory STOT RE 1
PFECAs & PFESAs	4 (6)	HFPO-DA	Liver, kidney, thyroid, metabolic, immune system	
	5 (7)	ADONA	Kidney	
	6	EEA-NH4	Liver	Under assessment (MCL)

PFAS sub-group	Perfluorinated Cn (total Cn)	PFAS abbr.	Target organs, tissues, systems	Classification*
	6 (3)	F-DIOX	Liver	Notified to ECHA C&L inventory STOT RE 2
	7 (8)	6:2 Cl-PFESA	Liver, metabolic, thyroid	
	9 (10)	8:2 Cl-PFESA		
	8 (8)	9Cl-PF3ONS		

* Mandatory classification, MCL classification proposed under GB CLP, or classification determined by supplier and notified to ECHA's C&L inventory by supplier; N.B. ECHA's C&L inventory does not contain information on the rationale for the self-classification or the underlying data.

STOT RE (2) proposed = HSE has published a GB CLP opinion and/or technical report in which the stated mandatory classification and labelling are proposed.

Under assessment (MCL) = HSE is assessing the substance for a mandatory classification and labelling proposal under GB CLP but neither a technical report nor an opinion has been published.

Key:

x	Meets the T criteria through mandatory, proposed (GB CLP) or self- (notified) classification
x	Likely meets T criteria; under assessment for relevant GB MCL, or data appear to meet T criteria
x	Data with findings but do not appear to meet T criteria
x	Data available; no adverse effects
x	No repeated-dose studies; no self-classifications for STOT RE notified to ECHA C&L inventory

2.3.4 Mutagenicity

Mutagenicity has not been highlighted as a potential concern for PFAS. The available information reviewed by EFSA (EFSA *et al.*, 2018; EFSA *et al.*, 2020a) indicated that PFOS and PFOA may have the potential to cause oxidative stress in cellular systems but there was no evidence that they had a direct genotoxic effect (COT, 2022). By extension, because of structural similarity with PFOA and PFOS, respectively, PFNA and PFHxS were unlikely to have a direct genotoxic mode of action. The EFSA CONTAM Panel concluded that the study and data availability were limited for other PFAS. None of the substances assessed in the recently published PFAS RMOA (HSE, 2023) showed mutagenic potential.

2.3.5 Carcinogenicity

Whilst carcinogenicity has been raised as a concern for PFAS, until recently adequate data were lacking to establish any specific substance as a human carcinogen. Several substances (PFOA, APFO, PFDA and PFNA and their sodium and ammonium salts, from the long-chain PFCAs group; PFOS and its potassium, ammonium, lithium and diethanolamine salts from the long-chain PFSA group) to have been reviewed for carcinogenicity have mandatory Category 2 classifications under GB CLP. This reflects that there is some evidence that these substances cause cancer in laboratory animals and/or humans, but that the information is insufficient to reach a firm conclusion on whether they are definitive human carcinogens. PFDA and PFNA and their sodium and ammonium salts were classified on the basis of read-across of carcinogenicity data from PFOA and APFO.

Most information on the carcinogenic potential of PFAS is from data on PFOA and PFOS. Long-term oral exposure to PFOA induced Leydig-cell adenomas, pancreatic acinar cell adenomas and hepatocellular adenomas in male rats. An increase in hepatocellular adenomas has also been observed in male rats exposed to PFOS, as have thyroid follicular cell adenomas in male and female rats (ATSDR, 2021).

The EFSA CONTAM Panel (EFSA *et al.*, 2018) opinion on PFOS and PFOA concluded that available epidemiology studies provided insufficient evidence to state that either substance is a carcinogen in humans. In 2020, the EFSA *et al.* (2020a) reviewed additional epidemiology data published since the 2018 opinion, comprising studies on other PFAS and one study on PFOS and PFOA. The Panel concluded that its previous conclusion on PFOS and PFOA still applied, whilst limited information was identified for the other PFAS. After reviewing this EFSA *et al.* (2020a) opinion, the COT (2022) concluded that the information published since 2018 did not provide any evidence of a link between PFOS, PFOA or other PFAS exposure and cancer risk in humans. COT (2022), summarising the information considered by EFSA *et al.* (2018), reported that PFOS and PFOA acted as tumour promoters in rodent livers and that PFOA might also induce Leydig-cell tumours in the testes of rats. COT noted that PFHxA (a short-chain PFCA) was not carcinogenic in a long-term study in animals, whilst PFNA and PFDA, but not 8:2

FTOH, showed tumour-promoting activity in a model system. There was no information for the other substances considered in the EFSA opinion.

In November 2023, an IARC Working Group reviewed the available literature for PFOS and PFOA. The Working Group concluded that PFOA was a Group 1 Carcinogen (carcinogenic to humans) because of ‘sufficient evidence for cancer in experimental animals and strong mechanistic evidence that PFOA exhibits key characteristics of carcinogens in exposed humans. There was limited evidence in humans for cancer of the testis and for renal cell carcinoma. NASEM concluded at a similar time that there was sufficient evidence of an association between PFOA exposure and an increased risk of kidney cancer in humans (NASEM, 2022), whilst ATSDR (2021) reported there were some associations between PFOA and prostate, kidney and testicular cancers in occupational epidemiology studies.

Regarding PFOS, the IARC Working Group concluded that it was a Group 2B Carcinogen (possibly carcinogenic in humans) based on strong mechanistic evidence, with limited evidence from experimental animals and inadequate evidence for cancer in humans (Zahm *et al.*, 2024). The subsequent IARC monograph containing the detailed PFOA and PFOS assessments was expected to have been published in 2024 but was not publicly available as of December 2024.

IARC has also recently published a monograph on the carcinogenic hazard of occupational exposure as a firefighter (IARC, 2023). Although there was a positive association between occupation as a firefighter and various types of cancer, this was attributed to factors associated with this occupation (such as exposure to carcinogenic chemical agents in combustion products and building materials, diesel exhaust, shift work, ultraviolet or other radiation) and not directly or exclusively to PFAS exposure.

In summary, a small number of long-chain substances have mandatory classifications as suspected human carcinogens (GB CLP Category 2). The short-chain PFCA PFHxA was not found carcinogenic in a study in animals, whilst the PFCA precursor 8:2 FTOH did not show tumour-promoting activity in a model system, unlike two of the long-chain PFCAs with mandatory carcinogenicity classifications that were tested in the same system. In a carcinogenicity study in rats, HFPO-DA induced tumours in the pancreas, liver and testes (ECHA, 2019c).

In experimental animals (rats), PFOA and PFOS have caused tumours in the testes, pancreas, liver and thyroid. The strongest evidence for a link between PFAS exposure and carcinogenicity in humans comes from PFOA, which has been associated primarily with cancer of the testes and kidney. These findings may reflect a difference in sensitivity between rats and humans. Rodent liver toxicity appears to be mediated, at least partially, by PPARα activation; this mode of action is less relevant to humans. However, other modes of action for the hepatotoxicity in rodents of PFAA (evidence primarily from PFOA and PFOS) is likely (ATSDR, 2021). PPARα activation has also been linked to the induction of Leydig cell tumours and pancreatic acinar cell tumours, although there is insufficient evidence to preclude a conclusion on the relevance of these tumours induced by peroxisome proliferating agents to humans (ATSDR, 2021). Likewise, rats are susceptible to the induction of thyroid tumours via liver-enzyme induction (see section on repeated-dose toxicity), whereas humans are not; however, other modes of action for thyroid effects in animals have also been proposed whereby PFAS interfere with thyroid metabolism on several levels (ECHA, 2023a), so that rodent thyroid tumours should be considered of relevance to humans.

A causal relationship between kidney cancer in humans and PFOA exposure is biologically plausible. As explained in the section on toxicokinetics, PFOA is, uniquely to humans, highly efficiently reabsorbed in the kidneys, which leads to much longer retention in the human body (IARC, 2016). Consequently, the body burden of PFOA in humans is much greater than in experimental animals. Because of this characteristic of reabsorption in the kidneys, it would not be appropriate to extrapolate the finding of kidney cancer in humans to other PFAS with a different toxicokinetic profile.

2.3.5.1 Key conclusions

- For a small number of long-chain substances (PFCA and PFSA), there is some evidence that they cause cancer in laboratory animals under experimental conditions.

- The strongest evidence for a link between PFAS exposure and carcinogenicity in humans comes from PFOA, which has been associated primarily with cancer of the testes and kidney.

- The mode of action for any carcinogenic hazard presented by PFAS are assumed to be non-genotoxic given the lack of a mutagenic response seen in standard tests with these substances.

- There is no evidence that short-chain substances and precursors are carcinogenic or show tumour-promoting activity. However, the information on these substances is much more limited and firm conclusions cannot be drawn.

Table 2.2: Carcinogenicity - data availability, target tissues in laboratory animals and classifications

PFAS sub-group	Perfluorinated Cn (total Cn)	PFAS abbr.	Target tissues	Classification*
Ultra short-chain PFCAs (C2-C3)	1 (2)	TFA		
	2 (3)	PFPrA		
Short-chain PFCAs (C4-C7)	3 (4)	PFBA		
	4 (5)	PFPeA		
	5 (6)	PFHxA	Not carcinogenic in laboratory animals	
	6 (7)	PFHpA		
Long-chain PFCAs (≥C8)	7 (8)	PFOA	Testes, pancreas, liver	Carc. 2
	7 (8)	APFO	Testes, pancreas, liver	Carc. 2
	8 (9)	PFNA	Testes, pancreas, liver (read-across)	Carc. 2
	9 (10)	PFDA	Testes, pancreas, liver (read-across)	Carc. 2
	10 (11)	PFUnDA		
	11 (12)	PFDoDA		
	12 (13)	PFTrDA		Notified to ECHA C&L inventory Carc. 2
	13 (14)	PFTeDA		Notified to ECHA C&L inventory Carc. 2
	14 (15)	PFPeDA		
	15 (16)	PFHxDA		
	16 (17)	PFHpDA		
	17 (18)	PFODA		
Ultra short-chain PFSAs (C1-C2)	1 (1)	TFMS		
	2 (2)	PFEtS		
Short-chain PFSAs (C3-C5)	3 (3)	PFPrS		
	4 (4)	PFBS		
	5 (5)	PFPeS		
	6 (6)	PFHxS		
	7 (7)	PFHpS		

PFAS sub-group	Perfluorinated Cn (total Cn)	PFAS abbr.	Target tissues	Classification*
Long-chain PFSAs (≥C6)	8 (8)	PFOS	Liver, thyroid	Carc. 2
	9 (9)	PFNS		
	10 (10)	PFDS		
	11 (11)	PFUnDS		
	12 (12)	PFDoDS		
	13 (13)	PFTrDS		
PASF -based substances	4 (4)	FBSA		
	6 (6)	FHxSA		
	8 (8)	FOSAA		
	8 (8)	PFOSA (FOSA)		
	8 (12)	N-EtFOSE		
	8 (9)	N-MeFOSA		
	8 (11)	N-MeFOSAA MeFOSAA Me-PFOSA-AcOH2		Notified to ECHA C&L inventory Carc. 2
	8 (12)	N-EtFOSAA EtFOSAA Et-PFOSA-AcOH		Notified to ECHA C&L inventory Carc. 2
FT-based substances	5 (8)	5:3 FTCA		
	4 (6)	4:2 FTS		
	6 (8)	6:2 FTS		
	8 (10)	8:2 FTS		
	6 (8)	6:2 FTOH		
	8 (10)	8:2 FTOH		Notified to ECHA C&L inventory Carc. 2
PFECAs & PFESAs	4 (6)	HFPO-DA	Pancreas, liver, testes	
	5 (7)	ADONA		
	6	EEA-NH4		
	6 (3)	F-DIOX		

PFAS sub-group	Perfluorinated Cn (total Cn)	PFAS abbr.	Target tissues	Classification*
	7 (8)	6:2 Cl-PFESA		
	9 (10)	8:2 Cl-PFESA		
	8 (8)	9Cl-PF3ONS		

* Mandatory classification, MCL classification proposed under GB CLP, or classification determined by supplier and notified to ECHA's C&L inventory by supplier; N.B. ECHA's C&L inventory does not contain information on the rationale for the self-classification or the underlying data.

Key:

x	Meets the T criteria through mandatory, proposed (GB CLP) or self- (notified) classification
x	Likely meets T criteria; under assessment for relevant GB MCL, or data appear to meet T criteria
x	Data with findings but do not appear to meet T criteria; or read-across from PFOA and APFO
x	Data available; no adverse effects
x	No cancer studies; no self-classifications for carcinogenicity on ECHA C&L inventory

2.3.6 Reproductive toxicity

Adverse effects on fertility and reproduction in animals exposed to PFAS have included reduced weights of reproductive organs, reduced sperm production and impaired semen quality, reduction in sex hormones, impaired oestrus cyclicity and reduced fertility (ECHA, 2023a).

2.3.6.1 Effects on sexual function and fertility

In humans, indirect evidence of infertility in time-to-pregnancy (fecundity) studies has been linked to increased PFAS exposures, specifically PFOA and PFHxS (ECHA, 2023a; Fenton *et al.*, 2021). PFOA specifically is reported as impairing human sperm motility *in vitro* and has been associated with a decreased sperm count (Song *et al.*, 2018; Yuan *et al.*, 2020). In women, PFAS exposures have been associated with altered endometrial regulation and progesterone activity (Di Nisio *et al.*, 2020).

PFNA has a mandatory classification (Category 2) for fertility owing to some effects on sperm counts in rodents.

2.3.6.2 Effects on development

In laboratory animals, the observed developmental effects following exposure to PFCAs and PFSAs have included (COT, 2022; ECHA, 2023a; EFSA *et al.*, 2020a):

- litter loss: PFBA, PFOA, PFNA, PFODA
- increased perinatal or postnatal mortality: PFHxA, PFOA, PFNA, PFODA, PFOS
- reduced offspring bodyweight or bodyweight gain/growth (possibly secondary to maternal toxicity): PFHxA, PFOA, PFNA, PFUnDA, PFTeDA, PFODA, PFBS, PFOS
- impaired development of mammary glands: PFOA
- delayed ossification (possibly secondary to maternal toxicity): reported for various PFAAs.

EFSA *et al.* (2018) concluded that PFOA and PFOS caused developmental neurotoxicity in rodents. It has also been reported that the long-chain PFCA PFDoDA can efficiently transfer into rat brain and cause cognitive behavioural changes (COT, 2022). As noted in the section on toxicokinetics, other PFAS have been shown to cross the blood-brain barrier in infants (Xie *et al.*, 2024), but there is no evidence that this has resulted in developmental neurotoxicity in humans (ATSDR, 2021; NASEM, 2022).

The COT (2022) summarised the available observations of reproductive toxicity of PFAS in humans (EFSA *et al.*, 2018). EFSA concluded that “there may well be a causal association between PFOS and PFOA and birth weight” (EFSA *et al.*, 2018) though it was not possible to make the same association for other PFAS. The ATSDR also concluded that the evidence suggested an association between PFOA and PFOS and small decreases in birth weight, but noted that cause-and-effect relationships had not been established (ATSDR, 2021). NASEM (2022) built on the reviews of EFSA and the ATSDR, amongst others, and supplemented with additional studies on PFOA and PFOS, in concluding that there was sufficient evidence of an association between PFAS exposure and decreased infant and foetal growth.

The ATSDR noted that oxidative stress, dysregulation of mitochondrial function and receptor-mediated events might be linked to the developmental effects of PFAS. The ATSDR also noted that mitochondria serve as the site for steroidogenesis. Metabolic disruption, resulting from changes in gene expression of those genes involved in lipid and glucose homeostasis, could be linked to the observed toxicity of decreased birth weights and postnatal growth. Other postulated modes of action are disruption of glucocorticoid and thyroid hormone metabolism (Fenton *et al.*, 2021; Liew *et al.*, 2018).

A potential impact of PFAS on bone mineralisation in humans has been investigated through epidemiology studies, with findings reporting an association between PFAS exposures and reduced bone mineral density in adults and children (Cluett *et al.*, 2019; ECHA, 2023a; Fenton *et al.*, 2021; Hu *et al.*, 2019; Lin *et al.*, 2014). However, the ATSDR (2021) and NASEM (2022) stated there was insufficient information to indicate that PFAS were associated with other adverse development or reproduction outcomes in humans.

Two substances, trifluoroacetic acid (TFA) (ultra short-chain PFCA) and EEA-NH4 (a PFECA) are currently (July 2025) under consideration by HSE for mandatory classification for developmental toxicity under GB CLP. Malformations were recorded in rabbits following administration of sodium trifluoroacetate (TFA-Na), whilst dose-related impacts on litter size and post-natal pup survival occurred in rats dosed with EEA-NH4. ECHA (2023a) reported that some other PFECAs (HFPO-DA, ADONA), and the precursor fluorotelomer alcohol 6:2 FTOH, increased neonatal or postnatal pup deaths in rodents, whilst the PFECA F-DIOX resulted in litter loss. ECHA (2019c) concluded that preliminary data on HFPO-DA indicated developmental toxicity in rats (early deliveries, reduced mean foetal body weight). Information on other groups and precursors is generally lacking. Although one review of PFBS (C4 PFSA) and direct precursors did not report reproductive effects (NICNAS, 2015h), PFBS is listed on the EU and UK candidate lists because of an equivalent level of concern for effects that include reproductive toxicity (developmental delays) in mice (ECHA, 2019b). Reproductive toxicity was not reported in the other short-chain PFSAs that were subject to assessment in the RMOA (HSE, 2023).

2.3.6.3 Effects on or via lactation

As noted in Section 2.3.1.2, PFCAs and PFSAs can distribute to breast milk and be transferred to offspring during lactation. Several long-chain PFCAs (PFOA, APFO, PFDA, PFNA and some salts) and PFOS have mandatory classifications for effects on or via lactation. ECHA (2023a) reported reduced pup weight gain during the lactation period with, amongst others, TFA-Na, PFHxA and F-DIOX, but acknowledged that, unless appropriate cross-fostering studies are available, it can be difficult to definitively assign effects on pup weight to lactational exposure.

2.3.6.4 Key conclusions

- Reproductive toxicity has been reported in animal studies following exposure to PFCAs ranging from ultra-short-chain (C2) to long-chain (up to

C18).

- Reproductive toxicity has also been reported in animals exposed to the long-chain PFSA PFOS.
- The primary effect comprises developmental toxicity, but adverse effects on reproduction have been reported for some substances. PFCAs and PFSAs distribute to breast milk, and some have been shown to cause effects on or via lactation in laboratory animals.
- Authoritative bodies have concluded there is sufficient evidence of an association between PFOA and PFOS exposure and decreased infant and foetal growth in humans.
- There is insufficient information to indicate that PFAS are associated with other adverse development or reproduction outcomes in humans.

Table 2.3: Reproductive toxicity – data availability, nature of effects in laboratory animals and classifications

PFAS sub-group	Perfluorinated Cn (total Cn)	PFAS abbr.	Nature of effect	Classification
Ultra short-chain PFCAs (C2-C3)	1 (2)	TFA	Development (sodium salt)	Under assessment (MCL)
	2 (3)	PFPrA		
Short-chain PFCAs (C4-C7)	3 (4)	PFBA	Development	
	4 (5)	PFPeA		
	5 (6)	PFHxA	Development	Repro. 1B proposed under GB CLP
	6 (7)	PFHpA	Development	Repro. 1B
Long-chain PFCAs (≥C8)	7 (8)	PFOA	Development; lactation	Repro. 1B
	7 (8)	APFO	Development; fertility; lactation	Repro. 1B
	8 (9)	PFNA	Development; fertility; lactation	Repro. 1B
	9 (10)	PFDA	Development; lactation	Repro. 1B
	10 (11)	PFUnDA	Development and/or lactation; possibly secondary to maternal toxicity	
	11 (12)	PFDoDA	Development; fertility	
	12 (13)	PFTrDA	Development	Notified to ECHA C&L inventory Repro. 1B
	13 (14)	PFTeDA	Development, lactation	Notified to ECHA C&L inventory Repro. 1B
	14 (15)	PFPeDA		
	15 (16)	PFHxDA		
	16 (17)	PFHpDA		
	17 (18)	PFODA	Development, fertility	
Ultra short-chain PFSAs (C1-C2)	1 (1)	TFMS	Data available; no adverse effects	
	2 (2)	PFEtS		
Short-chain PFSAs (C3-C5)	3 (3)	PFPrS		
	4 (4)	PFBS	Development, possibly secondary to maternal toxicity	
	5 (5)	PFPeS		
	6 (6)	PFHxS	Fertility (indirect evidence from humans)	

PFAS sub-group	Perfluorinated Cn (total Cn)	PFAS abbr.	Nature of effect	Classification
Long-chain PFSAs (≥C6)	7 (7)	PFHpS		
	8 (8)	PFOS	Development; lactation	Repro. 1B
	9 (9)	PFNS		
	10 (10)	PFDS		
	11 (11)	PFUnDS		
	12 (12)	PFDoDS		
	13 (13)	PFTrDS		
PASF-based substances	4 (4)	FBSA		
	6 (6)	FHxSA		
	8 (8)	FOSAA		
	8 (8)	PFOSA (FOSA)		
	8 (12)	N-EtFOSE		
	8 (9)	N-MeFOSA		
	8 (11)	N-MeFOSAA MeFOSAA Me-PFOSA-AcOH2	Development and/or fertility, lactation	Notified to ECHA C&L inventory Repro. 2
	8 (12)	N-EtFOSAA EtFOSAA Et-PFOSA-AcOH	Development, lactation	Notified to ECHA C&L inventory Repro. 1B
FT-based substances	5 (8)	5:3 FTCA		
	4 (6)	4:2 FTS		
	6 (8)	6:2 FTS		
	8 (10)	8:2 FTS		
	6 (8)	6:2 FTOH	Development	
	8 (10)	8:2 FTOH	Development, lactation	Notified to ECHA C&L inventory Repro. 1B
PFECAs & PFESAs	4 (6)	HFPO-DA	Development	
	5 (7)	ADONA	Development	
	6	EEA-NH4	Development	Under assessment (MCL)
	6 (3)	F-DIOX	Development and/or lactation	

PFAS sub-group	Perfluorinated Cn (total Cn)	PFAS abbr.	Nature of effect	Classification
	7 (8)	6:2 Cl-PFESA	Fertility	
	9 (10)	8:2 Cl-PFESA		
	8 (8)	9Cl-PF3ONS		

* Mandatory classification, MCL classification proposed under GB CLP, or classification determined by supplier and notified to ECHA's C&L inventory by supplier; N.B. ECHA's C&L inventory does not contain information on the rationale for the self-classification or the underlying data.

Repro. 1B proposed = HSE has published a GB CLP opinion and/or technical report in which the stated mandatory classification and labelling are proposed.

Under assessment (MCL) = HSE is assessing the substance for a mandatory classification and labelling proposal under GB CLP but neither a technical report nor an opinion has been published.

Key:

x	Meets the T criteria through mandatory, proposed (GB CLP) or self- (notified) classification
x	Likely meets T criteria; under assessment for relevant GB MCL, or data appear to meet T criteria
x	Data with findings but do not appear to meet T criteria
x	Data available; no adverse effects
x	No reproductive toxicity studies; no self-classifications for reproductive toxicity on ECHA C&L inventory

2.3.7 Summary and conclusions on human health hazards

Of the thousands of individual PFAS, fewer than 50 have toxicological data available, and the completeness and robustness of this evidence varies considerably across these substances. This assessment has focused on those substances considered of most relevance to past, current or potential future use in FFF: PFCAs, PFSAs, fluorotelomers, PASFs, PFECAs and PFESAs.

The long-chain, ‘legacy’ PFCAs and PFSAs, especially PFOA and PFOS, have been the focus of the most toxicological studies; research into their adverse effects in animals and health effects in humans have been well investigated and described. Information on toxicity in animals and health effects in humans is much more limited for the short-chain PFCAs and PFSAs, PFECAs, PFESAs, precursors and intermediates.

Although short-chain PFCAs and PFSAs generally have shorter half-lives in humans than PFAS with longer chains, this does not necessarily indicate a reduction in hazard. The short-chain PFCA PFHxA, for example, shows similar adverse effects in animals to the long-chain PFCAs. The available information on PFECAs and PFESAs also indicates that they have similar adverse effects in animals to the PFCAs and PFSAs.

Fluorotelomer substances are precursor substances that are metabolised in experimental animals and in humans to PFCAs. For example, 6:2 FTOH is metabolised to short-chain PFCAs in rats, whilst 8:2 FTOH is ultimately metabolised to the long-chain PFCAs PFOA and PFNA. These precursors and their intermediates to terminal degradation products can also have adverse effects themselves, although information on intermediates is very limited. However, Cousins *et al.* (2020) noted that some precursor PFAS or their intermediate degradation products might be more toxic than the terminal degradation products. For example, 6:2 FTOH is reported to be more toxic to rodents than its degradation product PFHxA (Rice *et al.*, 2020). McDonough *et al.* (2022) reported other examples of precursor substances being more toxic than their terminal degradation products.

Various authoritative bodies have considered potential associations between human exposure to PFAS (all sources, not specifically PFAS in FFF) and adverse health effects. The strongest evidence of such associations relates to:

- reduction in vaccine antibodies (PFOA, PFOS, some other long-chain PFCAs and long-chain PFSAs), although some authoritative bodies have noted inconsistencies in the evidence and the unknown functional consequences of the effects;
- dyslipidaemia (elevated serum cholesterol and triglycerides) in adults and children exposed to PFOA or PFOS, although some have noted uncertainty regarding causality; increased serum cholesterol (PFNA, which is a long-chain PFCA);
- liver-enzyme induction (can be an adaptive response rather than an adverse effect);
- reduced birth weight and possibly infant growth (PFOA and PFOS);

- cancer of the testes and kidney, for which IARC has concluded that PFOA is carcinogenic to humans (sufficient evidence in experimental animals, limited evidence in humans but mechanistic evidence that PFOA exhibits the key characteristics of carcinogens in exposed humans).

The most common findings in laboratory animals dosed with PFAS repeatedly comprise effects on the liver, kidney, thyroid, immune system and developing offspring. The liver effects have been found for most studied PFAS. Developmental toxicity has been recorded in laboratory animals for PFCAs ranging from ultra-short-chain (C2) to long-chain (C18); there is much less information on the reproductive toxicity of other PFAAs and their precursors, other than PFOS. For a small number of long-chain PFCAs and PFSAs, there is some evidence that they cause cancer in laboratory animals, which is assumed to be via a non-genotoxic mode of action.

2.3.7.1 Conclusion on toxicity

In the sections above on repeated-dose toxicity (Section 2.3.3, Table 2.1), carcinogenicity (Section 2.3.5, Table 2.2) and reproductive toxicity (Section 2.3.6, Table 2.3), those substances that meet the toxicity criterion of UK REACH Annex 13 have been highlighted. These are the substances for which:

- a mandatory classification for reproductive toxicity Category 1 or 2 or specific-target organ toxicity upon repeated exposure (STOT RE) Category 1 or 2 exists in the GB CLP MCL, or
- HSE has published an opinion and/or technical report to propose mandatory classification for one or more of these hazard classes, but they have not yet been added to the MCL list, or
- suppliers have notified one or more of these classifications to the ECHA classification and labelling inventory.

Substances with a mandatory, proposed or notified classification for carcinogenicity and/or mutagenicity Category 1 would also meet the toxicity criterion, but no such substances were identified.

As noted in Section 2.1, the available information indicates that PFAS present in FFFs are either PFAAs (primarily PFCAs or PFSAs), or PFAA precursors. PFAA precursors are expected to transform in the environment to PFAAs. Therefore, to inform on the PMT potential of PFAS in FFF, the toxicity of PFCAs (Table 2.4) and PFSAs (Table 2.5) in relation to the Annex 13 criteria is summarised below.

Table 2.4: PFCAs - summary of data availability (repeated-dose toxicity, carcinogenicity and reproductive toxicity) and conclusions on Annex 13 toxicity criterion

PFCA group	Ultra short-chain		Short-chain				Long-chain										
Carbon chain length	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Toxicity	🟧		🟧		🟥	🟥	🟥	🟥	🟥	▨	🟧	🟥	🟥		▨		🟧

Table 2.5: PFSAs - summary of data availability (repeated-dose toxicity, carcinogenicity and reproductive toxicity) and conclusions in relation to the Annex 13 toxicity criterion

PFSA group	Ultra short-chain		Short-chain		Long-chain												
Carbon chain length	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Toxicity	🟦			🟧		🟧		🟥									

Key to Tables 2.4 and 2.5:

🟥	Meets the T criterion through mandatory, proposed (GB CLP) or self- (notified) classification
🟧	Likely meets T criterion; under assessment for relevant GB MCL, or data appear to meet T criterion
▨	Data with findings but do not appear to meet T criterion

🟦	Data available on repeated dose toxicity, and/or carcinogenicity, and/or reproductive toxicity; no adverse effects
	No appropriate data to assess repeated-dose toxicity, carcinogenicity or reproductive toxicity

Table 2.4 illustrates that most PFCAs in the carbon chain length range C2 to C18 for which data are available meet or are likely to meet the toxicity criterion. Most substances from C6 to C14 meet the toxicity criterion because of mandatory, proposed or self-classifications for reproductive toxicity and/or STOT RE. Substances at the extremes of the range exhibited similar toxicity in the available studies: TFA (sodium salt; C2) and PFBA (C4) exhibited reproductive and repeated-dose toxicity, as did PFODA (C18). Currently, PFHxDA (C16) does not appear to meet the toxicity criterion, but there are no studies to inform on reproductive toxicity.

As shown by Table 2.5, there is much less toxicological information for the PFSAs as a sub-group. There is some information on the reproductive toxicity of TFMS (C1), but no repeated-dose, carcinogenicity or reproductive toxicity information on C2 and C3 substances and those from C9. However, the toxicological effects of those PFSAs for which information is available are comparable with those of the PFCAs.

Overall, for those individual PFCAs and PFSAs that do not meet the toxicity criterion, a comprehensive toxicological dataset to assess repeated-dose toxicity, reproductive toxicity and carcinogenicity is not available. Given the confirmed or likely toxicity of PFCAs across the span of carbon chain lengths and the similarity of adverse effects of those PFSAs for which information is available, it is concluded that toxicity is associated with substances across both the PFCA and PFSA sub-groups.

All of the other PFAAs assessed, i.e., the PFECAs and PFESAs, for which appropriate information is available also meet or are likely to meet the toxicity criterion. This is also the conclusion for the PFAA precursors (PASFs and derivatives, fluorotelomer-based substances) for which information is available. Therefore, it is concluded that these precursors are toxic in their own right. However, only a small number of precursors were assessed and it cannot be assumed that all PFAA precursors are toxic.

2.3.7.2 Key limitations

- Fewer than 50 PFAS have been subjected to robust toxicological studies, and even among those, few have been comprehensively assessed across all conventional toxicological endpoints for hazard assessment. Most available data come from studies with PFAAs, predominantly the legacy substances PFOA and PFOS and some other long-chain PFCAs and PFSAs.
- There is little toxicological data on PFAS precursors and intermediates. Some of these might be more toxic than the final degradation products.
- Effects of combined exposures to mixtures of PFAS have not been addressed in this report. Combined exposure to different PFAS affecting the same target organs could result in combined additive effects at lower doses than would be expected for individual substances. Some attempts have been made to assess combined effects (see ECHA, 2023a), and EFSA *et al.* (2020a) performed a risk assessment for the sum of PFOA, PFNA, PFHxS and PFOS. However, owing to the large number of PFAS and the lack of toxicological data for most of them, a combined assessment for all PFAS is not considered feasible within the scope of this restriction.

- Some authoritative bodies have given more weight to the findings reported in epidemiological studies than others. However, such data has limitations, owing to often undefined exposure routes, critical exposure windows and combined exposures. Epidemiological evidence can be difficult to interpret, complicating potential causal inferences.

2.4 Environmental hazard assessment

2.4.1 Approach

2.4.1.1 Environmental hazard assessment under UK REACH

There is regulatory concern for substances that can contaminate water resources from their combined persistence (P), mobility (M) and toxicity (T) in surface and sub-surface waters and soils (Neumann and Schliebner, 2019; UBA, 2021). Similar to the very persistent (vP) and very bioaccumulative (vB) concept, there is also regulatory concern for substances that are vP and vM. The combination of PMT or vPvM properties is of very high concern because it can lead to environmental contamination that, like PBT/vPvB substances, is difficult to reverse (Defra, 2025).

This assessment considers the physicochemical properties of PFAS, followed by the P, M and T properties that are relevant for environmental hazard identification.

2.4.1.2 Substances assessed

In line with the registration requirements of UK REACH, the identification of hazards considers the constituents of a substance and its relevant transformation products (UK Government, 2021). This environmental hazard assessment is therefore focused on PFAAs as the typical terminal transformation products. This is a comprehensive approach, which captures theoretically thousands of substances and intermediates that can be transformed into PFAAs within the scope of this restriction (see Section 2.1.1). The PFAAs typically comprise PFCAs, PFSAs and perfluoroalkyl phosphonic acids (PFPAs). PFCAs, PFSAs and their precursors are known to be used in FFFs. PFPAs and their precursors have not been identified in FFFs and have also been shown to transform under oxidative conditions to PFCAs (NICNAS, 2018; Wang *et al.*, 2016). It should be noted that PFSAs will also ultimately form PFCAs under oxidative conditions; however, the rate at which this will occur is unknown.

This assessment therefore focusses on the hazard properties of PFCAs and PFSAs.

2.4.1.3 Information Sources

2.4.1.3.1 Conclusions of hazard assessments from other regulatory agencies

To provide context regarding the status of PFAAs globally, the Agency has identified regulatory assessments produced through the UN Stockholm Convention, and by the UK, Australia, Canada, Europe, Japan and the USA. There are different threshold criteria and approaches to conclude on environmental hazard properties across regulatory jurisdictions; Annex E.1 summarises these for context. Given that assessment under UK REACH can take account of weight-of-evidence (WoE) and read across approaches

(OECD, 2019), the conclusions reached by other regulatory authorities are useful for context.

2.4.1.3.2 Published hazard data

The OECD fact cards on major groups of PFAS were consulted for each PFAA group assessed to provide an overarching picture of available data (OECD, 2022). These fact cards were prepared by the OECD/UNEP Global PFC Group between June 2018 and June 2021 with one aim being the provision of basic information on chemical identities, synthesis and inherent properties like bioaccumulation and transformation. They do not present regulatory conclusions of hazard and do not present toxicity data. Data from regulatory assessments was also drawn upon.

Publicly available European REACH registration and CompTox® data were not used because the UK RMOA review highlighted that they could not be used to draw reliable definitive conclusions for the PFAS groups assessed (including PFAAs) (HSE, 2023).

The Agency also has some reservations about the applicability of standardised tests used to derive various physicochemical data for PFAS; this is reviewed in Annex E.2. Where this brings uncertainty into the assessment, it has been highlighted below.

2.4.1.3.3 Monitoring data

The UK RMOA (HSE, 2023) presented information on concentrations of PFAS in the UK environment with an overview of national-scale environmental surveillance monitoring programmes and academic work. The latest version of these data from the Environment Agency Water Information Management System (WIMS) has been drawn upon to provide evidence of the presence of PFAAs in groundwaters and to inform on mobility; the WIMS data were downloaded on 13th December 2024 and the fully quantitative data from 1st July 2021 to 7th November 2024 are used in Section 2.4.4.4. The data cover England only.

2.4.1.3.4 Other sources

Additional evidence has been gathered from peer-reviewed publications, where gaps and uncertainties have been identified (Annex E.3).

2.4.2 Physicochemical properties

The physicochemical properties used in environmental hazard screening are summarised in Table 2.6.

Table 2.6: Physicochemical properties used as surrogate indicators for screening in environmental hazard assessment.

Parameter	Symbol	Units	Thresholds	Indicator for screening
Physical State	-	-	-	Solid, liquid, gas
Vapour pressure	V_P	Pa	> 25 kPa	Highly volatile (Boiling point < 50 °C)
			< 0.5 kPa	Low volatility (Boiling point > 150 °C)
Water solubility	S_W	mg/L	< 10	Low solubility, influences mobility and bioavailability
			10 - 1000	Moderately soluble, influences mobility and bioavailability
			> 1000	Highly soluble, influences mobility and bioavailability
n-octanol air partition coefficient	log K_{OA}	unitless	> 5	High potential for bioaccumulation in air breathing organisms when $K_{OW} > 2$
n-octanol water partition co-efficient	log K_{OW}	unitless	> 2	High potential for bioaccumulation in air breathing organisms when $K_{OA} > 5$
			> 4.5	High potential for bioaccumulation in aquatic organisms
Organic carbon normalised adsorption partition co-efficient	log K_{OC}	unitless	$< 3^1$	Mobile
			$< 2^1$	very Mobile
	HLC		0.01	Less volatile than water

Parameter	Symbol	Units	Thresholds	Indicator for screening
Henry's Law Constant		unitless or Pa.m^3.mol	> 1	Preferential partitioning to air
			1 - 10	Significant loss to air
			10 - 100	Very significant loss to air
			100	Rapid volatilisation
Dissociation constant	pK_a/pK_b	unitless	-	Influences mobility and bioavailability

[1] These thresholds reflect the legislation and criteria implemented in the European Union (EU)'s Classification Labelling and Packaging of substances and mixtures (CLP) Regulation No. 1272/2008 (European Commission, 2022).

Testing the physicochemical properties of PFAAs is challenging. There are uncertainties regarding the relevance and applicability of experimental or predictive data to the specific endpoint of interest, particularly when the metric or model was developed based on simpler organic molecules. This relates to their structural molecular properties and how they interact with themselves and the environment in which they are present. For example:

- PFAAs (with fluorinated carbon chains ≥ 2) are surface-active (amphiphilic, i.e. simultaneously hydrophobic (water hating) and hydrophilic (water loving)) and cover a wide range of vapour pressures. Surface-activity becomes more pronounced as the fluorinated chain length increases (Leung *et al.*, 2023).
- PFAAs have permanently ionised head groups at environmentally relevant pHs between 4 and 9 (pKa < 0.5 to 3.8) (Mejia-Avendano *et al.*, 2020).

A more detailed discussion is provided in Annex E.2 for experimentally derived water solubility, K_{OW} and log K_{OC}, where micelle formation, aggregation, and accumulation at interfaces of air and water, solid surfaces and water / air of the PFAAs need to be accounted for when measurements are made.

Likewise, predicted physicochemical parameters and partitioning coefficients for PFAAs should be treated with caution. Brusseau (2024b) provides a detailed review of the two most commonly used methods in the context of PFAS (quantitative-structure/property relationship (QSPR) approaches and physical-modelling methods (quantum chemical and molecular mechanical, of which quantum chemical is considered superior)). The accuracy of predictions using QSPR methods depends upon the quality of the training data sets used to develop the mathematical relationships (e.g. size and representativeness). Quantum modelling methods are based on the atomic structure of a substance and its behaviour in different solvents.

ECHA (2023a) provides tabulated estimated and experimental data for individual PFCAs with carbon tail chain lengths of 1, 4, 6, and 9 to 14, and PFSAs with carbon tail chain lengths of 1, 2, 3, 4, 6, 8, 10, 12, 13 and 14. The endpoints include log K_{OW}, log K_{OA}, log K_{aw}, pK_a, log K_{OC}, K_d, S_w, V_P, B_p and Henry's Law Constant (HLC). Of the 20 substances, only three are registered under EU REACH. These are TFA, TFMS, and PFBS. Limited experimental data are presented, and data gaps have been addressed through modelling using predictive software with different algorithms and estimation methods, e.g., COSMOTherm, EPISuite, ACD Labs or academic data. Data contained within the table have not been assessed by the Agency for relevance to the endpoint or reliability. The range of values reported between experimental and predicted data, and between predictive models, varies significantly for the majority of substances, so the values have to be carefully considered as surrogate indicators or as lines of evidence in the hazard assessment.

2.4.3 Persistence

2.4.3.1 What is persistence?

Persistence criteria are provided in Annex 13 of the UK REACH regulation, and described in the associated technical guidance (ECHA, 2017b, 2017c, 2017d, 2017e) (summarised in Annex E.1, Table E.1). A WoE determination using expert judgment is used when definitive data are lacking. Scientifically, persistence is a measure of a substance's resistance to degradation under environmentally relevant conditions. Degradation can include abiotic and biotic processes or a combination of both.

2.4.3.2 PFAA characteristics

The persistence of PFAAs is directly influenced by their chemical structure, specifically the presence of multiple carbon–fluorine (C–F) bonds along an aliphatic carbon chain (Buck *et al.*, 2011; Smart, 1994). The C–F bond energy is about 108–120 kcal / mole, making it one of the strongest covalent bonds in existence (Dixon, 2001; Parsons *et al.*, 2008). Fluorine also has the highest electronegativity of all elements in the periodic table (UN POPS, 2021). The strong C–F bond and electronegativity of fluorine atoms protects the carbon backbone from interactions with reagents (Colomban *et al.*, 2014; Hakli *et al.*, 2008; Parsons *et al.*, 2008). These properties also contribute to a high ionisation potential for the acid group, low polarisability, low inter- and intra-molecular interactions and low surface tension (Leung *et al.*, 2023; UN POPS, 2021). Consequently, all PFAAs are highly resistant to transformation by acids, bases, oxidants and reductants, as well as via thermolytic, photolytic and metabolic processes (UN POPS, 2021).

While evidence suggests that a limited number of unique microbial cultures can biodegrade organofluorine substances and in some cases defluorinate functional groups of PFAAs and their precursors (Berhanu *et al.*, 2023; LaFond *et al.*, 2024; Shu *et al.*, 2023), the observed biodegradation rates are extremely slow and often immeasurable in a laboratory setting. Wackett (2022) explores the reasons for this limited biodegradability; fluorine, unlike other halogens such as chlorine, bromine, and iodine, is rarely used by biological systems. These other halogens have played a crucial role in various biological processes throughout evolution and across diverse organisms, from bacteria to mammals. The unique physicochemical properties of PFAAs have distinct interactions within cellular environments. Furthermore, defluorination often releases fluoride ions, which are toxic to many microbial populations. This toxicity may significantly hinder the development of microbial pathways for the biosynthesis or biodegradation of organofluorine compounds compared to other organo-halogen substances.

2.4.3.3 Available data

The OECD fact cards (OECD, 2022) note that PFCAs generally do not undergo abiotic degradation in the environment (Prevedouros *et al.*, 2006) and no biodegradation of PFCAs (PFOA, PFNA, PFUnDA) under aerobic or anaerobic conditions was observed in closed bottle tests using sewage sludge over 15 weeks (105 days) (Saez *et al.*, 2008). Examples are provided of PFCAs present in surface waters (C4 to C10) and soils (C7 to C12) close to point sources; present in surface waters (C4 to C12) and drinking water treatment plant influents and effluents (C4 to C18) distant from point sources; and present in ice (C2 to C7) within remote regions (OECD, 2022). The presence of PFCAs in groundwaters, reviewed in Section 2.4.4.4, and remote regions (see Annex E.7.3) are additional lines of evidence of their persistence.

Regulatory persistence assessments of the PFCAs cover chain lengths ranging from C4 to C21. More national / international regulatory assessments have been carried out for long chain PFCAs than short chain (Annex E.5.1, Table E.7). In summary:

- Long chain: at the international level, C8 to C21 PFCAs have been concluded equivalent to vP under UK REACH (UN POPS, 2016, 2023). At the national level, NICNAS concluded PFOA as highly persistent (NICNAS, 2015e); Canada's regulator and federal government have concluded C9 to C20 PFCAs as extremely persistent (ECHA, 2012a, 2012b, 2012c, 2012d, 2013, 2015, 2016a; Environment Canada, 2012; Government of Canada, 2022); and ECHA (whilst the UK was a member) has concluded C8 to C14 PFCAs as vP (ECHA, 2012a, 2012b, 2012c, 2012d, 2013, 2015, 2016a).

- Short chain: No international conclusions have been made on the short chain (C4 to C7) PFCAs. At the national level, NICNAS and Environment and Climate Change Canada (ECCC) concluded that C4 to C7 PFCAs are highly/extremely persistent (ECCC, 2023; NICNAS, 2015c, 2015d). ECHA has concluded that PFHxA and PFHpA are vP (ECHA, 2019a, 2022a).

- Ultra-short chain: There has been no regulatory consideration of ultra-short chain (C2 and C3) PFCAs. However, there is direct evidence for the persistence of C2-PFCA (TFA) from the regulatory assessment of the pesticide flufenacet. TFA is a major degradation product in an aerobic soil degradation study, and did not show any sign of degradation for 60 days after its maximum formation had occurred (EFSA *et al.*, 2024). There is also supporting evidence for the persistence of C2- and C3-PFCAs from monitoring studies of surface and groundwaters, where they can make up a large proportion of the PFAS present (e.g. Neuwald *et al.*, 2022; Pelch *et al.*, 2023; Sadia *et al.*, 2023). Evidence of increasing concentrations of C2-PFCA in terminal lakes, defined as water bodies that receive surface and atmospheric water but lack a surface or subsurface outflow, has also been presented (Cahill, 2024).

The OECD fact cards (OECD, 2022) state that long-chain PFSAs are persistent (Buck *et al.*, 2011). OECD (2022) reports that PFOS photolysis in aqueous solution under highly energetic UV C light (wavelength 100–280 mm) at 90°C took 11 days (a long time under such conditions) (Lyu *et al.*, 2015); PFOS hydrolysis requires high temperatures of 300°C and above (Wang *et al.*, 2016); and PFSAs cannot be effectively removed by wastewater treatment plant activated sludge processes (Chen *et al.*, 2018b; Pan *et al.*, 2016); Wang *et al.* (2016). The OECD fact cards (OECD, 2022) state that short-chain PFSAs are expected to be similarly persistent as long-chain PFSAs (Buck *et al.*, 2011). Examples are provided of PFSAs present in surface waters (C4, C6, C7 and C8) close to point sources; present in surface waters (C4, C6, C8), drinking waters (C4, C6, C7, C8, C10), drinking water treatment plant influents and effluents (C4, C6, C8, C10) and sediments (C6, C8) distant from point sources; and present in soils (C6, C8, C10) within remote regions (OECD, 2022). The presence of PFSAs in groundwaters, reviewed in Section 2.4.4.4, and remote regions (see Annex E.7.3) are additional lines of evidence of their persistence.

National and international regulatory assessments of the persistence of PFSAs cover chain lengths ranging from C4 to C20. A greater number have been reported for long chain than short chain PFSAs (Table 2.8).

- Long chain: at the international level, PFOS (C8) and PFHxS (C6) PFSAs have been concluded equivalent to vP under UK REACH (UN POPS, 2006, 2018). At the national level, the Environment Agency (England) has concluded PFOS (C8) as vP (Environment Agency, 2004); NICNAS has concluded C6 to C10 PFSAs as highly persistent (NICNAS, 2015a, 2015b, 2015f); ECCC / Environment Canada has concluded C6 to C20 PFSAs as extremely persistent (ECCC, 2023; Environment Canada, 2006); and the EU (whilst the UK was a member) has concluded PFHxS (C6) as vP (ECHA, 2017a).

- Short chain: No international conclusions have been made on the short chain (C3 to C5) PFSAs. At the national level, NICNAS and Canadian regulators have concluded that PFBS (C4) and PFPeS (C5) are highly/extremely persistent (NICNAS, 2015a, 2015h); and ECHA (whilst the UK was a member) has concluded that PFBS (C4) is vP (ECHA, 2019b).

- Ultra-short chain: There has been no regulatory consideration of the ultra-short chain (C1 and C2) PFSAs. TFMS is not readily biodegradable according to a study submitted for EU REACH registration (ECHA, 2023d) and there is evidence that it is ubiquitous in sources of drinking water in Germany (Neuwald *et al.*, 2022). This would be insufficient evidence to conclude on P in its own right but, given the persistency of other PFAS, including PFSAs, and the properties imparted by the C–F bond, it is considered likely that TFMS is also highly persistent; by extrapolation, the C2- (and the short chain C3-) PFSAs would be too.

It should be noted that degradation data for long chain PFCAs were located for C8, C9, C12 and C14 chain lengths within the regulatory assessments. For the majority of PFCAs with chain lengths longer than C13, data gaps necessitated the use of read-across techniques from PFCAs with chain lengths of C8 to C12 (Annex E.5.1, Table E.7). The regulatory assessments of short chain PFCAs generally used experimental data generated for the respective chain lengths. However, where data gaps were identified, read across from the experimental data of PFOA was used, i.e. PFHpA and PFHxA in some assessments (Annex E.5.1, Table E.7). In summary, read across from the relatively data-rich PFOA has been used heavily across all assessments of PFCAs. Similarly, the regulatory assessments of long-chain PFSAs rely on read-across from PFOS because of a lack of degradation data for PFHxS, PFHpS, PFNS and PFDS (Annex E.5.1, Table E.7). Assessments of short-chain PFSAs used degradation data available for the substance(s) being assessed, with some read-across from PFOS data.

Established predictive models have been developed to provide a probability of degradation for relatively simple molecules, e.g. BIOWIN (EPISuite™; US EPA, 2012). These were trained and validated using substances that had measured degradation data. The Agency has not modelled degradation for PFAAs because relevant substances and fragments are not in the training sets, and the outputs would be associated with a high degree of uncertainty in terms of relevance and reliability.

In summary, there is an international regulatory consensus that PFAAs are very / highly persistent, based upon the presence of the C–F bond along with read-across arguments using the available degradation data, supported by monitoring data in environmental compartments. Where higher-tier laboratory studies conducted to internationally recognised test guidelines exist, little to no degradation is observed and a realistic environmental transformation half-life cannot be determined. In other words, the half-lives will exceed the length of those studies and thus may significantly exceed the vP threshold criteria under UK REACH. Further detail is provided in Annex E.1, Table E.1.

Table 2.7: Number of persistence assessment conclusions* reached by international/national regulatory jurisdictions at each chain length for PFCAs. Shading provides heatmap visualisation of where conclusions have been made+

PFCA Group		Ultra-short chain		Short chain				Long chain													
Carbon chain length		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Report conclusion	Persistent	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Very persistent	0	0	2	2	3	3	3	3	3	3	3	3	3	2	2	2	2	2	2	2
	Uncertain persistence	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Not persistent	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Not considered	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

*Some jurisdictions do not distinguish between 'P' and 'vP', but where discussion of persistence in the assessments included descriptions such as 'very persistent', 'extremely persistent' or 'highly persistent', this has been reflected here by categorising their 'persistent' conclusion as 'very persistent'.

+Orange shading highlights where a conclusion of persistent was made (darker shading means more assessments).

Table 2.8: Number of persistence assessment conclusions* reached by international/national regulatory jurisdictions at each chain length for PFSAs. Shading provides heatmap visualisation of where conclusions have been made +

PFSA Group		Ultra-short chain		Short chain			Long chain															
Carbon chain length		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Report conclusion	Persistent	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Very persistent	0	0	0	3	2	4	2	4	2	2	1	1	1	1	1	1	1	1	1	1	0
	Uncertain persistence	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Not persistent	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Not considered	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

*Some jurisdictions do not distinguish between 'P' and 'vP', but where discussion of persistence in the assessments included descriptions such as 'very persistent', 'extremely persistent' or 'highly persistent', this has been reflected here by categorising their 'persistent' conclusion as 'very persistent'.

+Orange shading highlights where a conclusion of persistent was made (darker shading means more assessments).

2.4.3.4 Conclusion on persistence

The Agency considers that all PFAAs are vP, with environmental half-lives that are expected to far exceed the UK REACH Annex 13 criteria in water, sediment and soil based on the minimal degradation observed in experimental studies, the chemical structure of PFAAs and field monitoring evidence.

2.4.4 Mobility

2.4.4.1 What is mobility?

Mobility describes the potential of a substance to move through natural barriers between aqueous environmental compartments (Zhang *et al.*, 2023). Intrinsic properties of a substance that can lead to this movement include a low sorption potential, high water solubility, and environmental stability. From a regulatory perspective, there is a concern associated with the movement of chemicals to water bodies; that is, substances that are mobile in soils and sediments can reach groundwaters (which may be drinking water sources), from which they may be difficult to remove owing to their weak interaction with sorbents (because of their low sorption potential).

There are no defined criteria for identifying substances as “mobile” (M) or “very mobile” (vM) within UK REACH or GB CLP. Adsorption of a substance to environmental matrices can be determined from direct measurement, simulation testing, standard adsorption studies (or predictions) and an adsorption control within an inherent biodegradability test. In general, substances with a K_{OC} < 500 to 1000 L/kg are not likely sorbed to sediment (Hill *et al.*, 1993). Subsequently, to avoid extensive testing of chemicals, a log K_{OC} or log K_{OW} of ≥ 3 is used as a trigger value for sediment effects assessment (ECHA, 2017e). ECHA (2017b) notes that a cut off value of log K_{OW} of 3 can be applied for adsorption potential but should be treated with caution as substances that are water soluble and have a low log K_{OW} do not necessarily have a low adsorption potential. Further mobility classification approaches for substances in soil are used extensively for plant protection products, for example, McCall’s soils mobility classification scheme (McCall *et al.*, 1981) and the FAO (2000) Soil Mobility Classification Criteria, which are recommended by the US EPA (2022b).

Consequently, by analogy with Annex 13 of the REACH Regulation for PBT assessment, the Agency considers that a WoE determination by expert judgment is appropriate. The Agency considered the following lines of evidence to assess the mobility potential of PFAAs in the environment:

- Physicochemical data, including adsorption coefficients, water solubility and volatilization potential; these provide an indication of the environmental fate of substances, where a high water solubility and low volatilisation potential indicate a substance will be found in the aqueous phase, and the adsorption coefficients in particular can provide a proxy to indicate mobility.

- Field monitoring data, particularly groundwater monitoring data; these can indicate that a substance has moved across natural barriers between environmental compartments.
- Wastewater treatment plant (WwTP) influent and effluent monitoring data; these can indicate a low level of removal to biosolids (i.e., demonstrating difficulty in removal due to low sorption potential).

In relation to adsorption coefficients, two metrics can be used as a proxy to indicate mobility:

- the soil adsorption coefficient, K_d, which is a measure of the partitioning of a substance between a soil/sediment and an aqueous phase. It is influenced by the characteristics of both the substance and the soil/sediment used. It can only be used to compare mobility between substances in similar soils/sediments (Pawlowski *et al.*, 2023).
- the organic carbon normalised adsorption coefficient (also known as the soil organic carbon–water partition coefficient), K_{OC}, which is a measure of the partitioning of a substance between a soil/sediment and an aqueous phase, normalised to the organic carbon content of the soil/sediment.

The lower the value of either the K_d or K_{OC}, the lower the degree of binding, hence a higher probability of mobility for a specific substance.

K_{OC} and K_d are related to each other via the following equation:

$$K_{OC} = \frac{K_d}{f_{OC}}$$

Where, f_{OC} is the fraction of organic content in the soil/sediment.

For example, a log K_{OC} of 3 (K_{OC} = 1,000) measured in a soil with 2 % organic carbon equates to a K_d of 20. In a sediment with 5 % organic carbon, the equivalent K_d would be 50.

Normalising the K_d based on the organic carbon content of the matrix is a common approach to address the variability inherent in natural soils and sediments. It allows for a more consistent comparison of different substances by minimising the influence of the matrix itself. The concept is widely accepted as providing a suitable measure of sorption of neutral organics to topsoil with relatively high organic carbon contents (Pawlowski *et al.*, 2023).

However, this approach assumes that the primary sorption mechanism is hydrophobic interaction with organic matter. It does not account for the variety of sorption behaviour that polar or ionised substances can possess, which is mainly driven by the inorganic components of soils (European Commission, 2022; Neumann and Schliebner, 2019). In addition, sorption behaviour in sub-surface soils (e.g. at a depth of 20 – 70 cm) may differ from the topsoil because of differences in biogeochemistry and temperature, and sharp declines in organic carbon content and changes to the redox environment and pH (Jarvis, 2016). For example, in surface soils, organic components can mask available ion exchange sites through weak and strong electronic interaction, which is not observed in sub-surface soils. Soils have neutral net charge but are predominantly anion exchange systems. Charged species may therefore be displaced by substances with cationic functional groups. Consequently, some ionic/polar substances may undergo varying degrees of sorption, with some permanently retained and others passing through sub-surface soils relatively easily due to repulsion, e.g. short chain PFAAs that are permanently ionised anions under environmental conditions (Pawlowski *et al.*, 2023).

A further complication is that the mobility potential of an ionic substance that speciates into both neutral and ionic forms in the environmental pH range cannot currently be measured using standard methods (Sigmund *et al.*, 2022; Zhou *et al.*, 2021). Likewise the influence of polarity of a substance is not well understood (Strawn, 2021). Unusual sorption behaviour of surface-active substances including PFAAs has also been reported (Bierbaum *et al.*, 2023; Campos-Pereira *et al.*, 2023; Luft *et al.*, 2022; Mejia-Avendano *et al.*, 2020; Nguyen *et al.*, 2022). This is due to their ability to form micelles (i.e., aggregates) as their concentrations increase in aqueous solutions, and also their overall preference to assemble at interfaces between air-water, soil-air, and water-air (Brusseau, 2018, 2019; Brusseau, 2024a; Brusseau and Guo, 2022; Brusseau and Van Glubt, 2019). Leung *et al.* (2023) noted that the shape of the micelles formed by PFAAs changes depending on the fluorinated carbon tail length and the concentration of salts, which in turn influences their interactions with soils and each other.

These factors mean the K_{OC} can sometimes be a misleading indication of mobility. There is a growing body of evidence that the non-organic carbon normalised soil-water partition coefficient (K_d) may be the more appropriate measure of mobility for substances with polar or ionisable functional groups, because it is both soil and substance specific (Jarvis, 2016; Pawlowski *et al.*, 2023).

Criteria for mobility have been implemented in the EU's Classification Labelling and Packaging of substances and mixtures (CLP) Regulation No. 1272/2008 (European Commission, 2022; Neumann and Schliebner, 2019), where a substance is considered mobile (M) when the log K_{OC} is < 3 and very mobile (vM) when the log K_{OC} is < 2. The Agency considers that these may be used as a guide, but it is important to note that K_{OC} is not a universal measure of mobility, because in some cases (including for PFAAs) substance interactions with soil organic matter may not be the dominant retention mechanism (i.e. there may be important interactions with other soil/sediment components that are not fully taken into account by the K_{OC}) (EA, 2025).

2.4.4.2 Regulatory landscape

Few national / international regulatory assessments have been carried out for mobility (Annex E.5.2, Table E.8). Given that mobility is a relatively new endpoint of concern in a hazard context, historical regulatory assessments of PFAS have not generally considered it. This is evident for the long chain PFCAs and PFSAs (Table 2.9 and Table 2.10), where the primary concern was PBT/vPvB at the time of assessment. However, ATSDR (2021) describes all perfluoroalkyls as mobile.

Countries and jurisdictions that have included conclusions on the mobility of PFCAs in the aquatic environment, or described mobility as a property of concern, as part of their regulatory assessments include:

- Long chain: No regulatory assessments have considered mobility for long-chain PFCAs.
- Short chain: ECHA concluded that both PFHxA and PFHpA are vM ECHA (2019a, 2022a). NICNAS considered C4 to C6 PFCAs to be highly mobile and ECCC discussed C4 to C7 PFCAs as mobile in their report ECCC (2023); NICNAS (2015c).
- Ultra-short chain: No regulatory assessments have considered mobility for ultra-short chain PFCAs.

Countries and jurisdictions that have included conclusions on the mobility of PFSAs in the aquatic environment, or described mobility as a property of concern, as part of their regulatory assessments include:

- Long chain: ECCC identified the C6 to C20 long-chain PFSAs as mobile in their discussion around LRTP, although no clear distinction was drawn between mobility and LRTP (ECCC, 2023).
- Short chain: ECHA (whilst the UK was still a member) concluded that PFBS (C4) is vM (ECHA, 2019b). NICNAS identified PFBS as likely mobile (NICNAS, 2015h). ECCC identified the C4 and C5 PFSAs as mobile in their discussion (ECCC, 2023).
- Ultra-short chain: No regulatory assessments have considered mobility for ultra-short chain PFSAs.

Table 2.9: Number of mobility assessment conclusions reached by international/national regulatory jurisdictions at each chain length for PFCAs. Shading provides heatmap visualisation of where assessments have been made*

PFCA Group		Ultra-short chain		Short chain				Long chain													
Carbon chain length		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Report conclusion	Mobile	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Very mobile	0	0	1	1	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Uncertain mobility	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Not mobile	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Not considered	0	0	0	0	0	1	3	3	3	3	3	3	3	2	2	2	2	2	2	2

*Orange shading highlights where a conclusion of mobility was made; pink shading highlights where assessments have been conducted but mobility has not been considered (darker shading means more assessments).

Table 2.10: Number of mobility assessment conclusions reached by international/national regulatory jurisdictions at each chain length for PFSAs. Shading provides heatmap visualisation of where assessments have been made*

PFSA Group		Ultra-short chain		Short chain			Long chain															
Carbon chain length		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Report conclusion	Mobile	0	0	0	2	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0
	Very mobile	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Uncertain mobility	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Not mobile	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Not considered	0	0	0	0	1	3	1	4	1	1	0	0	0	0	0	0	0	0	0	0	0

*Orange shading highlights where a conclusion of mobility was made; pink shading highlights where assessments have been conducted but mobility has not been considered (darker shading means more assessments).

2.4.4.3 Physicochemical properties relating to mobility

PFAAs are all mobile in the environment to varying degrees owing to their physicochemical properties. PFAAs have a fluorinated alkyl tail, polar head group and are generally ionised at environmental pH; the polar head group is hydrophilic, resulting in a high water solubility and low sorption to organic carbon (ECCC and Health Canada, 2024). In general, the association of PFAAs with aqueous media decreases and sorption to soils and sediments increases with increasing chain length, as the hydrophobicity of the fluorinated alkyl tail becomes more influential in sorption (ECCC and Health Canada, 2024).

For example, increasing K_d values were noted with increasing chain length for long chain PFAAs in soils (Chen *et al.*, 2018a; Guelfo and Higgins, 2013; Mejia-Avendano *et al.*, 2020; Nguyen *et al.*, 2020). Guelfo and Higgins (2013) examined the transport of PFAAs in different soils and observed increased retardation for long chain PFAAs ($C > 6$).

The trend is less prominent for shorter chain PFAAs as sorption becomes increasingly dominated by ionic interactions through the polar head group over the hydrophobic interactions of the tail. For example, similar K_d values were noted for short chain PFAAs in soils, which indicates a minor role of the fluorinated tail group in sorption (Lyu *et al.*, 2022; Nguyen *et al.*, 2022; Nguyen *et al.*, 2020). Zhou *et al.* (2013) reported similar log K_{OC} values for PFCAs with carbon chain lengths < 7 in a field study using sediment. Guelfo and Higgins (2013) reported rapid penetration, with no obvious retention, for short chain PFAAs ($C \leq 6$).

To help understand mobility, adsorption coefficients, water solubility and volatilisation potential data for PFCAs and PFSAs have been identified in regulatory reports and the OECD fact cards and are collated in Annex E.6. In summary:

- Long chain PFCAs: log K_{OC} values vary from 1.89 to 3.7 for PFOA, 2.3 to 3.1 for PFNA, 2.65 to 4.4 for PFDA and 2.96 to 5.1 for PFUnDA; log K_{OC} values of 4.3 for PFDoDA and 4.3 for PFTeDA are reported. Log K_d values were only found in the OECD fact cards (OECD, 2022), which noted an increase in log K_d values between sediment and water with increasing chain length from 0.04 (PFOA) to 0.72 (PFDoDA) (Lam *et al.*, 2014). Vapour pressures at 25°C vary from –0.98 Pa (for PFUnDA) to 4.2 Pa (for PFOA). Water solubility varies from 1.9×10^{-6} g/L (for PFTeDA) to 9.5 g/L (for PFOA).

- Short chain PFCAs: log K_{OC} values vary from 0.7 to 2.62 for PFBA, 1.2 to 2.54 for PFPeA, 1.3 to 3.7 for PFHxA and 1.63 to 3.6 for PFHpA. Log K_d values of 1.18, 1.14, 1.33 and 1.24 are reported for PFBA, PFPeA, PFHxA and PFHpA respectively. Vapour pressures vary from 2.63 to 1333 Pa at 25°C (for PFBA), and 1.32 (at 25°C) to 17.7 (at 15°C) for PFHpA; a value of 264 Pa for PFHxA is reported. Water solubility is reported as 15.7 g/L for PFHxA and 0.00365 g/L for PFHpA.

- Ultra-short chain PFCAs: There are no data relating to mobility for the ultra-short-chain PFCAs in the OECD fact cards or regulatory reports. TFA is poorly absorbed to soil and considered mobile with log K_d values ranging between –0.77 and 1.3 at

25°C L/kg (geometric mean of –0.02 L/kg) based on two batch equilibrium tests (one performed in line with OECD 106), according to the ECHA registration dossier (ECHA, 2024). The ECHA registration provides a water solubility of 1520 g/L at 20°C (GLP but not to guideline) and a vapour pressure of 12.4 kPa at 20°C (method "similar to the EC guideline").

- Long chain PFSAs: Data are mainly available for PFHxS and PFOS. Log K_{OC} values vary from 0.74 to 2.76 for PFHxS, 2.68 to 3.4 for PFOS and 3.53 to 3.66 for PFDS. One log K_d value was found for PFHxS of –1.52; values for PFOS vary from –1.15 to 1.26. Vapour pressures at 20°C are between 3.31×10^{-4} Pa (for the potassium salt of PFOS) to 213 Pa (for PFOS). Water solubility varies from 0.00029 g/L to 0.68 g/L (for PFOS) and 1.4 g/L to 2.3 (for PFHxS).

- Short chain PFSAs: Data were only identified for PFBS. Log K_{OC} values vary from 1.2 to 2.7 and log K_d values are –0.55 to 1.42. Vapour pressures at 20°C are between $<1.22 \times 10^{-5}$ Pa (for the potassium salt) and 7 Pa. Water solubility varies from 52.6 g/L at 22.5–24°C to 'fully miscible' at 20°C.

- Ultra-short chain PFSAs: There are no data relating to mobility for the ultra-short-chain PFSAs in the OECD fact cards or regulatory reports. TFMS is expected to have a low potential for adsorption according to the EU REACH registration, where a log K_{OC} of 1.176 was calculated using Sabljić *et al.* (1995) from the log K_{OW} (ECHA, 2023d). The ECHA registration also provides a water solubility of 1604 g/L at 20°C (according to OECD 105) and a vapour pressure of 2.4 hPa at 20°C (according to OECD 104). The reliability of these studies is not known.

There is some uncertainty in the absolute values of the data above. As a result of increasing surfactant properties with the length of the fluorinated tail, the properties of the PFAAs become more difficult to determine practically or estimate reliably; that is, data from standardised test methods should only be considered for screening purposes (Annex E.2). Predictive models are available but inherent uncertainty is associated with the estimated data they provide for PFAAs (Annex E.2.4). Nevertheless, the vapour pressure and water solubility values indicate the PFAAs partition to the water phase and the K_{OC} and K_d values reported are relatively low, indicating potential mobility.

2.4.4.4 Field monitoring data

The widespread presence of substances in groundwaters is considered to provide evidence of mobility as, to reach the groundwaters, substances generally have to move across natural barriers. Therefore, this section focuses on UK groundwater monitoring data. Groundwater data from other locations are presented where UK data are unavailable. The available evidence is presented below.

- Long chain PFCAs: All of the nine long chain PFCAs monitored for have been detected in UK groundwaters (Table 2.11). Figure 2.2 provides an overview of groundwater sites where samples have been analysed for PFOA, demonstrating the breadth of groundwater locations where the substance has been found in England. The exposure case studies in Section 3.1.6 show that long chain PFCAs were found in groundwater samples from Angus Fire (C8, C9 and C11), Duxford airfield (PFOA) and RAF St Athan (C8, C9 and C16), sites connected to PFAS-containing FFF contamination.

- Short chain PFCAs: All four of the short chain PFCAs monitored for have been detected in UK groundwater monitoring (Table 2.11). Figure 2.2 provides an overview of groundwater sites where samples have been analysed for PFBA, demonstrating the breadth of groundwater locations where the substance has been found in England. The case studies in Section 3.1.10 and Annex E.9 show that short chain PFCAs were found in groundwater samples from the Angus Fire (C4-7), Duxford airfield (C4 and C6) and RAF St Athan (C4-7), sites connected to PFAS-containing FFF contamination.

- Ultra-short chain PFCAs: UK groundwater samples have not been analysed for ultra-short chain PFCAs. However, the widespread occurrence of TFA and PFPrA in groundwaters across Germany was demonstrated (Neuwald *et al.*, 2022; Scheurer *et al.*, 2017). Groundwater near to a firefighting training site was also found to contain TFA and PFPrA in Sweden (Frank *et al.*, 2002; Pickard *et al.*, 2020).

- Long chain PFSAs: Seven of the eight long chain PFSAs monitored for have been detected in UK groundwater monitoring (Table 2.11); PFUnDS has not been found above the limit of detection. Figure 2.3 provides an overview of groundwater sites where samples have been analysed for PFOS, demonstrating the breadth of groundwater locations where the substance has been found in England. The case studies in Section 3.1.10 and Annex E.9 show that long chain PFSAs were found in groundwater samples from the Angus Fire (C6-8), Duxford airfield (C6 and C8) and RAF St Athan (PFOS), sites connected to PFAS-containing FFF contamination.

- Short chain PFSAs: Both PFBS and PFPeS have been found in UK groundwaters (Table 2.11). Figure 2.3 provides an overview of groundwater sites where samples have been analysed for PFBS, demonstrating the breadth of groundwater locations where the substance has been found in England. The case studies in Section 3.1.10 and Annex E.9 show that short chain PFSAs were found in groundwater samples from the Angus Fire (C4 and C5) and Duxford airfield (C4), sites connected to PFAS-containing FFF contamination.

- Ultra-short chain PFSAs: UK groundwater samples have not been analysed for ultra-short chain PFSAs. However, the widespread occurrence of TFMS in groundwaters across Germany was demonstrated (Neuwald *et al.*, 2022). Groundwater near to a firefighting training site was also found to contain TFMS and PFEtS in Sweden (Björnsdotter *et al.*, 2019).

The presence of PFAAs in remote regions globally (e.g., the Arctic and Antarctic; see Annex E.7.3) could be a result, in part, of movement in oceanic currents, providing an additional line of evidence for aquatic mobility. However, it may also result from movement in atmospheric currents, and/or the transport of volatile precursors that have then transformed to PFAAs either during transport or once deposition has occurred (see Annex E.7.3).

Table 2.11: Minimum and maximum concentrations of PFAAs measured in Environment Agency groundwater samples between July 2021 and November 2024.

PFAA Group	Substance	Minimum concentration (µg/L)	Maximum concentration (µg/L)
Long chain PFCAs	PFODA (C18)	<LOD	0.013
	PFHxDA (C16)	<LOD	0.005
	PFTeDA (C14)	<LOD	0.0098
	PFTrDA (C13)	<LOD	0.00328
	PFDoDA (C12)	<LOD	0.022
	PFUnDA (C11)	<LOD	0.072
	PFDA (C10)	<LOD	0.0052
	PFNA (C9)	<LOD	0.02
	PFOA (C8)	<LOD	0.48
Short chain PFCAs	PFHpA (C7)	<LOD	0.15
	PFHxA (C6)	<LOD	0.21
	PFPeA (C5)	<LOD	0.24
	PFBA (C4)	<LOD	0.96
Long chain PFSAs	PFTrDS (C13)	<LOD	0.0047
	PFDoDS (C12)	<LOD	0.0069
	PFUnDS (C11)	<LOD	<LOD
	PFDS (C10)	<LOD	0.0016
	PFNS (C9)	<LOD	0.00101
	PFOS (C8)	<LOD	0.86

PFAA Group	Substance	Minimum concentration (µg/L)	Maximum concentration (µg/L)
	PFHpS (C7)	<LOD	0.02
	PFHxS (C6)	<LOD	0.15
Short chain PFSAs	PFPeS (C5)	<LOD	0.038
	PFBS (C4)	<LOD	0.038

<LOD - below limit of detection (LODs varied depending on the sample run and substance).

Figure 2.2: Maximum concentrations of PFOA and PFBA measured in Environment Agency groundwater samples between July 2021 and November 2024. Data were available for England only.

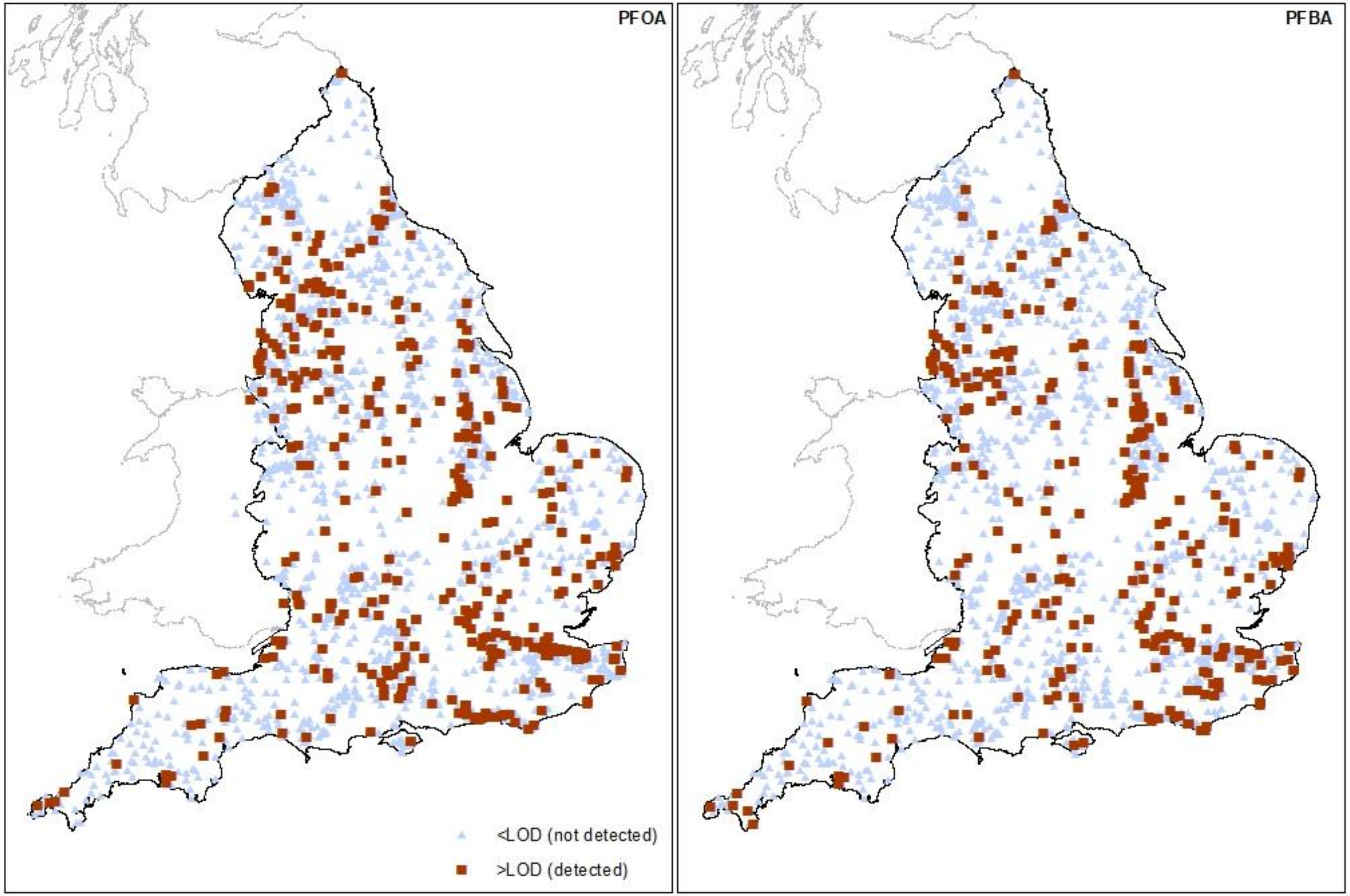
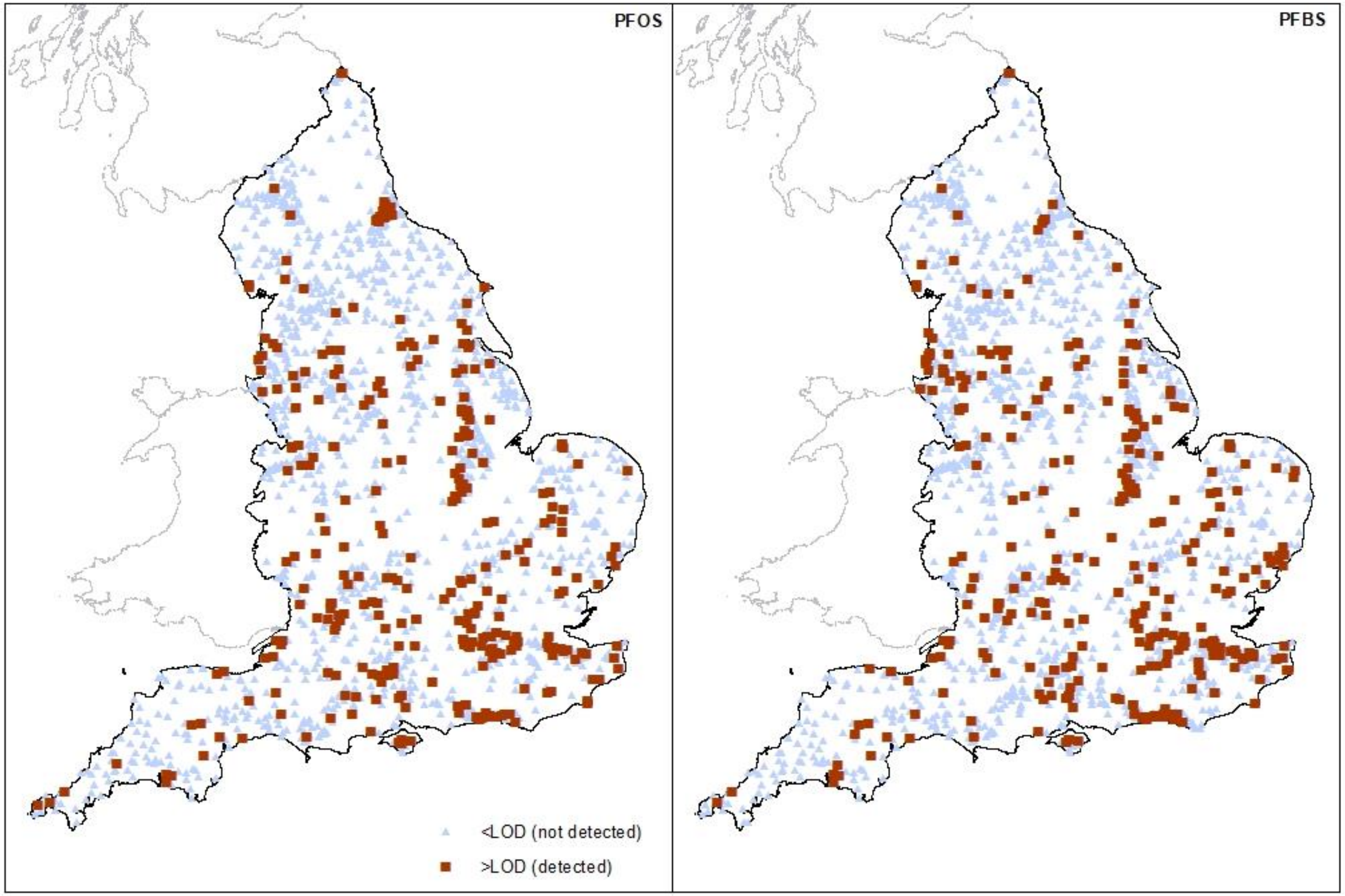


Figure 2.3: Maximum concentrations of PFOS and PFBS measured in Environment Agency groundwater samples between July 2021 and November 2024. Data were available for England only.



2.4.4.5 Wastewater Treatment Plant data

Monitoring data from WwTP influent and effluent can demonstrate if a substance is difficult to remove from the aqueous phase. Three examples include:

- Eriksson *et al.* (2017) investigated various PFAS, including precursors, intermediates, and emerging compounds, in influent and effluent wastewater, as well as sludge, from three Swedish municipal WwTPs. Table 2.12 shows the concentrations of PFAAs (including long chain and short chain PFCAs and PFSAs) that were measured in the influent and effluent at each site. Generally, concentrations remained the same or increased, demonstrating ineffective removal. The authors hypothesised that where an increase was seen, it was because precursors were degrading to the terminal arrowhead substances during the treatment process.

Table 2.12: Concentration (ng/L) of PFAAs in influent and effluent water at three Swedish municipal WwTPs in 2015. Table adapted from Eriksson *et al.* (2017).

PFAA Group	PFAA	LOD	Henriksdal		Gässlösa		Umeå	
			Influent	Effluent	Influent	Effluent	Influent	Effluent
Long chain PFCAs	PFDA (C10)	0.2	0.3	0.5	<0.2	<0.2	0.4	0.4
	PFNA (C9)	0.1	0.7	0.6	0.2	0.4	0.6	0.4
	PFOA (C8)	0.5	5.1	5	4.1	5.2	2.8	4.1
Short chain PFCAs	PFHpA (C7)	0.1	2.6	2.7	1.9	2.8	1.6	1.4
	PFHxA (C6)	0.4	5.5	7.3	6.8	16.8	3.2	5
	PFPeA (C5)	0.06	3.3	4.9	4.6	10.2	3.1	2.2
	PFBA (C4)	3.4	5.5	12.3	<3.4	30.1	n.q.	8.2
	PFOS (C8)	0.7	1.1	1	0.9	1.5	1.7	1.5

PFAA Group	PFAA	LOD	Henriksdal		Gässlösa		Umeå	
			Influent	Effluent	Influent	Effluent	Influent	Effluent
Long chain PFSAs	PFHpS (C7)	0.04	0.1	<0.04	<0.04	0.2	0.2	0.1
	PFHxS (C6)	0.1	1.6	1.9	1	1.3	0.9	1.2
Short chain PFSAs	PFPeS (C5)	0.02	0.3	0.5	0.3	0.4	0.3	0.3
	PFBS (C4)	0.06	3.2	3.7	1.2	1.1	0.6	0.9

n.q. – not quantified due to low recovery of internal standards and/or matrix effects.

- Moneta *et al.* (2023) monitored twenty-five target PFAS in influent and effluent wastewater from four municipal WwTPs located in Milan, Italy in July and October 2021, and February and May 2022. Table 2.13 shows the concentrations of PFAAs (including long chain and short chain PFCAs and PFSAs) that were measured in the influent and effluent at each site in July 2021. The data indicate that there were higher concentrations of some PFAAs in the influent than the effluent, though this was not always the case. Similar pictures were seen in October 2021, February 2022 and May 2022. The authors noted biotransformation of PFAA precursors to the terminal arrowheads during biological treatment and that secondary biological treatment and membrane bioreactors (MBRs) were ineffective in removing the PFAS.

Table 2.13: Concentration (µg/L) of PFAAs in influent and effluent waters of four Italian WwTPs in July 2021. Table adapted from Moneta *et al.* (2023).

PFAA Group	PFAA	Site A		Site B		Site C		Site D	
		Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
Long chain PFCAs	PFTeDA	0.78	1.01	1.13	3.07	0.98	0.71	0.61	0.8
	PFTrDA	3.93	0.82	1.93	1.42	0.36	4.4	0.47	5.06
	PFDoDA	0.18	0.17	0.21	0.95	<LOQ	0.21	0.19	0.16
	PFUnDA	0.22	0.24	0.16	0.17	<LOQ	<LOQ	<LOQ	<LOQ
	PFDA	<LOQ	<LOQ	0.02	0.25	0.03	0.33	0.04	<LOQ
	PFNA	0.02	0.21	0.35	0.2	0.82	0.57	1.09	0.83
	PFOA	1.82	3.64	2.72	1.47	2.65	2.44	2.48	3.13
Short chain PFCAs	PFHpA	1.57	1.89	2.67	1.74	1.93	1.74	1.83	2.96
	PFHxA	2.29	3.6	5.65	2.69	3.54	7.32	4.93	7.24
	PFPeA	5.32	8.16	6.14	2.1	21.37	7.94	5.61	6.27
	PFBA	1.74	1.55	3.34	2.11	1.66	5.78	1.68	2.26
Long chain PFSAs	PFDS	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
	PFOS	3.77	3.97	<LOQ	2.48	1.32	3.65	2.27	3.3
	PFHpS	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
	PFHxS	5.06	0.54	3.8	0.12	<LOQ	<LOQ	<LOQ	<LOQ
Short chain PFSAs	PFPeS	<LOQ	<LOQ	<LOQ	<LOQ	0.76	<LOQ	<LOQ	<LOQ
	PFBS	3.21	3.74	1.58	1.37	2.71	3.76	<LOQ	4.28

<LOQ – below limit of quantification

- Nguyen *et al.* (2024) compared PFAS concentrations in the influents and effluents of 75 Australian WwTPs. PFAAs were widely detected in the effluents and biosolids from the WwTPs, although there was significant variation between WwTPs. They found that there were generally higher concentrations of PFCAs in the effluents

> than the influents among the WwTPs, particularly so for C5 to C8 PFCAs. They hypothesised that these were a result of unknown PFAA precursors in the WwTP influents that formed the terminal arrowheads during treatment. It should be noted that they did identify the potential removal of long chain PFSAs through sorption into biosolids, which they attributed to the sulfonic acid functional group exhibiting a stronger affinity to organic matter compared with the carboxylic acid group.

In summary, PFAAs are generally characterised by a lack of retention on biosolids and ineffective removal. However, this is confounded by degradation of PFAA precursors leading to formation of PFAAs in WwTPs.

2.4.4.6 Conclusion on mobility

Regulatory thresholds to define M and vM have not been established under UK REACH. Although it is generally accepted that a log K_{OC} less than 3 is a screening indicator of mobility for many organic chemicals, surface active properties and polarisation/ionisation of a molecule complicate matters. Therefore, established regulatory metrics and thresholds have to be carefully considered and may be unsuitable for quantitatively assessing or benchmarking the mobility potential of PFAAs. Given the uncertainty around the K_{OC} and K_d data for PFAAs, the Agency considers that groundwater monitoring data should receive the highest weighting as a line of evidence.

The reported widespread presence of both long chain and short chain PFAAs in groundwaters across England demonstrates that they are mobile in the aquatic environment. The Environment Agency does not monitor ultra-short chain PFCAs and PFSAs, but their presence in groundwaters has been demonstrated elsewhere (Frank *et al.*, 2002; Pickard *et al.*, 2020). These data demonstrate that PFAAs penetrate natural barriers and enter vulnerable water sources.

Reported K_d and K_{OC} values for PFAAs indicate generally increasing mobility with decreasing chain length. The relationship is not maintained for short chain and ultra short chain PFAAs, possibly because hydrophobic interactions with organic matter are not the dominant mechanism of retention for these PFAAs. Nevertheless, although there is some uncertainty in the absolute values of experimental K_{OC} and K_d data, they are consistently low enough to suggest that both short chain and ultra-short chain PFAAs are likely to be very mobile in the aquatic environment. K_{OC} and K_d data for the long chain PFAAs also indicate potential mobility.

Further supporting information is provided by comparison of WwTP influent and effluent concentration data, which generally indicate low removal efficiencies for both long chain and short chain PFAAs. This is likely to be at least partly due to the poor adsorption of PFAAs to biosolids.

Due to the direct evidence from field data, supported by the results of laboratory and WwTP studies, the Agency considers that all PFAAs are sufficiently mobile to reach environmental compartments of concern, including those remote from sources.

2.4.5 Toxicity

2.4.5.1 What is Toxicity?

Toxicity (T) criteria are provided in Annex 13 of the UK REACH regulation and described in the associated technical guidance (ECHA, 2017b, 2017c, 2017d, 2017e) (summarised in Annex E, Table E.1). The criteria include both human health and environmental endpoints.

2.4.5.2 Regulatory landscape

Conclusions on the toxicity status of PFAAs within regulatory PBT and PMT assessments have considered available data on toxicological and/or ecotoxicological effects. Table E.1 in Annex E sets out the criteria by which each regulatory authority or jurisdiction determines if a substance is toxic or not. In some cases, these criteria are not equivalent to the criteria for assigning toxicity under Annex 13 of UK REACH; for example, in the case of toxicological effects, the UK REACH Annex 13 criteria are linked to specific human health classifications under GB CLP.

More national / international regulatory assessments have been carried out for long-chain than short-chain PFAAs (see Annex E.5.3, Table E.9).

Regulatory toxicity assessments of the PFCAs cover chain lengths ranging from C4 to C21 (Table 2.14). In summary:

- Long chain: Adverse effects equivalent to the T criterion have been confirmed at both UK (when part of the EU) and UN level for C8 to C10 PFCAs (PFOA, PFNA and PFDA) (ECHA, 2013, 2015, 2016a; UN POPS, 2016, 2023). NICNAS also found PFOA to be toxic (NICNAS, 2015e). Adverse effects were also confirmed at UN level for C11 to C21 PFCAs (UN POPS, 2023) and in Canada the regulator and federal government concluded that C9 to C20 PFCAs are harmful to organisms (Environment Canada, 2012; Government of Canada, 2022).

- Short chain: NICNAS identified uncertain toxicity for PFHpA (C7) (NICNAS, 2015d) and concluded that C4 to C6 PFCAs are not toxic (NICNAS, 2015c). In contrast (and more recently), ECCC concluded that C4 to C7 PFCAs are toxic (ECCC, 2023). ECHA has concluded that PFHpA (C7) is toxic (ECHA, 2022a), while a mandatory classification of PFHxA (C6) that would meet the toxicity criterion has been proposed under GB CLP.

- Ultra-short chain: No regulatory assessments for the ultra-short chain PFCAs were found. However, TFA (C2), sodium trifluoroacetate and other inorganic salts of trifluoroacetic acid are under consideration for mandatory classification under GB CLP that would meet the toxicity criterion.

Regulatory toxicity assessments of the PFSAs cover chain lengths ranging from C4 to C20 (Table 2.15). In summary:

- Long chain: Adverse effects equivalent to the T criterion were confirmed at UN level for C8 PFSA (PFOS) (UN POPS, 2006), which concurs with an Environment Agency assessment (Environment Agency, 2004). Adverse effects were also confirmed by the UN for PFHxS (C6) (UN POPS, 2018). NICNAS concluded C8 to C10 PFSAs are toxic (NICNAS, 2015b, 2015f), but found uncertain toxicity for PFHxS (C6) and PFHpS (C7)

(NICNAS, 2015a). The Canadian regulator found PFOS to be ‘harmful to the environment’ via toxicity/exposure analysis Environment Canada (2006), and C6, C7 and C9 to C20 PFSAs as toxic (ECCC, 2023).

- Short chain: NICNAS (2015a, 2015h) concluded that PFBS (C4) is not toxic and PFPeS (C5) has uncertain toxicity. In contrast, ECCC concluded that PFBS (C4) and PFPeS (C5) are both toxic (ECCC, 2023), and similarly ECHA (whilst the UK was still a member) concluded that PFBS (C4) is toxic for ecotoxicological effects (ECHA, 2019b).
- No regulatory assessments for the ultra-short chain PFSAs were found.

It should be noted that read across has been relied upon heavily in regulatory assessments (Annex E.5.3, Table E.9). For example:

- C9–C20 PFSAs were concluded to be toxic based on PFOS (read across) and PFDS endocrine-related effects data, noting a lack of acute or chronic data for the C9–C20 PFSAs (ECCC, 2023); and
- PFNS and PFDS were concluded to be toxic based on a comparison between PFDS and PFOS acute aquatic toxicity data, read across from PFOS chronic aquatic toxicity data, and the pattern of increasing toxicity with increasing chain length (NICNAS, 2015f, 2015g).

Table 2.14: Number of toxicity conclusions reached by international/national regulatory jurisdictions at each chain length for PFCAs. Shading provides heatmap visualisation of where conclusions have been made*

PFCA group		Ultra-short chain		Short chain				Long chain													
Carbon chain length		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Report conclusion	Toxic	0	0	1	1	2	2	3	3	3	2	2	2	2	2	2	2	2	2	2	2
	Uncertain toxicity	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Not toxic	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Not considered	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0

*Orange shading highlights where a conclusion of toxicity was made; blue shading highlights where a conclusion of not toxic or uncertain toxicity was made; pink shading highlights where assessments have been conducted but toxicity has not been considered (darker shading means more assessments).

Table 2.15: Number of toxicity conclusions reached by international/national regulatory jurisdictions at each chain length for PFSAs. Shading provides heatmap visualisation of where conclusions have been made*

PFSA group		Ultra-short chain	Short chain			Long chain																
Carbon chain length		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Report conclusion	Toxic	0	0	0	2	1	2	1	4	2	2	1	1	1	1	1	1	1	1	1	1	0
	Uncertain toxicity	0	0	0	0	1	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Not toxic	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Not considered	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

*Orange shading highlights where a conclusion of toxicity was made; blue shading highlights where a conclusion of not toxic or uncertain toxicity was made; pink shading highlights where assessments have been conducted but toxicity has not been considered (darker shading means more assessments).

2.4.5.3 Available toxicological data

The toxicological and health effects of PFAAs in scope of this report and conclusions on toxicity were described in Section 2.3.

2.4.5.4 Available ecotoxicity data

Functional group (i.e., PFCA versus PFSA) and carbon chain length (i.e., long chain versus short chain) significantly influence environmental toxicity (ECCC and Health Canada, 2024; ECHA, 2023a; Wang *et al.*, 2024). Wang *et al.* (2024) performed a critical evaluation and meta-analysis of 91 peer-reviewed studies (of which 65 contained datapoints on PFCAs and 50 contained datapoints on PFSAs) containing population-level ecotoxicological data for PFAS in freshwater species. The critical review indicated that C8 to C10 PFCAs and C6, C8 and C9 PFSAs tended to be more toxic than PFAAs below C6, and the ultra-short chain PFAS (C2 and C3 PFCAs) typically had much lower toxicity levels (though there were few data points for the ultra-short chain PFAS). Notably, Kadlec *et al.* (2024) report that while PFSAs were more toxic than PFCAs for *Chironomus dilutus*, the toxicity of PFSAs was similar to PFCAs for *Ceriodaphnia dubia* and *Hyallela azteca*, so these patterns may depend on the species exposed.

In general, there are a lack of data and great variations in the effects observed for PFAAs. ECHA (2023a) provide an overview of ecotoxicological threshold values taken from the PFAS-Tox Database (Pelch *et al.*, 2022), accessed on 07 October 2021; the effects relevant to the PFAAs are shown in Annex E.8.1. The studies reported include long chain, short chain and ultra-short chain PFCAs, and long chain and short chain PFSAs. They show a wide variation in effects, across orders of magnitude. There are a small number of non-standard multigenerational studies on aquatic invertebrates (for PFOA, PFBS, and PFOS) and fish (for PFOA, PFNA, PFBS, and PFOS) that have reported adverse effects at concentrations below 0.01 mg/L. However, although the Agency has not reviewed the studies for reliability and they do not appear to be standardised studies, overall, the data do not indicate a level of toxicity that would be classified as ‘T’ under UK REACH. Nevertheless, some of the concentrations shown are environmentally relevant. Although this review does not include any ultra-short chain PFSAs, given their likely lower toxicity levels than their longer chain counterparts, data on these have not been sought.

ECCC and Health Canada (2024) also provides a general overview of effects that have been observed for PFAAs, summarised in Annex E.8.2, which indicates that PFAAs are associated with a wide range of effects in many taxonomoic groups. Similarly, Ankley *et al.* (2021) provide a comprehensive overview of collated ecotoxicity data for aquatic and terrestrial invertebrates, fish, amphibians, birds, reptiles, mammals and other wildlife species not routinely used in ecotoxicity assessments. Key messages from Ankley *et al.* (2021) are:

- Understanding of ecotoxicity is limited, considering the number and diversity of PFAS.
- Most data available consider acute rather than chronic effects; this is an important data gap considering the potential for long-term exposure arising from their

persistence. There are a small number of multigenerational studies on aquatic invertebrates (PFOA, PFBS and PFOS) and fish (PFOA, PFNA, PFBS and PFOS); the Agency has not evaluated these studies directly, but Ankley *et al.* (2021) report that they have shown adverse effects – some at concentrations less than 0.01 mg/L – emphasising the importance of gaining a better understanding of long-term toxicity for the PFAAs as a group.

- The potential impacts on terrestrial organisms remain largely unknown.
- Existing standard ecotoxicological tests are of relatively short duration, so may not adequately capture effects caused by continuous intergenerational exposure.

2.4.5.5 Overall conclusion on toxicity

The toxicity (T) criteria provided in Annex 13 of UK REACH include both human health and environmental endpoints.

Ecotoxicity data are only available for a limited number of individual PFAAs and most studies focus on short-term aquatic toxicity. There are a small number of non-standard multigenerational studies on aquatic invertebrates and fish that have reported adverse effects at concentrations below 0.01 mg/L. Nevertheless, it is not possible to conclude that all PFAAs are T under UK REACH for environmental toxicity, but intergenerational, long-term effects remain a concern.

There are generally more toxicological data on PFCAs and PFSAs than there are ecotoxicological data. In particular, there is no information on toxicity to birds or other terrestrial vertebrate groups. The toxicological and health effects of PFCAs and PFSAs are described in Section 2.3. Whilst noting the limitations in availability of toxicological data for some substances, the Agency has concluded that toxicity is associated with substances across both the PFCA and PFSA sub-groups, based on the GB CLP classifications given in Annex 13 (see Section 2.3.7.1).

2.5 Conclusion on hazard assessment

The properties of concern reviewed in this hazard assessment in relation to PFAAs are summarised in Table 2.16.

Table 2.16 – Environmental hazard properties and concern of PFAAs.

Property	Concern
Persistence	All PFAAs meet the criteria to be concluded as vP under UK REACH.
Mobility	All PFAAs are sufficiently mobile to reach environmental compartments of concern, including those remote from sources.
Toxicity	It is concluded that toxicity is associated with substances across both the PFCA and PFSA sub-groups. Owing to the limited scope and uncertain reliability of the available data, definitive conclusions regarding the long-term ecotoxicity of PFAAs as a group cannot be drawn.

Although the primary focus of this environmental hazard assessment has been to understand if the PFAAs have PMT and/or vPvM properties, it should be noted that some PFAAs have already been concluded to be persistent, bioaccumulative, toxic and have long range transport potential under the Stockholm Convention. These substances include:

- PFHxS, its salts and PFHxS related compounds (UN POPS, 2018)
- PFOS and PFOS derivatives (UN POPS, 2006)
- PFOA, its salts and PFOA-related compounds (UN POPS, 2016)
- C9-C21 PFCAs (UN POPS, 2023).

C8 to C10 PFCAs were also confirmed to be bioaccumulative, while C11 to C14 PFCAs were confirmed to be very bioaccumulative, by the UK (when part of the EU) in ECHA (2012a, 2012b, 2012c, 2012d, 2013, 2015, 2016a).

3 Exposure Assessment

3.1 Use and Environmental Exposure

3.1.1 Overview of approach to environmental exposure assessment

An overview of the environmental fate and behaviour of PFAAs in the environment is provided in HSE (2023) and is summarised in the following text. Additional details have been provided for PFAS in FFFs intentionally released through training activities routinely carried out at military, aviation and chemical plant facilities, or during live response to incidents.

The two dominant factors that impact the fate and transport (partitioning) of PFAAs and their precursors (ITRC, 2022) are:

- their intrinsic physicochemical properties: PFAAs are stable, permanently ionised at environmentally relevant pHs, and demonstrate increasing surface-active properties as their fluorinated tail increases in length, or increasing mobility as their fluorinated tail length decreases; and
- the physicochemical properties of the environmental matrices (soil, water/sediment and air) into which they are released.

PFAS are typically encountered in the environment as poorly characterised complex mixtures of PFAAs, PFAA precursors and intermediate compounds (Hatton *et al.*, 2018; Maizel *et al.*, 2023; Wanzek *et al.*, 2024). This muddles the already complex partitioning relationships between matrices due to the potential for competitive binding, formation of micelles (aggregation) and immiscible aggregate layers, etc (Hatton *et al.*, 2018).

There are very few environmental fate studies of PFAS conducted using standardised simulation test methods. These typically show negligible rates of degradation over laboratory timescales. Therefore, environmental transformation half-lives cannot be measured as they will exceed the length of the study. For this reason, PFAS as a group in general, and PFAAs in particular, are internationally recognised as being highly persistent, with anticipated half-lives in excess of the UK REACH vP criterion (Section 2.4).

Subsequently, there is ambiguity around:

- the extent to which PFAA-precursor transformation occurs at different scales (e.g. local, regional or global),

- which environmental compartments are most important for transformation (e.g. water, soil or atmosphere), and

- how transformation processes, rates and pathways are affected by different environmental conditions (see Annex C.1.1, Case study 1).

Despite the limited degradation potential of many PFAS, biological activity within WwTP can convert some PFAA precursors in the influent that are currently undetected using quantitative analytical methods into terminal PFAAs in the effluent (Ankley *et al.*, 2021). Whilst many PFAS – particularly shorter chain PFAAs – can pass through sewage treatment works with minimal removal (due to their resistance to degradation and limited sorption potential), longer chain PFAAs and their precursors have a greater tendency to sorb to biosolids in sewage treatment works, which may then be applied to soils.

Once PFAS enter aquatic or terrestrial environments, they can spread widely and recirculate due to the lack of removal mechanisms. Some can be subject to bioaccumulation in aquatic organisms, thereby entering the food chain (Chiesa *et al.*, 2022; Torres and De-la-Torre, 2022). Contaminated waters may also be used for irrigation of agricultural land or abstracted for drinking purposes. PFAS can move from land to groundwaters through leaching, or be subject to uptake in plants, entering the food chain via a terrestrial route (Wang *et al.*, 2020).

PFAAs and their precursors can also reach the atmosphere through direct emission or volatilisation, or when bound to soil particles disturbed by wind. Limited degradation means they can move over large distances within air flows, returning to the terrestrial or marine environments through precipitation or other forms of deposition (Cousins *et al.*, 2022; Faust, 2022; Pfotenhauer *et al.*, 2022). They may move to deep marine sediments, bioaccumulate in long-lived marine organisms or return to the atmosphere through sea spray aerosols (Sha *et al.*, 2022).

These diverse pathways contribute to both short- and long-term exposure of aquatic and terrestrial ecosystems and humans. It is currently not understood whether there is a true environmental ‘sink’ for these substances. However, as they continuously cycle and are highly persistent, they are likely to reach vulnerable environmental compartments such as groundwaters and drinking water sources, and PFAA concentrations are expected to increase over time (HSE, 2023). PFAAs are therefore expected to represent an increasing proportion of the total PFAS load in the environment, owing to gradual transformation of precursors and the lack of any further removal of the PFAAs via degradation or adsorption (ITRC, 2022).

The use of source – pathway – receptor models is a standard approach in environmental chemical risk assessment to determine whether there is potential for exposure, and therefore, impacts, to occur. A fully quantitative exposure assessment has not been performed for this report because:

- The amount of FFF used in different applications is needed, along with the level of release under different scenarios. The Agency does not have sufficient data on this for GB, although the available information is summarised later in Sections 3.1.2 and 3.1.3.
- The composition of most FFF formulations is unknown, as the manufacturers of the PFAS surfactants usually consider the information to be commercially confidential.

- The number of individual PFAS in FFF is potentially large, and the environmental behaviour of all of these substances would need to be taken into account.
- The role of transformation products, which may behave differently in the environment than both the parent substance and the terminal PFAA, adds a further complication.
- As discussed in Section 2.4.2 (and Annex E.2), there is a high degree of uncertainty associated with the empirical measurement of physicochemical properties of PFAS using standard methods and estimation models. Direct measurements of partitioning to solids and biota are therefore essential, but relevant data are generally not available.
- The applicability of existing exposure models, such as the European Union System for the Evaluation of Substances (EUSES), is compromised by the complex and unusual partitioning behaviour of PFAS mixtures.

Nevertheless, the use pattern of FFF results in direct emission to the environment, with 'hot spots' around areas with highest use. The available information on the releases of PFAS-containing FFF to the GB environment and PFAS concentrations in environmental compartments that can be linked to the use of these products is reviewed in the following sections. The exposure assessment has focussed on monitoring data and other information from sites where the use of PFAS-containing FFF is known to have occurred and other potential PFAS sources are unlikely. These include formulation sites, airports, and industrial sites where large fires have taken place. This gives a snapshot of the extent of contamination that may arise, which can be used as surrogate information for sites without such data.

3.1.2 Quantities used in GB

Due to the lack of domestic UK data on the use of firefighting foams, it has been necessary for the Agency to make assumptions regarding the annual tonnages of FFF concentrate sold in GB per year, as follows:

Table 3.1: Estimates of PFAS-containing foam concentrate sales.

PFAS-containing foam concentrate sales (t/year)	
Low	1,300
Central	2,000
High	2,500

Table 3.2: Estimate of fluorine-free foam (F3) concentrate sales.

Fluorine-free foam (F3) concentrate sales (t/year)	
Low	2,000
Central	2,900
High	3,600

These estimates are from WSP (2023), extrapolated from ECHA's market analysis, which used a 3-year sample from Eurofeu (2016-2018) to estimate annual sales of PFAS-containing firefighting foam concentrate to various EU use sectors. ECHA estimate a low, central, and high annual sales figure of **14,000 t, 18,000 t,** and **20,000 t**, respectively. They estimated sales of fluorine-free foams to range from **7,000** – **9,000 t** a year.

WSP (2023) extrapolated these figures to the UK market through several approaches to form a low, central, and high range estimate of the UK market based on a share of the EU market, as follows:

1) Extrapolation based on population, where the UK is assumed to use the same quantity of foams per capita per year, would scale the EU figure by **~15%** based on data from the World Bank. They note that this may underestimate UK use, as they state that certain uses like marine and (petro)chemical situations may be more prevalent in the UK than the EU.

2) Extrapolation based on the number of firefighters in the UK relative to the EU would result in the UK market being **~21%** of the EU's, based on 2019 data from Eurostat (2020).

3) Extrapolation based on gross domestic product (GDP) would result in the UK market being **~18%** the size of the EU market, using 2023 World Bank data.

They also noted that progression in the market for F3 has progressed since the Eurofeu study was conducted. Through consultation with industry, they estimated a reduction of 35-55% in the sales of PFAS-based foams (transferred to the PFAS-free market) to have taken place up to and including the year 2023, relative to the years (2016-2018) when the Eurofeu survey took place. They also noted that a UK manufacturer estimated the share of the UK market comprised of fluorine-free foams to be almost 60% in 2023. Based on this evidence, WSP (2023) assume **40%** of the PFAS-foam estimate has been subsequently replaced with F3, which results in an F3 market share of just under 60%. The figures shown in Table 3.1 and Table 3.2 above include this transition away from PFAS foams to F3 alternatives.

As noted in Section 3.1.5, AFFF concentrates typically contain 2-3% PFAS. Taking the average concentration to be 2.5%, this would result in **32.5 tonnes** – **62.5 tonnes** of PFAS on the market each year. Using the assumptions in the Agency’s central economic assessment scenario (Section 6.4.2.1.10), the Agency estimates **48 tonnes** of PFAS could be emitted annually.

The Agency acknowledges the uncertainty inherent in this approach, in addition to the fact that UK manufacturer Angus Fire announced in late 2023 that they would cease production and supply of PFAS-based foam concentrate from the first quarter of 2024.

Angus Fire’s withdrawal from the PFAS-foam market could have a range of impacts on the share of the market comprised by PFAS versus alternative foams. If users still demand PFAS-containing foams rather than alternatives, other suppliers (in the UK or abroad) may step in to fill the gap. Similarly, industry may avoid investing in the labour and capital to fill the gap due to the fact that they are aware a restriction proposal is in preparation. This would likely result in some downstream switch to alternatives under the baseline; a reduction in PFAS-foam supply will result in a relative price increase compared to alternatives and likely induce some substitution.

Following publication of this report, the Agency will continue to seek information that will help model the baseline market activity based on domestic data, rather than extrapolation from EU estimates.

The Agency notes that the above discussion relates to the UK rather than GB. Northern Ireland (NI) falls within EU REACH jurisdiction. However, for the current time, the Agency makes no distinction between UK and GB figures when it comes to modelling quantities. The populations of England, Wales, and Scotland comprise 97% of the UK population; it is unlikely that using UK data to represent GB makes any substantive difference to modelling outputs given the range of uncertainties in other parameters. Nonetheless, during the consultation period the Agency will explore whether greater specificity of UK vs GB impacts is necessary.

For further analysis on sector-specific market information, in addition to the estimated abatement resulting from the Agency’s restriction proposal, see Section 6.4.

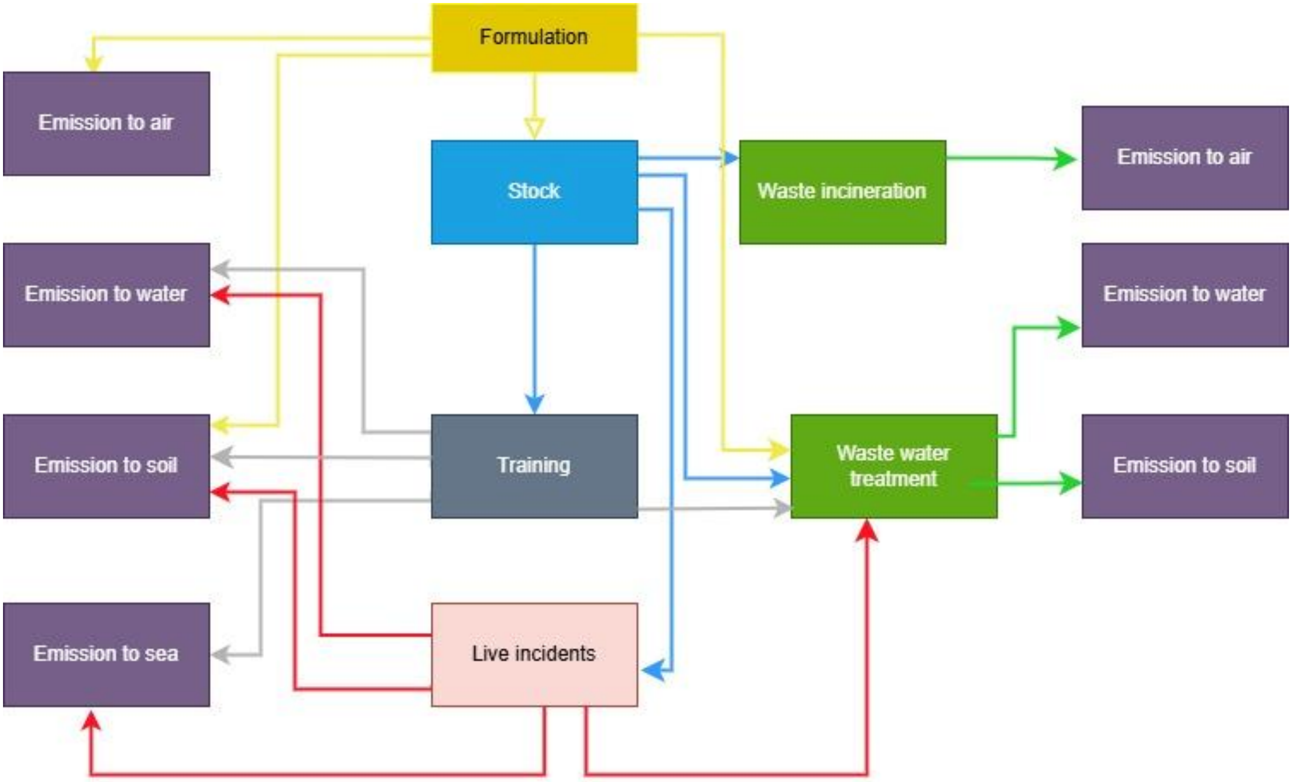
3.1.3 Life cycle stages and releases

In this section the life cycle stages relevant for the release of PFAS from FFF in GB are discussed, as follows:

1. Formulation
2. Storage
3. In use (training and live incident)
4. Waste disposal

There is no manufacture of PFAS for use in FFF in GB. Therefore, this life cycle stage has not been considered. The different life cycle stages and respective releases are shown in Figure 3.1.

Figure 3.1: Material flow chart showing the releases from each life cycle stage.



Although the Agency has not conducted a quantitative exposure assessment, the release rates used in ECHA (2023e) are summarised below to give an indication of expected emissions from each life cycle stage. These are all based on ECHA guidance (ECHA, 2016b), the UNECE inventory guidebook (EEA, 2019) and the OECD Emission Scenario for AFFF (OECD, 2021a).

3.1.3.1 Formulation

Formulation is the blending of substances to form FFF concentrate and can result in PFAS emissions directly to soil and air, and indirectly to water, soil and air via the wastewater system (e.g. sewers and WwTPs). The ECHA emission scenario considers *“default worst case emission rates of 2.5 % w/w to air, 2 % w/w to water (assumed to be wastewater system rather than direct release) and 0.2 % to soil as a direct release from spillages / deposition during formulation*” (ECHA, 2023a). Testing of new formulations can be done on the formulation sites or at external testing facilities (more information on this is in Section 3.1.4). This testing was not included explicitly in the estimates from ECHA.

3.1.3.2 Storage

Transport and storage of foam concentrate prior to use can lead to losses to the environment. ECHA (2023e) considered a leakage value of 1 % of total stocks to wastewater based on the opinion of industry experts, as no data for leakage rates were identified in the literature. In general, the Agency expects that typical usage sites (such as fire stations, airports, refineries, COMAH sites, etc.) will have appropriate containment measures whereby any spills are either contained and disposed of as waste or released via the wastewater system and therefore a release of 1 % would be worst case.

3.1.3.3 In Use

Use comprises both training activities and live incidents.

For training by the Fire and Rescue Services (FRS), it is expected that the majority of sites will have risk management measures in place to allow capture and retention of FFF; these will either be disposed of as hazardous waste or via an onsite or external wastewater system. The National Fire Chiefs Council (NFCC) is an independent membership association that supports FRS, representing their members' needs in development, policy support and production of guidance. One of these guidance documents is the Environmental Protection Handbook, developed with the Environment Agency, Scottish Environmental Protection Agency, Natural Resources Wales and the Northern Ireland Environment Agency (NFCC, 2015). The Handbook indicates that foam used by FRS during training incidents or testing should never be allowed to enter surface and/or groundwater (NFCC, 2015). For training, ECHA (2023e) assumes 100 % to water for marine applications. For on-land applications, they assume 97 % is contained and directed to wastewater treatment, with 3 % emitted to soil.

For live incidents, it is possible that some risk management measures may be in place to avoid direct release to surface waters or soils on site (e.g. drains, bunding, etc.), depending on the site, location, and scale of the incident. All land-based sites with firefighting assets for large scale fuel fires (i.e. airports, COMAH sites and petrol stations) where oils or non-miscible fuels are present will have drain interceptors. For other incidents such as a road traffic accident or an off-airport air crash, as well as in marine or offshore situations, it is unlikely that any containment measures would be available. In guidance issued by the NFCC every effort should be taken to prevent firefighting foam entering surface and groundwater during an incident attended by the FRS due to high biological oxygen demand, potential toxicity and other contaminants from the fire (NFCC, 2015), although the Agency has no information on how often containment is possible on live incidents or how effective this containment is. For live incidents, ECHA (2023e) assumes 100 % release, split evenly between surface waters and soil, which would be considered worst case.

3.1.3.4 Waste

PFAS-containing foam concentrates have an expiration date, which is commonly 10 years post formulation, although foam suppliers do offer a foam testing service to ensure it is still fit for use. An estimate, derived by Eftec (Eftec, 2019), for the use of PFOA-based foams concluded that 4.2 % of foam would expire each year, based on the average yearly consumption rate being 1.2 % for system testing and 1.2 % for actual incidents and the oldest foams being used first. ECHA (2023e) assumes that for the purpose of its emissions model, as a worst case, all foam concentrate would have been used for either training or on a fire prior to the expiry date.

Emissions can result from all life cycle stages and some of these will end up in waste streams. Waste streams encompass all PFAS-containing foam material not lost directly to the environment, e.g., capture of run-off from incidents or training, drainage to the wastewater system of spillages/leaks during storage, as well as disposal of unused product. Waste streams would also include PFAS-containing decontamination washes and rinsate and solid wastes such as pipes, nozzles, tanks, containers, equipment and appliances that are contaminated with PFAS.

3.1.4 Formulation sites

There are two PFAS-based firefighting foam formulation companies in GB: Oil Technics Ltd and 3FFF Ltd. A third company – Angus Fire Ltd – has historically formulated PFAS-based foams but has recently ceased that operation. It is still relevant to this report given the amount of data available on local PFAS contamination.

3.1.4.1 Angus Fire Ltd

Angus Fire was a supplier of firefighting foams, hoses and equipment based in High Bentham, North Yorkshire. The site has formulated synthetic FFF concentrates since the 1970s. The PFAS surfactant mixtures were all imported. In early 2024, Angus Fire stopped formulation and supply of all fluorinated foams. This site is discussed in more detail in the case study below and in the Annex E.9.

3.1.4.2 Oil Technics Ltd

Oil Technics has developed and formulated firefighting foams on their site at Gourdon, Aberdeenshire since 2008 (Oil Technics, 2024). The site formulated approximately 311 tonnes of PFAS-based foams in 2023 (Oil Technics, HSE call for evidence 2024). The testing of new foams is initially done indoors on site and then is subcontracted out for additional large-scale testing outside of GB (stakeholder meeting, Oil Technics, September 2024 and Call for evidence, Oil Technics). There is no environmental monitoring data from the local area (personal communication, SEPA, May 2024).

3.1.4.3 3FFF Ltd

3FFF, otherwise known as ABC MacIntosh, is based in Corby, Northamptonshire. They formulate foam concentrates using Capstone 1183™, Capstone 1470 ™, Capstone 1460 ™, DYNAX 1026 ™ and DYNAX 5011 ™, all of which are based on C6 PFAS technology. The site formulated approximately 100 tonnes of PFAS-based foams in 2023 (HSE call for evidence 2024). All testing of the foams is done at Norwich Airport (stakeholder meeting, Last Fire, June 2024). The Environment Agency does not have any PFAS monitoring data for the area around the site (Environment Agency, 2025).

3.1.5 Use of FFF

Different types of FFFs are used for different applications, however not all of them contain PFAS. Firefighting foams are grouped into several classes based on the type of fire they are appropriate for use on (Eftec, 2019):

- Class A (solid materials),
- Class B (liquids or liquefiable solids),
- Class C (gases),

- Electrical
- Class F (cooking oils and fats).

PFAS-containing foams are generally used on class B fires in GB. This includes fires involving flammable liquids, such as burning oil, gasoline, and jet fuel. Handheld portable extinguishers containing PFAS foams may also be used on class A fires.

PFAS surfactants are used in a number of different types of FFF, for example:

- Aqueous Film Forming Foam (AFFF) – The foam blanket covers the burning fuel surface, providing a barrier and separating the fuel from oxygen. As the bubble structure of the foam collapses a fluorosurfactant film rapidly spreads across the surface of the flammable liquid which isolates oxygen from the fuel preventing it from reigniting. Additionally, evaporation of water in the foam generates a cooling effect (Jahura *et al.*, 2024). AFFF can be used with either an aspirating or non-aspirating discharge device. The foam solution and air are mixed before discharge in the former. Foam discharged from a non-aspirating device will travel further and generally have a faster fire knockdown affect.
- Alcohol Resistant Aqueous Film Forming Foam (AR-AFFF) – similar to AFFF, but with the ability to deal with polar solvent or alcohol fires. AR-AFFF comprises a high molecular weight polymer in addition to the AFFF liquid, which precipitates out on contact with a polar solvent producing a barrier layer interface and preventing destruction of the bubble structure. It can be used on non-polar and polar liquid fires using an aspirating or non-aspirating discharge device. On a polar solvent fire, an aspirating discharge device tends to improve performance.
- Fluoroprotein Foam (FP) – a combination of hydrolysed proteins and fluorocarbon surfactants that is resistant to fuel pick up and is mobile across the surface of the liquid fuel.
- Film Forming Fluoro-Protein (FFFP) – similar to the fluoroprotein foam but comprising an increased proportion of fluorosurfactants to generate a mobile surface film and increase the fire knockdown effect in a similar manner to AFFF. FFFP foam can be generated with either air-aspirating or non-air-aspirating nozzles.
- Alcohol resistant film-forming fluoroprotein foam (AR-FFFP) comprising hydrolysed proteins, fluoro-surfactants and polymers, for use on polar solvent/alcohol liquid fires. A polymer membrane is formed protecting the foam blanket in a similar manner to AR-AFFF.

3.1.5.1 PFAS concentrations and proportioning rates

Depending on the manufacturer and intended use(s), PFAS-containing FFF concentrate products will contain variable concentrations of PFAS to deliver the required fire suppression properties. According to Wood (2020), 2018 data provided by Eurofeu from foam manufacturers representing 60 – 70 % of the EU market suggested that the minimum PFAS concentration that would deliver functionality was 0.1 %. Wood (2020) estimated that based on market analysis the average PFAS concentration in FFF concentrates was between 2 – 3 %.

PFAS-containing FFF concentrates are typically marketed as 1 %, 3 % or 6 %. This does not relate to the concentration of PFAS but to the proportioning rate (also termed the dilution or mixing rate) i.e. a 3 % foam requires 3 parts concentrate to 97 parts water, 6 % requires 6 parts concentrate to 94 parts water.

3.1.5.2 Standards

There are national and international standards that firefighting foams need to meet in order to be marketed for application against Class B fires. The provision of firefighting capability is regulated by several regulations, including BS EN 1568 Part 1-4, IMO, LASTFIRE, ICAO, MILSPEC, UL 162, GESIP, NFPA 11, and BS EN 13565 Part 1 & 2 for Fixed Firefighting Foam Systems. The standards have been developed to ensure that the foams or equipment meet minimum standards of effectiveness to extinguish a fire. Further information on these standards is provided in the Annex E.10.

All foam systems must be thoroughly inspected and tested for correct operation at least annually, ensuring the system remains in full operating condition until the next inspection. Foam concentrates and their tanks or storage containers must also be inspected for evidence of excessive sludging or deterioration. Samples of concentrates must be sent to the manufacturer or qualified laboratory for quality condition testing.

It should be emphasised that in order to be operationally functional and commercially viable, respective firefighting foams must be demonstrated to have met the relevant test standard(s)/certification for use in a particular sector. These standards apply to both PFAS-containing foam and fluorine-free alternatives, unless specifically mentioned otherwise.

3.1.6 Sectors

For each of the sectors identified the uses and potential releases are discussed in more detail below.

3.1.6.1 Fire and rescue services

3.1.6.1.1 Overview

There are 52 Fire and Rescue Services (FRS) in GB and they all attend fires in residential and industrial premises, at the roadside and on the rail network. This means that they cover a wide variety of fires, from petrol stations to tanker fires, large industrial sites, ports and airports, where Class B foams are generally used. Each FRS assesses their own individual fire safety risks based in part on the types of industry they have in their area and some locate foam tenders close to large petrochemical complexes (NFCC, 2024). Following the Buncefield fire (see Section on Buncefield), local and national mutual aid systems were put in place, as fires of the size of Buncefield require significantly more foam than is held by a single FRS or individual industrial site. This means that foam and equipment is readily available when necessary as the FRS works with the petrochemical industry to ensure there are sufficient stocks of foams held locally (NFCC, 2024).

The Agency does not have specific information on the quantities of PFAS-containing foams used by FRS on an annual basis, with the exception of a Freedom of information

(FOI) response from Cumbria County Council on behalf of Cumbria FRS who stated that they had not used any such foam in 2017–2022 (Cumbria CC, 2022).

The National Fire Chiefs Council (NFCC) is an independent membership association who supports FRS through representing their members needs in development, policy support and production of guidance. One of these guidance documents is the Environmental Protection Handbook (NFCC, 2015). This document sets out how the FRS can protect the natural environment during their work, from planning for incidents to on the ground measures during a fire. Incident commanders must consider the environmental and health implications of using foam when considering the firefighting strategies. Considerations include the requirement for foam against alternatives, controlled burning, foam quantity, application, foam concentration, and foam run-off prevention. Collaboration with municipal authorities and sewerage service providers is necessary for effective run-off containment and treatment. During an incident every effort should be taken to prevent firefighting foam from entering surface and groundwater because of its high BOD, potential toxicity, and other polluting effects (NFCC, 2015). However, in many of the locations where the FRS use foams, there is no opportunity to completely contain the firewater, with the exception of large industrial plants which are subject to COMAH, or airports. The guidance, which does set out the legislative requirements around waste disposal, including hazardous waste, does not specify what disposal method should be used for the firewater which contains PFAS foam, and the Agency does not have any information on how the firewater is disposed of. This will be further explored during the consultation phase.

3.1.6.1.2 Industrial / commercial sites

The FRS attends fires at industrial sites, some of which will be COMAH sites, which are discussed in more detail in COMAH section. Other industrial sites, including commercial properties, waste sites and smaller sites which contain flammable liquids, are not subject to COMAH.

3.1.6.1.3 Transport network

The transport sector comprises the rail and road network, road freight, commercial and public vehicles, receipt of goods from ships at ports and petrol stations. Generally, fires on trains or train tracks would be attended by the FRS using their own equipment and foams.

Most UK road tunnels use a high-pressure water system for fire management, including the Tyne and Dartford tunnels (Highways England, 2016; Tyne Tunnels, 2018). The New Tyne Crossing was the first fire suppression system to be installed in a UK road tunnel (FOGTEC, 2017). Therefore, there is not expected to be any PFAS releases from these fixed systems.

The Channel Tunnel does have a PFAS-based foam suppression system in the tunnel, but although still active, it is being replaced by a water drench system. There is PFAS foam on the rolling stock, but this is currently being replaced by a halon replacement system (stakeholder meeting, Office of Rail and Road (ORR), June 2024). If the system in the tunnel is activated, the foam / water is collected in the drainage system for treatment, although there is no information on what this treatment might include.

The Agency does not have any information on fire suppression systems in other rail tunnels and will be following this up following publication of the Annex 15 report.

3.1.6.1.4 Training

FRS also undertake regular training of their staff at their own training facilities, some of which will be using foams. There is also the Fire Service College in Moreton-in-Marsh, Gloucester, where more specialist industrial-based training is done (FSC, 2024). There are a number of other specialist sites such as the Fire Service College in the Cotswolds (FSC, 2024), Newcastle International Training Academy in Tyne and Wear (NITA, 2024) and the International Fire Training Centre in County Durham (IFTC, 2024), where more advanced and intensive training takes place. Training sites are generally located in dedicated areas with hard standing and managed drainage.

A number of foam manufacturers supply fluorine-free training foams, for example Trainer E-lite^{TM} from Fomtec (Fomtec, 2025) or Trainol^{TM} 3 and 6 from Angus Fire (Angus Fire, 2025a, 2025b). However, there are no requirements for the FRS to use these during their training exercises and it is possible that PFAS-containing foams are still being used for training at a number of FRS sites. At least one FRS does use up PFAS-containing foam as it reaches the limit of its shelf life (SWFRS, 2019).

The foams used for training are now generally fluorine-free, but the Agency does not have any information on the current or historic containment of foams used at these training centres and therefore does not know how much PFAS has been (and is still being) released from them. Guidance from the NFCC states that foams used during training or exercises should not be allowed to enter surface and/or groundwater (NFCC, 2015).

3.1.6.1.5 Conclusion

The use of FFF by FRS, either for training purposes or on a fire, will result in releases to the local environment unless the sites have sufficient containment measures. Depending on the location, these emissions could be to surface water, soil and groundwater or to sewer. The concentrations of PFAS in the local areas around training facilities or very large incidents would be expected to be higher than the general background levels, further information on this can be found in Section 3.1.10.

3.1.6.2 Petrochemical, chemical and industrial sites

3.1.6.2.1 Overview

The Control of Major Accident Hazards (COMAH) Regulations 2015 implement the European Seveso III Directive within the United Kingdom. They aim to prevent major accidents involving dangerous substances and to mitigate the effect on people and the environment of those that do occur. They apply to establishments that store or handle large quantities of a broad range of substances of a hazardous nature (including explosives, self-reactive substances and petroleum products). Two categories of establishments exist under COMAH, Upper and Lower Tier, based on the nature and quantities of dangerous substances handled. Lower Tier sites are required to provide details on planning for emergencies in a Major Accident Prevention Policy (MAPP), whilst

Upper Tier sites are required to provide a MAPP as part of a safety report, as well as further details of measures such as firefighting, to limit the consequences of any major accident that may occur, both to people and the environment.

As of May 2024, there are approximately 350 COMAH Upper Tier Sites and 525 COMAH Lower Tier Sites in the UK (What Do They Know, 2024). COMAH Upper and Lower Tier sites can include establishments as diverse as large chemical and petrochemical sites, oil and gas production and storage, explosives manufacturing and storage, water companies, distilleries, nuclear power generation and large-scale storage of dangerous substances. Firefighting provisions at COMAH sites can differ. Many of these sites are likely to have stocks of FFF (Eftec, 2019).

Active fire protection systems such as water sprinklers and spray systems are widely used for protection of storage vessels, process plant, loading installation and warehouses. Some situations will require foam pourers or fixed water spray nozzles, known as monitors, or specialist inert gases and halogen based systems, the latter of these are not in scope of this restriction (HSE, 2024). The operator is required to implement and demonstrate effective and practical firefighting plans taking into account factors such as the fire hazard of the substance(s) handled, the toxicity of the substance(s) and the smoke product, inventory size, frequency of hazardous operations, distance to other hazardous installations, available access to fight a fire, firefighting capability of the on-site emergency response team, response time of the nearest fire brigade and the resource they have available. Firewater capture should be considered within the design of the site when active fire protection systems are installed to minimise environmental damage, with a disposal plan in place for collected waste. There is a requirement for bunds to have a minimum capacity of either 110% of the capacity of the largest tank or 25% of the total capacity of all the tanks within the bund, whichever is the greater, to allow for tank failure and firewater management (SEPA *et al.*, 2008).

According to the UK Protocol for Disposing of Contaminated Water and Wastes at Incidents (Water UK, 2018), it is necessary to take all reasonable efforts to contain contaminated or potentially contaminated runoff from any site. The COMAH Regulation further specifies that firewater lagoons must contain potentially toxic firewater. As a result, it is safe to assume that industry actors have implemented and will continue to implement firewater containment measures, regardless of the type of FFF used.

A number of companies who operate COMAH sites responded to the call for evidence to indicate that while several UK oil refineries are currently using PFAS foams, other sites have already transitioned to fluorine-free alternatives.

Some sites also have their own emergency response teams who are trained in firefighting. Some training potentially takes place on site, although there are also external specialist training organisations who offer offsite training (Cotswold Airport, 2024; FSC, 2024; IFTC, 2024). The FRS can also be called in and some large chemical sites have mutual aid agreements whereby the foam stored on their site can be used by either their own emergency response teams or the FRS.

The Agency does not know how may sites currently have stocks of PFAS-containing firefighting foams, how many sites undertake training on their own sites or how much foam has been used on live incidents on these sites.

3.1.6.2.2 Ports / docks

There are approximately 120 commercial ports in the UK (Maritime UK, 2024; accessed 16/12/24). Added to this, there are over 400 non-cargo handling ports and harbours around the UK. Approximately 40 % of cargo handled by UK ports is liquid bulk, according to the Port freight annual statistics 2022 (DfT, 2022) which equates to around 180 million tonnes. Liquid bulk encompasses materials such as liquified natural gas (LNG) and oil products such as derivatives of petroleum (diesel, gasoil, aviation fuel and gas condensate). Many of these sites are also COMAH sites, hence they are described in this section.

Legislation surrounding loading and unloading cargo is overseen by HSE, and movement of dangerous goods through ports and harbour areas is regulated by the Dangerous Goods in Harbour Areas Regulations 2016 (DGHAR) (UK Government, 2016a). However, when at sea, the Maritime and Coastguard Agency (MCA) oversee all aspects of safety onboard, including firefighting provisions. The “bulk transfer of dangerous liquids and gases between ship and shore” guidance document (HSE, 1999) addresses firefighting requirements with specific mention of firefighting foams (discussed further below). Prior consultation with the fire brigade is recommended to assess firefighting needs and separation between cargo transfer facilities and site boundaries are advised. The fire brigade will assume responsibility for fires once they arrive on site.

Milford Haven, the largest liquid bulk handling port in the UK, is equipped with a number of tugs which are equipped for firefighting (Port of Milford Haven, 2024). They can also be used in certain circumstances to supply firefighting water to industrial plants located at ports. At Milford Haven, firefighting facilities are available at berths owned by individual companies, which include tower mounted foam/water monitors (Puma Energy, 2020). The HSE guidance “The bulk transfer of dangerous liquids and gases between ship and shore” HSG 186 recommends foams for spill fires and the use of foam or dual foam/water monitors and further state aspirated low-expansion foam to prevent re-ignition (HSE, 1999). AFFF are recommended when greater reach is essential, as these foams can be used unaspirated.

Factors to consider for the volume of foam a site requires include availability of back-up supplies, ease of access to the berth and cost, all of which will vary between sites, but sufficient foam should be stored to supply all monitors covering one berth to allow complete evacuation of the vicinity (HSE, 1999).

It is unclear what firefighting provisions and the requirement for FFF exist at GB ports as a whole – further engagement with stakeholders is required.

3.1.6.2.3 Routine testing of equipment

In the call for evidence, information was supplied regarding a paper mill which had a stock of 1000 L of PFAS-containing foam concentrate on site for the past 15 years, and which used 1 L per year during an annual service (Call for evidence, CPI).

3.1.6.2.4 Conclusion

The Agency has no information on the amount of PFAS-containing foams typically released annually from petrochemical and chemical industry sites within GB either due to training activities or tackling live incidents. The fire at Buncefield did lead to environmental release of a large amount of PFAS, more information on this can be found in the Buncefield case study (See Buncefield Section). However, due to the materials held on these sites and the need to protect lives and property, PFAS-containing foams do have the potential for use and therefore release into the environment.

3.1.6.3 Offshore

3.1.6.3.1 Overview

The offshore sector encompasses oil and gas drilling platforms and rigs, floating production storage and offloading (FPSO) and pipelines. FPSO are floating vessels, sometimes converted tankers, for the storage and processing of oil and gas.

There are approximately 300 oil and gas fields in the UK Continental Shelf (UKCS) (UK Government, 2019). It is understood that for GB, there are 143 manned operational offshore oil and gas platforms (either fixed or floating) that HSE regulates on the continental shelf outside of GB waters, which use integrated firefighting foam systems (internal communication, HSE, May 2024). Offshore Energies UK (OEUK) stated that at any given time some 20,000 people are present on offshore installations (usually 75 – 150 people per installation), located 75 – 200 km from the mainland (Call for evidence, OEUK).

The presence of oil and combustible gases on offshore platforms and floating vessels present a serious risk of fire and explosion. This includes gases released from wells, production equipment or surface equipment such as tanks and shale shakers. Additionally, there will potentially be large capacity hydrocarbon fuel storage tanks for plant and vessel operation. In the case of FPSOs, large amounts of crude oil and gas are stored on the vessels and fire protection is required for process areas, accommodation modules, power generation and product transfer.

ECHA observed that for the offshore sector there is potential for extensive environmental pollution in the event of an uncontrolled fire (ECHA, 2023b). However, they also observed that where PFAS-containing foams are used there is limited potential to collect the firewater, making direct environmental releases of PFAS more probable. This was confirmed in our call for evidence where information was provided that initially, following training or system activation for in-service testing, the foam is sent to a drainage system and then discharges into the sea (Call for evidence, OEUK). Such testing (and associated release) may be required at regular intervals, such as annually. A second respondent stated that foam is not used for training offshore by their company (Call for evidence, OEUK).

The southern end of the North Sea consists of mainly unmanned gas platforms. These have no integrated firefighting systems and only have portable firefighting equipment on the helidecks. As such, the number of landings per year is limited by the Civil Aviation Authority and therefore the quantity of foam that could be released is reduced (internal communication, HSE, May 2024).

One of the design requirements of a helideck is a capture system that captures run off firefighting foam (so it does not enter the water). Use of foams is largely centred to the helidecks, but some of the bigger platforms have foam systems/'rings' that run throughout the platform. For gas-only platforms, there is no integrated foaming system aside from the helidecks. For drilling, these are mobile installations that use foaming systems on helidecks (internal communication, HSE, May 2024).

3.1.6.3.2 Conclusion

Releases from the offshore sector are emitted directly to the marine environment as there are no control or containment measures possible on offshore infrastructure.

3.1.6.4 Marine

3.1.6.4.1 Overview

The marine sector is defined in this document as all civilian sea going or inland water vessels, which would also include vessels used for firefighting such as tugs stationed at ports. The provision for naval vessels is covered by the military / defence applications below. On civilian vessels, rapid control and suppression of any fire to avoid spread, further damage and likely risk to human life is essential. The vessels vary in size from small craft to ferries, tugboats, large oil tankers and container ships, and some of these carry hazardous or flammable materials. Marine fire-suppression systems incorporating foam include mobile (e.g., handheld extinguishers and hoses) as well as fixed systems such as monitors or fixed foam distribution systems, which are generally used on larger vessels. With the exception of handheld extinguishers, it is expected that foam concentrates must be compatible with seawater where the vessel operates in a marine/saline environment (Maritime and Coastguard Agency, 2023). Foam fire-suppression systems can entail onboard use (for example engine room, galley or fuel tank fires) or as part of fire-safety and rescue boat systems.

For marine applications, it is assumed that for both live incident and training exercises there is little possibility to retain run-off, and it is allowed to flow directly into the sea with no capture and control. During a fire drill, a proportion of the onboard portable fire extinguishers are discharged each time (Maritime and Coastguard Agency, 2023). The Agency has no information on whether there is any containment of this foam. In a discussion of transition periods, Wood (2020) suggests that marine applications should be a priority for a quick transition partly as the potential for retention of runoff and clean-up after incidents is particularly low.

3.1.6.4.2 Conclusion

Releases from this sector are expected to be to the marine environment as there are no control measures in place.

3.1.6.5 Aviation

3.1.6.5.1 Overview

The Civil Aviation Authority (CAA) requires the provision of fire and rescue services at airports and the use of foams meeting International Civil Aviation Organization (ICAO) criteria based on airport size. There are 60 airports in GB (CAA, 2023). The primary goal of an on-site fire and rescue service at airports is to save lives. As a result, the availability of procedures for dealing with an aircraft accident or incident that occurs on or near an airfield is critical. These must always be based on the possibility and necessity of putting out a fire, which could happen during rescue operations or immediately after an aviation accident or event (CAA, 2022). The fuel storage areas on a number of airports are also categorised as COMAH sites, including Heathrow, Gatwick, Manchester and Glasgow (What Do They Know, 2024).

In Aircraft Rescue and Firefighting, key factors for controlling/extinguishing Class B fires are the time required for the foam agent to effectively suppress the fire and the length of time that the suppression can be maintained. As well as mobile firefighting systems for aircraft crash rescue crews might incorporate hose systems, or monitors/tenders/fire engines. Aircraft hangars can also incorporate fixed foam dispersal systems where concentrate is drawn from a tank and proportionated with water before dispersal through fixed nozzles to distribute around the hangar.

Airports have been identified as a significant source of PFAS in the environment (da Silva *et al.*, 2022) and as a leading source of PFAS contamination in local environments (Environment Agency, 2021). In particular, higher levels of PFAS in soil and groundwater have been associated with airport fire training areas (Ahrens *et al.*, 2015), including PFOS, the use of which has been banned since June 2011 (Environment Agency, 2021).

Training is usually undertaken on dedicated hard surfaced areas within the airport boundary. The maintenance and containment of training areas on airports is variable, with some having bunding to minimise releases and systems to collect/ treat runoff (i.e., reed beds then discharge, holding lagoon to recirculate and reuse water, or divert to foul water), while others do not have any measures in place. The Agency is unaware of any airports which currently treat their contained training area wastes for PFAS.

Other potential sources of PFAS at airports include releases from live incidents and storage / movement of the foams around the site (Environment Agency, 2021). Newcastle Airport hosts the Newcastle International Training Academy in Tyne and Wear (NITA, 2024) and this will lead to additional foam usage and potentially release from the site. In addition, 3FFF tests their new foams at Norwich Airport (stakeholder meeting, Last Fire June 2024) and this leads to additional foam usage and potentially release from the airport.

The CAA has published a document containing guidance on managing the responsibilities and liabilities of PFAS on airports for the sites they regulate (RPS Group, 2024). This contains information on the work being done by the Environment Agency to better understand the level of land contamination involved, releases from airport operations and changes to legislation, including the POPs Regulations. The document advises that airports should better understand their risk of PFAS contamination and releases and take steps to manage these risks.

The potential emissions as a result of use on airports is demonstrated by the case studies in Section 3.1.10 and Annex E.9 on Heathrow Airport and Duxford Aerodrome. There is also evidence of exposure in other European airports (ECHA, 2023a) (ECHA, 2023e). For example, in Kallinge-Ronneby Military and Civilian Airbase, Sweden, highly elevated levels of PFHxS, PFOA and PFOS were found in the local area drinking water supply (e.g. up to 8 µg/L for PFOS) (Nordic Council of Ministers, 2019). The fire drill site at the adjacent military airfield, where PFOS-containing AFFF had been used since the 1980s, was found to be the cause of the contamination (ECHA, 2023e; Nordic Council of Ministers, 2019).

A number of GB airports have transitioned to fluorine-free foams in recent years. These include Blackpool, Bristol, Edinburgh, Gatwick, Leeds-Bradford, London City, London Heathrow and Manchester (IPEN, 2019). Others, such as the Highlands and Islands Airports hold C6 foams but are currently in the process of procuring PFAS free foams (Highlands and Islands, call for evidence). A survey of large aerodromes undertaken by the CAA found that 71 % now use fluorine- and organohalogen-free foam concentrate. This shows that there has been a transition in the aviation sector, although there are still some concerns from some of the smaller airports regarding their infrastructure, in particular their deluge systems (CAA, 2024). It is anticipated there will be minimal PFAS releases from current or future activities from the sites that have already transitioned to alternatives, with the exception of any contamination levels in the legacy equipment. However, there will be potential releases resulting from the historical use of PFAS foams, due to soil / water contamination.

3.1.6.5.2 Spaceports

Legislation governing spaceports includes the Space Industry Act 2018 (UK Government, 2018), which regulates a wide range of spaceflight technologies, including traditional vertically launched vehicles, air-launched vehicles, sub-orbital spaceplanes, and balloons. The UK-US Technology Safeguards Agreement, (TSA) (UK Government, 2020), allows US companies to operate from UK spaceports and export space launch technology. Other international partnerships include Ireland, Iceland, Portugal, the Faroe Islands and Norway to enable UK launch activities.

Currently, there are seven spaceports in GB. Of these, 4 have facilities for horizontal launch mode, which the Agency understands would lead to the use of conventional aviation fuels and therefore the potential for PFAS-containing FFF use and exposure.

The Agency understands that horizontal launch carrier aircraft will use traditional aviation fuels and be subject to firefighting measures of corresponding aviation sector requirements at Cornwall Airport Newquay, Cornwall; Snowdonia Aerospace Centre; Campbeltown Airport; Glasgow Prestwick Airport.

Vertical launch facilities will require fuel and propellant storage. Preliminary research has identified liquified gases, including bio-propane (UK Space Agency *et al.*, 2023) but also RP-1 and RP-2 which are refined forms of kerosene (Haltermann, 2021). The Agency considers there is therefore a possible use for foams on liquid fuel fires. Some of the locations are coastal, so there is potential that they may require seawater compatible foams, but the Agency does not have information to verify this.

3.1.6.5.3 Conclusion

The releases of PFAS to the environment from aviation sites are now generally from historic contamination as many of the airports have already transitioned to fluorine-free foams. On those sites that have not yet transitioned (approximately 30%), releases to the environment will still occur, unless all emissions are contained and the PFAS are treated. Awareness of the issues of PFAS contamination at airports is increasing due to work being done by the Environment Agency.

3.1.6.6 Military / Defence

3.1.6.6.1 Overview

Military / defence is defined as the use of FFF on land either owned by the Ministry of Defence (MoD), or where the MoD has rights to the land or assets owned by or operated on behalf of the MoD. There is a wide variety of assets within this, including army bases, training bases, airforce bases, naval combat and resupply vessels, land and sea defence fire services and bulk fuel storage areas. Firefighting capabilities are provided by Defence Fire and Rescue, which comprises military and civilian personnel (DFR, 2024). Defence/military applications do, however, present certain unique circumstances compared to other sectors, such as the potential presence of flammable liquids, ammunition, high explosives, pressurised gases, and people in close proximity, which necessitates exceptionally prompt fire control to prevent incident escalation. Timing and extinguishing effectiveness may also be more important while combating fires in a range of climates and under hostile circumstances (ECHA, 2023e).

Releases of FFF from military assets are varied. The release pattern for onshore bases are similar to civilian airports and training centres as there is a concentration of use in a relatively small area, generally the fire training area or where active fires have taken place. There could also be contamination of drainage or water collection systems. Defence Infrastructure Fire Standards require aircraft hangars to have automated fire suppression systems (DSA, 2024).

The emissions from naval vessels are similar to the marine sector, where the foams are likely to be released into the sea. Use of FFF on naval vessels covers protecting the runway and aircraft bays on aircraft carriers, helidecks on smaller vessels and other areas where the need is identified. Fixed and mobile foam fire suppression systems are also used in military naval vessel aircraft hangers and on the aircraft dispersal and flight decks (Darwin *et al.*, 2005).

The MoD uses fire extinguishers with PFAS-containing foam in office spaces, kitchens, etc., and foam is used widely across MoD sites for firefighting (MOD, 2018). When these extinguishers are used it is unlikely that it will be in an area where containment of the foam is possible, so releases from this are expected.

In the Defence Fire & Rescue Structural Fire-fighting Regulations (2024) there is a requirement that the "foam products should be free of any PFOA, PFOS and PFAS, or any derivative that is persistent in the environment (there should be no acceptable lower limit or threshold)". Further, it requires that the "foam solution should be acceptable to the local water utilities for discharge into the foul sewer. Where this is not possible, during training [where foam effluent cannot be captured during training, the training should not take place] and operational use, the fire-fighting effluent (where possible) should be captured to minimise, the impact on the environment and reducing the risk of enforcement action from an environmental release". However, "alternative approaches may be utilized where this produces an outcome as good as required by the regulation" (DSA, 2024). This shows that future releases should be reduced as PFAS-containing foam is replaced in all the applications where alternatives already exist.

3.1.6.6.2 Conclusion

The MoD has a wide range of assets which require fire protection, often under challenging and hazardous conditions, such as on active operations, or jet fuel storage areas on naval vessels. PFAS-containing FFF have been used on many of these sites and will have resulted in releases (as seen in the other sectors), but in general they are moving to alternatives.

3.1.6.7 Ready-to-use

3.1.6.7.1 Overview

The ready-to-use sector primarily consists of handheld and portable fire extinguishers. Handheld fire extinguishers, using existing PFAS-containing FFF foam, are found ubiquitously in residential and commercial settings and provide firefighting capability against Class A (flammable solids e.g. paper, wood) and Class B (some flammable liquids e.g. petrol, diesel. There are unlikely to be containment measures in place for many of the situations where the extinguishers are used on fires and therefore the foam will be released into the wastewater system or soil. The quantity of foam released is expected to be small in this situation.

The Environment Agency issued a Regulatory Position Statement (RPS) in March 2023 allowing companies whose main business is supplying and maintaining fire extinguishers to store and treat waste fire extinguishers before metal recovery in the absence of an environmental permit for a limited period of time (Environment Agency, 2024). This was only valid in England. The deadline for application for an environmental permit to operate a waste site recycling fire extinguishers was September 2024. During the determination of these applications the sites can continue to operate on the condition that the site must not pollute the environment or endanger human health, and it must not endanger water, air, soil, plants, animals, noise, odours, or negatively impact the countryside or particular locations.

The main condition that the operator must meet is that during the refurbishment or disposal of fire extinguishers any foam, water or separated fractions that could contain PFOS, PFOA or PFHxA should be collected and disposed of via high temperature incineration (Environment Agency, 2024). It also states that no foam should be discharged to sewer, whether or not it is thought to contain POPs; and release to land is already prohibited. Therefore, since the PFAs waste should be sent for high temperature incineration, there should be no environmental releases of PFAS from the recycling stage in future.

3.1.6.7.2 Conclusion

Releases from the ready-to-use sector are varied. Where training, testing or use is undertaken on industrial, professional or residential sites containment of the foams is unlikely and, therefore, they are expected to be released to either sewer or soils. For refurbishment and recycling sites, the Environment Agency RPS requires that all foams that may contain PFOS, PFOA or PFHxA should be collected and disposed of via incineration, and that no foam is discharged to sewer, so releases should be minimal. The Agency has no information on how many fire extinguishers are sold or used, and no information on how many extinguishers are recycled each year.

3.1.7 Rebound

Owing to their physicochemical properties PFAS can form water-resistant layers on the inner surfaces of fire fighting equipment and systems, which are difficult to remove by water flushing alone. As a result, “rebound” of PFAS into replacement F3 has been observed, originating from prolonged contact within firefighting equipment that has previously used PFAS-containing FFF even after flushing out with water (Lang et al., 2022; Oshaughnessy and Calveley, 2024; Ross, 2023; Ross and Storch, 2020). This means that firefighting equipment and systems (i.e. tenders, monitors, tanks, pipework, hoses, nozzles, etc) can continue to be a source of PFAS even after they have been emptied and cleaned and alternative F3 foams used. Further details of the potential for rebound, concentrations observed and decontamination techniques are detailed in Annex E.11.

The potential for rebound of PFAS means that even after transition from PFAS-containing foams there may be continued environmental emissions from these sectors.

3.1.8 Conclusion for the releases of PFAS-containing foams

In all sectors, PFAS-containing foams have the potential to reach the environment during storage, live incidents, training or maintenance, either directly, or via subsequent disposal into the sewer network. The total amount released has been estimated at 48 tonnes based on total sales, but environmental concentrations have not been modelled as the agency does not have sufficient details of the quantities used by the different sectors, where PFAS-containing foams are currently used, the number of times they are deployed or what levels of containment and subsequent disposal are in place. There is a large variety and number of sites where FFF could be used. Steps are being taken in some sectors to phase out PFAS-containing foams, and there is some guidance in place to encourage disposal via high temperature incineration, although the extent to which this occurs is unknown.

3.1.9 Waste and waste disposal

3.1.9.1 Emissions from waste

As previously described in Section 3.1.3, emissions can result from all life cycle stages and some of these will end up in waste streams. In addition, disposal of unused foam concentrate and cleaning operations (e.g. drained foam solutions, decontamination washes and rinsate) or replacement of firefighting equipment that has previously held PFAS-containing liquids (e.g. solid wastes such as pipes, nozzles, tanks, containers, equipment and appliances) may result in PFAS emissions.

The majority of PFAS are not designated POPs, nor classified under GB CLP, and the low concentrations involved mean it is unlikely for hazardous waste classifications to be triggered. Therefore, PFAS-containing foam wastes could potentially result in releases to sewer or landfill.

There are significant technical challenges to removing PFAS from wastewater (HSE, 2023). The Agency considers that WwTPs have no ability to fully mineralise PFAS (i.e., complete defluorination) and, therefore, any release to the wastewater system will result in direct discharge to the environment via sludge (and thereby to soil) and effluent (to surface water) (see Section 2.4.3). Volatile PFAS may also be emitted to air from WwTPs and then may have the potential for long range transport (see Section 2.4.4) (Arvaniti *et al.*, 2014; Campo *et al.*, 2014; Lenka *et al.*, 2021). ECHA considers that the total environmental emission arising from the wastewater system is the same as if firewater/foam concentrate could not be collected, i.e. a 100 % release to water (ECHA, 2023a).

Similarly, PFAS substances are detected in raw landfill leachates in many non-hazardous landfill sites in England. Modern hazardous and non-hazardous landfills are designed to contain the liquid and gas products of waste biodegradation. Cells are designed with a geological barrier, bottom and sidewall liners, leachate drainage blankets, gas extraction and impermeable caps. However, older landfills (pre-2001) were built to lower engineered standards; pre-1990s sites were designed on the principle of ‘Dilute and Attenuate (Disperse)’, allowing for the discharge of liquids and gases through the base, sidewalls and tops of the landfills. A recent study of UK landfills provides evidence of widespread PFAS contamination (Defra *et al.*, 2024); all 35 samples of leachate from 24 operational, closed, and historical landfills contained concentrations of PFAS ranging from 1.04 to 107 µg/L (median of 14 µg/L). The Landfill Leachate project (Defra *et al.*, 2024) found PFOA (a long chain PFCA), PFHxA and PFBA (short chain PFCAs) and PFBS (short chain PFSA) to be among the five PFAS that dominated the contamination (together accounting for 85 – 90 % of the total PFAS in most samples). Where non-hazardous landfill leachate (both raw and treated) is discharged to a WwTP, it also undergoes treatment and potential transformation before final discharge to the surface water and/or sludge to land.

The Environment Agency is planning further work to establish whether to intervene regarding PFAS-containing wastes at landfills in England and is also planning further investigations into the presence of PFAS being released via landfill gas. The US EPA has published some preliminary studies (US EPA, 2024b) indicating the presence of PFAS in landfill gas from landfills in the USA (personal communication, Environment Agency Waste Regulation, Jan 2025).

Based on the above discussion, the Agency considers that it is probable that PFAS from non-hazardous landfill leachate will enter controlled waters from either non-direct discharge via WwTP, or direct discharge to groundwater/surface waters from leachate treatment plants with discharge consents, or from older (non-contained) landfills. It is also likely that PFAS are being discharged to land via sludges.

3.1.9.2 PFAS Waste Disposal Methods

Disposal methods for dealing with PFAS-containing liquids effectively fall into two categories: destruction (e.g., incineration) and sequestration by separating and concentrating PFAS molecules from solution (e.g., granular activated carbon, ion exchange resin, stabilisation in cement), which would ultimately need to be disposed of appropriately depending on the technology.

The high stability of the carbon-fluorine bond presents significant challenges to achieving complete destruction (≥ 99.9 % degradation) such that temperatures ≥ 1,100 °C and residence times of 2 to 3 seconds are required to achieve mineralisation of PFAS to carbon dioxide and hydrogen fluoride (ECHA, 2023e; Held and Reinhard, 2020; Meegoda *et al.*, 2022). Incineration of PFAS wastes is therefore energy intensive and can release greenhouse gases due to emissions from energy usage. If incineration temperatures are too low and/or residence times are inadequate, then destruction will be incomplete. Products of incomplete combustion (PICs) include shorter chain PFAAs and other fluorinated species, some of which are extremely potent and persistent greenhouse gases (Davies *et al.*, 2024; ECHA, 2023e; Stoiber *et al.*, 2020). For example, it has been reported that incineration of PFOS at 900 °C can generate fluorocarbons such as CF_4, C_2F_6, CHF_3 and $C_2H_2F_2$ (ECHA, 2023c). Unattenuated (i.e. intact) parent PFAS may also be emitted to atmosphere or to bottom/fly ash, which may be landfilled providing additional pollutant pathways to controlled waters and land. However, whilst quantitative analysis of emissions of PFAS and PICs as a result of incineration has not yet been undertaken, it has been reported that the quantity of PFAS measured in bottom/fly ash is very low, in the pg/g range. In the EU, ashes from high temperature incinerators are commonly reused in construction, e.g., for road construction or as cement aggregate; or sent to landfills (approximately 70% of ash is disposed of in landfills in Germany) (Environment Agency, 2025). However, it is the Agency’s understanding that ash from hazardous waste incinerators (HWI) is not reused in construction materials in GB. Additionally, there is uncertainty regarding the fate of PFAS in liquid waste streams from incineration as the high temperatures required may result in loss of PFAS through steam discharge from the stack (Ross, 2020).

ECHA considered that PFAS destruction efficiency from thermal treatment is not 100 % and assumes an emission factor of 1 % with emitted PFAS going to air or found in the bottom/fly ash (ECHA, 2023a, 2023e).

A study to assess the destruction efficiency in UK Energy from Waste incinerators was unable to draw any robust conclusions regarding the destruction of PFAS-containing materials but concluded that a *"specific PFAS-rich feedstock trial would be required to evaluate the PFAS destruction efficiency"* (Davies *et al.*, 2024). Monitoring and analysis of emissions from incineration of PFAS wastes to demonstrate complete destruction are challenging. Inadequate analysis protocols risk failing to detect multiple PFAS species, reporting false negatives and incorrect destruction efficiencies. According to the US EPA (US EPA, 2021), *"the current lack of standardized methods to measure PFAS emissions and the limited availability of data on the performance of methods to measure PFAS introduce uncertainty in the understanding of the release of PFAS into the air from these sources. The lack of validated stationary source measurement methods for PFAS also leads to inconsistent findings, incomparable measurements, and lack of coordination between policy makers, facilities and control technology development"*. The US EPA is currently undertaking a detailed review of incineration and has developed analytical methods: Other Test Method 45 (OTM-45) for semi-volatile polar PFAS, and OTM-50 for volatile non-polar PFAS (US EPA, 2021, 2024d). It is understood that OTM-55 is under development *"for non-polar semi-volatile and non-volatile PFAS compounds, including fluorotelomer alcohols"* (Envirotech, 2023; Trozzolo and Howard, 2024).

In GB, there is a shortage of HWI with currently only two in operation capable of running at the requisite temperatures to destroy PFAS (Environment Agency, 2025). These are permitted installations regulated by the Environment Agency and located in Southampton and Ellesmere Port. Both installations use a two-stage procedure: initial thermal desorption followed by catalytic oxidation in the secondary combustion chamber to achieve mineralisation (Environment Agency, 2025). In November 2024, the Environment Agency issued permit variations (EPR/SP3409LC/V005 and EPR/FP3935KL/V012) for the two HWIs to ensure that a minimum secondary combustion chamber of 1,100 °C is maintained when burning waste firefighting foams. In the call for evidence response Fuels Industry UK expressed concerns regarding the UK's limited HWI incineration capacity, and lack of information from the regulators on management and disposal of PFAS in FFFs which may lead to a waste management / stockpiling issue for the companies (Call for evidence, Fuels Industry UK). There are options for regulatory actions that would allow for the export of these PFAS wastes for incineration or any new equivalent treatment techniques, pending increased UK capacity.

Similarly, the Chemical Industries Association (CIA) felt that many companies would face difficulties with the disposal of PFAS-containing FFFs due to additional costs (Call for evidence, CIA). Potentially additional containment facilities would be needed while waiting to dispose of stocks that could not be immediately incinerated due to the lack incineration capacity, which in turn would generate additional costs. However, a report undertaken on behalf of the Environment Agency (WSP, 2023) suggests that GB stocks of PFAS-containing foams (anticipated to be between 10,800 to 20,800 tonnes) would account for between 5 to 20 % of GB's annual incineration capacity. The report concluded that even though other competing waste streams such as those related to the POP Regulations would need to be taken into account it was unlikely there would be significant capacity shortages given the likely transition timescales (WSP, 2023).

Some questions remain regarding the efficacy of HWI to fully degrade PFAS. In the USA, the 2020 National Defence Authorisation Act required the DoD to phase out PFAS-containing foam by October 2024 (Miller, 2024). The US EPA had concerns regarding the lack of studies of real-world incineration scenarios and the lack of understanding of byproducts formed during the process (US EPA, 2020). In April 2022, the DoD issued a temporary moratorium suspending the incineration of materials containing PFAS, specifically PFAS-containing firefighting foams. The moratorium will remain until the DoD issues guidance implementing the EPA interim guidance on the destruction and disposal of PFAS (US DoD, 2022, 2024b).

The interim guidance published by the US EPA in April 2024 provides a comprehensive review of destruction and disposal technologies for PFAS. Regarding incineration, it concludes that *"thermal treatment units operating under certain conditions are more effective at destroying PFAS and minimizing releases or exposures"*, but recognises uncertainties remain. It encourages additional testing with validated methods (e.g., OTM-50) for PICs and PFAS to evaluate environmental emissions (US EPA, 2024a). Similarly, the Environment Agency systematic scoping review concludes that high-temperature incineration has the potential to achieve near complete destruction of PFAS, but stringent operational controls and further research are necessary to address safety and effectiveness concerns (Environment Agency, 2025). Further information on waste disposal methods are available in Annex E.11.2.

As discussed in sections 3.1.9.1 and 3.1.9.2 above, PFAS containing foams are generally not classed as hazardous waste and therefore their disposal is not controlled under Hazardous Waste Regulations (The Hazardous Waste (England and Wales) Regulations 2005).

3.1.10 Detection of PFAS in GB close to known firefighting foam sources

To demonstrate how use of PFAS-containing foams may result in emissions to the GB environment, a series of case studies have been undertaken by the Agency. They cover foam formulation, sites where foam is regularly used (such as airports and fire training centres), and the Buncefield incident (a fuel storage depot that suffered a catastrophic fire where significant quantities of foam were used). Conclusions from each are provided below, with further details available in Annex E.9.

3.1.10.1 Formulation sites

Angus Fire Ltd has formulated FFF concentrates in North Yorkshire since the 1970s, with monitoring data available from 2008. The main releases at the Angus Fire site were likely from the testing of the foams during product development and the on-site lagoons for waste storage. The monitoring data from both the Environment Agency and Ramboll (2018) show that the use of PFAS on site has led to contamination of the water in the lagoons and the groundwater beneath the site. PFOS, the use of which had stopped at the site by 2009, continues to be detected in groundwater. This demonstrates the persistence of PFOS and the ability for PFAS such as PFOS to contaminate groundwater.

3.1.10.2 Airports and airfields

Airports are considered to account for a significant source of PFAS from firefighting foams into the environment as discussed in Section 3.1.6.5. The Environment Agency commissioned a project to sample water courses upstream and downstream of eight UK airports in 2023, with samples analysed for 17 different PFAS including those commonly (or historically) found in AFFF such as 6:2 FTS, PFOA and PFOS. The monitoring data show that these substances have been found at greater concentration in surface water samples downstream than upstream at 7 of the 8 airports. This indicates that, following the use of AFFF at airports, PFAS move through environmental compartments, re-entering water courses downstream from the site of use such that further contamination can be detected.

A further analysis of information relating to AFFF at Heathrow Airport shows that there are hotspots of PFOS contamination on the site arising from legacy use, despite usage stopping over 9 years previously.

The DWI concluded that the use of PFOS-containing firefighting foam on the Duxford airfield has contaminated the local aquifer and subsequently impacted drinking water supplies. The analysis conducted by Cambridge Water and the investigation undertaken by the DWI only looked at PFOS (DWI, 2022a). The Environment Agency monitoring data shows that the groundwater also contains PFOA, PFHxA, PFBA, PFBS and PFHxS (linear), all of which are PFAA arrowheads. This analysis has not necessarily identified all of the PFAS that may be present. As the DWI concluded in their investigation that the PFOS originated from the use of firefighting foams on site the Agency considers it likely that the other PFAS present are from the same source.

3.1.10.3 Fire Training College

The Fire Service College, located on the outskirts of Moreton-in-Marsh village in Gloucester, provides training for firefighters, and advanced training for senior fire officers and industrial staff. Samples taken downstream of the Moreton-in-Marsh WwTP had significantly higher concentrations of PFOS and PFOA than samples taken upstream, or from the WwTP effluent. This indicates that there is an additional source of these PFAS which has not passed through the WwTP and is entering groundwater. Due to the location of and activities undertaken at the Fire Service College the Agency considers it likely that the PFAS detected are from this source.

3.1.10.4 Military sites

The use of FFF on military sites, including fire training areas, has also led to PFAS contamination in surface water and groundwater, as demonstrated by the high levels at the fire training area at RAF St Athan and the identification of FFF as the source of PFAS in the drinking water at RAF Mildenhall.

3.1.10.5 Industrial sites

Buncefield is a large oil storage depot in Hemel Hempstead, Hertfordshire. In December 2005 there were a number of explosions at the site, which led to a catastrophic fire that burned for 3 days. During the operation to extinguish the fire approximately 786,000 litres of firefighting foam were used, of which some contained PFOS. Monitoring conducted on site showed that the firefighting efforts during the incident led to significant PFAS contamination that took a number of years to remediate, and the closure of a drinking water abstraction point. PFOS and PFOA were still found in local soils and groundwater beneath the site in 2014, following the remediation.

Due to the use PFAS-containing FFF the contamination is *particularly long-lasting* being detected at mg/kg levels 9+ years later.

3.1.10.6 Summary

The case studies show that FFF formulation (at least if testing takes place on site), training with FFF, use at airfields and during a large incident have resulted in emissions of PFAS to the environment that remain measurable for many years after the event. The Agency considers that use of PFAS-containing FFF in other sectors would result in similar emission pathways and long-term environmental exposure.

Of particular concern is the potential for PFAS emitted from use in FFF to contaminate drinking water sources, whether that be groundwater or surface water. The case studies from Duxford airfield and Buncefield show that PFAS contamination from use in FFF can result in drinking water abstraction points being closed in order to prevent human exposure. Full details of the case studies are provided in the Annex E.9.

3.2 Human health exposure

The main health concern and justification for the proposed restriction relates to the exposure of humans to PFAS via the environment. The release of PFAS-containing firefighting foams contributes to this global issue. Although not the focus for this restriction, the potential for occupational exposure to PFAS derived from firefighting foams is also discussed briefly in this section as this will also likely be impacted by any proposal to take action on these foams.

3.2.1 Humans via the Environment

Humans are exposed to PFAS via the environment through dietary exposure (ingestion of contaminated drinking water and food), inhalation of indoor air and dust. As described in Sections 2.4 and 3.1, the use of PFAS-containing firefighting foams results in direct emissions to the environment of substances that are persistent, mobile and toxic in their own right and/or when degraded to PFAAs. Because they are mobile in water, these released substances and their degradation products can contaminate drinking water sources and, owing to their persistence, their concentrations are expected to increase over time unless emissions are prevented.

One example of where contamination of drinking water was directly linked with emissions of PFAS-containing foams is Ronneby in Sweden. The use of PFAS-containing foams at a nearby defence airfield from the mid-1980s led to water from one of two municipal waterworks becoming contaminated with PFAS. Samples of the outgoing drinking water taken in December 2013 when use of the contaminated water source ceased revealed high levels of multiple PFAS, including PFHxS, PFOS and PFOA; total PFAS levels in the outgoing water were around 10,000 ng/L. Results from blood samples taken between June 2014 and December 2015 revealed that population geometric means for serum PFHxS, PFOS and PFOA for all Ronneby residents were 135, 35 and 4.5 times higher, respectively, than levels measured in a reference group. The reference group comprised subjects from a neighbouring municipality that was supplied with drinking water that had not been contaminated with PFAS from the airfield, from whom samples were collected in 2016 (Xu *et al.,* 2021). This shows that prolonged exposure to elevated levels of PFAS in drinking water may result in higher body burdens compared with people who drink uncontaminated water.

Data showing links between environmental contamination arising from the use of PFAS-based foams and exposure of the general public are not available for GB. However, Section 3.1.10 and Annex E.9 describe cases where the use of water abstraction sources in GB has been discontinued owing to contamination by PFAS that originated from PFAS-based foams.

Generally, however, it is difficult to link exposure of humans via food and drinking water to the use of PFAS-based foams. These substances enter the environment (and therefore food and water) from multiple sources; typically, it is not possible to separate the contributions made by the use of PFAS-based foams from other sources, especially when PFAS are detected far from potential sites of release.

Nevertheless, exposure via the environment to PFAS that originated from FFF has the potential to contribute to the total body burdens of these substances amongst the general population. Long serum half-lives in people of some PFAS, notably most of the PFAAs (see Section 2.3 and Annex D.2.2, Table D.5), indicate that they would remain in the body for a long time, up to several years in the case of some PFAAs, even if all exposure were to cease. However, when people continue to be exposed via any source, PFAA levels are likely to accumulate and so lead to increasing body burdens.

3.2.2 Workers

Besides exposure via environmental routes relevant to the general population, those who work with or formulate PFAS-containing foams have additional potential sources of exposure.

In addition to firefighters, such workers include those involved in formulating or processing of PFAS into FFF or who clean-up sites where foams have been used once firefighters have moved off them. For PFAS-containing foams, there is potential for exposure by inhalation, skin contact or orally. However, inhalation is the most likely route for exposure of such workers (ATSDR, 2021).

There is some evidence of firefighters having increased serum concentrations of PFAS compared with the general population, although this tends to relate to the older, long-chain PFCAs and PFSAs (Rotander *et al*., 2015b; Trowbridge *et al.,* 2020; Graber *et al*., 2021; Nilsson *et al*., 2022; Burgess *et al*., 2022). Firefighters may be exposed to PFAS in firefighting foams through various occupational routes. These include direct exposure during use and handling, exposure from contaminated personal protective equipment (PPE), handling of contaminated equipment, transfer of foam concentrate from bulk containers to appliances, managing foam wastes, and exposure to PFAS-containing dusts in fire stations. In addition to inhalation and skin contact, accidental ingestion is possible by inadvertent hand-to-mouth transfer if suitable hand-washing is not carried out after handling contaminated firefighting equipment and PPE.

The Agency did not identify information on PFAS concentrations in GB firefighters (literature search strategy presented in Annex D.3). ECHA (2023e) was not able to identify reliable information on measured biological concentrations of PFAS in European firefighters, but reported levels of PFAS in firefighters from the USA and Australia (see Annex D.2, Table D.6). From these studies, ECHA concluded that short-chain PFCAs and PFSAs were mainly measured at around the limit of detection, whereas blood serum levels of long-chain PFCAs and PFSAs were elevated in firefighters compared with the general population. ATSDR (2021) and Health Canada (Health Canada, 2024; plus some additional studies, which are included in Annex D.2 Table D.6) reviewed many of the same studies as ECHA and reached the same conclusions, as did De Silva *et al*. (2021). Information on the composition of the foams was usually not available. The differences that have been observed between detection of long-chain and short-chain PFAAs have not been explained.

Health Canada (2024) compared 13 serum PFAS studies in firefighters to background populations, either US or Canadian background PFAS data, and demonstrated that six PFAS detectable in human serum / urine (PFOA, PFNA, PFDA, PFUnDA, PFHxS and PFOS) were all elevated in firefighters when compared with background populations. PFHxS was the most greatly elevated, followed by PFOS, PFOA and PFDA, which is in line with the ECHA conclusion that was based on many of the same studies. One of the studies reviewed by ECHA (2023e) tracked serum PFAS levels in eight Finnish aviation firefighters exposed to a single AFFF product in a simulation of aircraft accidents (Laitinen et al. (2014)). Serum concentrations of PFOS, PFHxS, PFOA, PFNA and PFDA were elevated after training with the foam. However, the number of participants was very low and therefore no statistical significance could be derived (ECHA determined that the study was unreliable).

In addition to PFAS exposure from foams, firefighters can be exposed from other sources, which can complicate interpretation of biological monitoring and other epidemiological data. One of these pathways comprises the textiles used in firefighter turnout gear. Turnout gear was found to have high levels of total fluorine (up to 2%), and individual PFAS were identified and measured on both new and used firefighting turnout gear. The amount of PFAS in new turnout gear varies depending on the specific textile used in manufacturing (Maizel et al., 2023; Thompson et al., 2024). A follow-up study indicated that wear and tear can increase the release of PFAS from turnout gear compared with release from “unstressed” textiles (Maizel et al., 2023).

Another consideration is that during incidents (and training), firefighters’ protective clothing / turnout gear may become saturated with FFF, which creates significant opportunity for dermal exposure (stakeholder meeting, JOIFF, June 2024). The extent of saturation and duration of wear will impact the contribution of dermal exposure to PFAS body burden. Also, the physicochemical characteristics of different PFAS and the condition of the skin of individual firefighters will influence the extent to which PFAS in the foam or present in the turnout gear are absorbed by the skin (IARC, 2023).

Other potential confounding factors when interpreting biological monitoring data on firefighters include the frequency and duration of use, dependent on the requirements of the role; background environmental PFAS levels; blood donation (which can reduce PFAS body burdens); toxicokinetic differences between males and females, such as elimination via menstrual bleeding; differences in exposures between volunteer and career firefighters (for example, in frequency of foam use, extinguishing methods, PPE, durations of service). There may also be region-specific practices within fire stations and training facilities (Tefera *et al.*, 2022, Mazumder *et al.*, 2023; Muensterman *et al.*, 2022; Yeerken *et al.*, 2019; Young *et al.,* 2021).

There is evidence to suggest that serum PFAS levels in firefighters can decrease over time following transition to PFAS-free foams, but longitudinal data are only available from outside the UK and in a small number of studies (Nematollahi *et al*., 2024; Nilsson *et al.*, 2022; Tefera *et al*., 2023).

3.2.3 Human Exposure Summary

Humans are exposed to PFAS via the environment through dietary exposure (ingestion of contaminated drinking water and food), inhalation of indoor air and dust. The use of PFAS-containing firefighting foams results in direct emissions to the environment of substances that are persistent, mobile and toxic in their own right and/or when degraded to PFAAs. These released substances and their degradation products can contaminate drinking water sources and, owing to their persistence, their concentrations are expected to increase over time and contribute to PFAS exposures at the population level.

In general, it is difficult to link PFAS in food and drinking water to the use of PFAS-based FFF. It is therefore difficult to understand the extent to which the use of PFAS-based FFF contributes to PFAS body burdens. In the case of a cohort in Ronneby, Sweden, it was possible to link PFAS contamination of drinking water to the use of PFAS-based FFF at a nearby airfield. Measurements of blood PFAS levels in residents drinking the contaminated water provided evidence that prolonged exposure to drinking water contaminated with PFAS originating from FFF can result in elevated serum PFAS levels.

Firefighters are at particular risk of direct exposure to PFAS from firefighting foam, especially during training and incidents where these foams are used. The available studies show firefighters have been exposed to PFHxS, PFDA, PFOS and PFOA and experienced elevated serum levels of these PFAS compared with the general population. However, owing to the use of PFAS-containing products in the manufacture of turnout gear, and to non-occupational exposure, it is difficult to identify the contribution that exposure from FFF makes to the total PFAS body burden of firefighters.

ECHA (2023e) concluded that owing to limitations in the available studies, the data are not sufficient to determine if there is or is not a statistically significant association between serum PFAS concentrations and biomarkers of effect or increased risks of disease in firefighters occupationally exposed to FFF (see Section 2.3.3). The studies that have been published since ECHA reviewed the data suffer from many of the same limitations. The Agency considers that although the new data is consistent in the identity of PFAS which appear to be elevated in firefighters, it is still not possible to make an unequivocal link between serum PFAS levels and exposure to FFF.

4 Risk Characterisation

4.1 Risk characterisation

4.1.1 PMT-type concerns

Section 1.2.4 identified that the PFAS used in FFF are all either PFAAs or PFAA-precursors. This means that all the PFAS emitted to the environment from FFF will transform to PFAAs, although this will be over extended time periods. The available hazard information for important PFAA groups (PFCAs and PFSAs) was reviewed in Section 2, as these are the common transformation products of all PFAS in FFF.

Several long chain PFAAs have already been concluded to meet the criteria to be considered POPs, i.e. PFCA: PFOA, C9 - C21 PFCAs; PFSA: PFOS, PFHxS. This includes an assessment of persistence, bioaccumulation, toxicity and long-range travel potential.

From an evaluation of the available hazard evidence the Agency considers that:

- All PFAAs would meet the criteria to be considered vP under UK REACH Annex 13, with transformation half-lives expected to be far in excess of the threshold criteria.
- All PFAAs are sufficiently mobile to reach environmental compartments of concern, which leads to their detection in groundwater and surface water in GB and other countries and the potential to travel long distances from the original source.
- Based on the available evidence, it appears that most PFCAs in the carbon chain length range C2 to C18 meet or are likely to meet the toxicity criterion of UK REACH Annex 13. There are data for far fewer of the PFSAs. However, the toxicological effects of those PFSAs for which information is available are comparable with those of the PFCAs. Given the confirmed or likely toxicity of PFCAs across the span of carbon chain lengths and the similarity of adverse effects of those PFSAs for which information is available, it is concluded that toxicity is associated with substances across both the PFCA and PFSA sub-groups. Furthermore, given the unknown composition of PFAS-containing FFF, formed of complex mixtures, the PFAS present in any particular foam could degrade to a combination of various PFCAs and PFSAs.

Persistent, Mobile and Toxic (PMT) or very Persistent, very Mobile (vPvM) type concerns could be considered equivalent to the other types of concerns included in Article 57(a) to (e) of UK REACH with regard to the identification of Substances of Very High Concern (SVHCs). Two PFAS – PFBS (a PFAA) and HFPO-DA (GenX®, a PFAA precursor) – are on the UK Candidate List of Substances of Very High Concern (SVHC) owing to PMT/vPvM-type concerns. They were added when the UK was subject to EU REACH, although the decision for PFBS was taken in 2019, when UK officials were no longer actively participating in EU discussions. These were case-by-case decisions as no

PMT/vPvM criteria or policy framework was in place in the EU to ensure consistency in decision-making.

The combination of persistence and mobility in particular gives rise to the potential for increasing environmental concentrations over extended timescales and on a wide geographic scale (far from the original source), which will be slow to respond to emission reduction interventions. Rising environmental concentrations increase the potential for exposure of humans and wildlife to levels that may have (eco)toxicological consequences. This means that a quantitative risk assessment is likely to involve considerable uncertainty.

A UK Defra position statement on the risk management approach for PMT/vPvM-type concerns has since been published (Defra, 2025). Although the position statement does not provide formal PMT/vPvM criteria, it does describe how screening level data could be used to identify chemicals with the potential to reach aquatic environments that are physically and temporally remote from their origin. The hazard section (Section 2) describes how PFAAs fall within its scope as they have been demonstrated to reach environmental compartments of concern (particularly groundwaters) because of their persistence and mobility.

It is also necessary to consider whether PMT/vPvM substances should be treated as threshold or non-threshold concerns as this will determine how risk is assessed and what risk management actions may be required. A threshold approach assumes there is an acceptable concentration below which risks are presumed to be adequately controlled. A non-threshold approach assumes that it is not possible to establish an acceptable concentration, and so exposure needs to be minimised to be as low as possible.

As evidenced by the availability of health-based guidance values for a small number of PFAS (for example, ATSDR, 2021; EFSA *et al.* (2020a)), it could be possible to derive meaningful thresholds of effect for those PFAS in firefighting foams where the data are sufficient to do so. However, since these substances are extremely persistent in the environment, with their continued emission it would seem reasonable to conclude that any threshold would be breached over time. For persistent and mobile substances, there is also concern over difficulty in remediation. Available data indicate that it is difficult to remove PFAAs from water using currently available conventional techniques. For these reasons, taking the same approach to risk assessment as for non-threshold substances is considered the most appropriate method for addressing emissions of PFAS from FFF.

This approach aligns with the Defra position statement on PMT/vPvM-type concerns. It also aligns with the approach taken for PBT/vPvB chemicals, including POPs.

Following this approach, emissions to the environment are considered to be a proxy for environmental and health risks. The scale of the risk can be estimated based on the total emissions to the environment.

Section 3 has reviewed the uses and potential for environmental exposure from the formulation and use of FFF that contain PFAS. There is a lack of information on any emissions from the formulation life stage. However, where testing takes place on such sites, there is a clear potential for environmental releases. Emissions to the environment were demonstrated for all the service life stages, with releases to surface waters (fresh water and marine water) and soils identified.

The Agency estimates the annual emissions of PFAS associated with the use of FFF foam to be ~48 tonnes. Environmental exposure modelling has not been conducted by the Agency due to the general lack of reliable information and complexity posed by the properties of PFAAs and their precursors (Section 3). However, based on the emission pathways, information on the mobility of PFAAs and monitoring data, surface and ground waters were identified as compartments of particular concern. As such, this is considered by the Agency to represent a risk that is not adequately controlled.

4.2 Justification

The Agency has concluded that the use of PFAS in FFF presents a risk to the environment and to human health via the environment. The hazards and exposures of concern are summarised in Section 4.1 above, as is the rationale for taking a non-threshold approach to risk assessment.

An analysis of existing GB regulatory measures which cover PFAS in FFF at various points in their life cycle can be found in Annex F. The Agency concludes that:

- Gaps are particularly notable in regulation with regard to controlling emissions of substances to the environment where, as established above, these substances persist and are able to contaminate ground and surface water.
- Although remediation measures are proposed (in guidance in England and Wales and in regulation in Scotland) to monitor and limit the concentration of individual PFAS in water sources, this does not prevent further emission to the environment. Increasing concentrations as a result of continued emissions could impact on the cost-effectiveness and viability of remediation of water sources.
- Owing to the non-threshold nature of the risk identified, emissions to the environment are representative of the risk. With respect to the existing pieces of legislation outlined in Annex F, none will be fully effective at controlling these emissions, as the majority of the measures seek to control exposure only once emissions have taken place. Only restriction under UK REACH implements control at source via supply management.

The Agency therefore concludes that the use of PFAS in FFF presents a risk to the environment, and human health via the environment, that is not adequately controlled under the existing regulatory framework.

For the purpose of the restriction, PFAS will be defined as any substance that contain at least one fully fluorinated methyl (CF_3) or methylene (CF_2) carbon atom without any hydrogen, chlorine, bromine, or iodine atom attached to it. Adopting a broad definition will minimise potential for regrettable substitution with PFAS not currently known to be used in firefighting foams, but which have the same risks as those already identified.

Regulatory options are further explored and analysed in Section 6 (SEA analysis).

5 Analysis of Alternatives

5.1 Alternatives overview, chemistry and mode of action in fire suppression

5.1.1 Composition of fluorine-free firefighting (F3) foams

The exact composition of both AFFF and F3 foams is unknown due to producers maintaining a high level of confidentiality for their proprietary foam formulations. Whilst current F3 foams are marketed as ‘fluorine-free’, it is possible that some will still contain fluorosurfactants or other fluorine-containing substances that do not meet the OECD (2021a) definition of PFAS. However, according to Wood (2020), “analysis suggests that fluorinated non-PFAS alternatives in the area of fire-fighting foams do not exist.”

The definition of F3 varies depending on the certifying organisation. A review comparing PFAS-containing foams and F3 undertaken by Jahura *et al.* (2024) gave examples of PFAS-free definitions, including:

- GreenScreen certification “defines PFAS-free firefighting foam as having no intentionally added PFAS, and PFAS contamination level must be less than 1 part per million (ppm), measured as total organic fluorine using combustion ion chromatography.”
- US military specification (MIL-F-24385): “F3 must not contain intentionally added PFAS in the formulation and the foam concentrate may contain a maximum of 1 part per billion (ppb) of PFAS.”

According to Wood (2020) the component substances of F3 or more specifically PFAS-free foams essentially fall into four separate categories:

- Hydrocarbons: hydrocarbon components of F3 typically include fatty acids, xanthan gums, sugars, alcohols, polyethylene glycol, and alkanes (Jahura *et al.*, 2024; Wood, 2020).
- Detergents: the detergents group, whilst generally being hydrocarbons, are considered separately based upon their amphiphilic nature and may belong to non-ionic, anionic, or zwitterionic surfactant categories (Jahura *et al.*, 2024; Wood, 2020). Detergents comprise a polar head group and a variable length non-polar alkyl chain. The polar head group is required to act at aqueous interfaces (to lower surface tension and form micelles) and comprises moieties such as betaines, sulphates, amido betaines and triethanolamines (Wood, 2020).
- Siloxanes: the siloxane group of foams tend to comprise silicone surfactants, such as siloxane, carbohydrate siloxane, or carbosiloxane and include F3 and synthetic alcohol-resistant fluorine-free foams. Wood (2020) found only a single substance that could be identified by its CAS number relating to siloxane/silicones (CAS No. 117272-76-1; poly[dimethylsiloxane-co-methyl(3-hydroxypropyl)siloxane]-graft-poly(ethylene glycol) methyl ether; found in certain products by Denko (Denko, 2024). Additionally, certain siloxanes and their degradation products, in particular some cyclic siloxanes, are UK SVHCs owing to PBT/vPvB properties, and have potential endocrine disruption concerns (Jahura *et al.*, 2024; Wood, 2020).

- Natural proteins: these comprise naturally occurring hydrolysed proteins, foam stabilizers, bactericides, corrosion inhibitors, and solvents and result in a highly stable foam. Because of this stability, the foam is relatively slow moving. It requires the use of an air aspirating type discharge device and can become contaminated with fuel if plunged directly onto the fuel surface, limiting their effectiveness (Jahura *et al.*, 2024; Wood, 2020).

5.1.2 Properties and Performance of F3 foams

Unlike the fluorosurfactant foams, F3 do not form an aqueous film to extinguish fires. Their mode of action relies on mixing the specific components of the foam with air to establish a stable blanket of bubbles above the fuel surface, providing a barrier between the fuel vapours and oxygen, and providing a cooling effect to extinguish the fire (Jahura *et al.*, 2024; Wood, 2020). Properties such as expansion ratio, foam thickness, bubble size and distribution, fuel / vapour transport rate through the foam, foam mobility as well as the type of foam generation device all influence the fire suppression effectiveness of the foam produced (Jahura *et al.*, 2024). Ideally, a foam should have good heat stability, be able to rapidly spread across the fuel surface creating a vapour seal and have resistance to fuel pick-up (Jahura *et al.*, 2024).

From Jahura *et al.* (2024), performance tests of firefighting foams (both AFFF and F3) are based on several characteristic parameters:

- *“Knockdown - The time it takes for the foam blanket to spread across a fuel surface.*
- *Heat resistance or burnback resistance - The ability of foam bubbles to withstand an elevated temperature.*
- *Fuel tolerance - Foam’s ability to minimise fuel uptake to prevent it from getting saturated and burnt.*
- *Vapor suppression - The ability of the foam blanket to suppress flammable vapours and prevent their release from the fuel.*
- *Alcohol resistance - The ability of the foam blanket to create a polymeric barrier between the fuel and the foam to avoid foam destruction by fuel absorption.*
- *Drainage rate - The time it takes for 25% of the solution to drain from the foam over a given time period. This is often referred to as 25% drainage time.*
- *Expansion ratio* - The volume of foam produced by vigorously mixing a given volume of foam solution with air.*
- *Application rate - The rate at which foam solution is applied to the fire, measured in gallons per minute per square foot (gpm/ft^2) or liters per minute per square foot (L/min/ft^2).”*

*Further explanation of Expansion Ratio: the volume of finished foam divided by the volume of foam solution used to create the finished foam. Foams are classed as having low medium or high expansion rates:

- Low Expansion Foam: Expansion ratio ≥ 2:1 ≤ 20:1
- Medium Expansion Foam: Expansion ratio ≥ 20:1 ≤ 200:1
- High Expansion Foam: Expansion ratio ≥ 200:1

5.2 Hazards of alternatives

The human health and environmental hazards of PFAS in FFF have been described in the previous chapters of this report. It is equally important to understand the hazard profile of alternatives, to avoid regrettable substitution and understand the future challenges that could arise through the widespread use of F3.

Similarly to AFFF, some of the constituents and active ingredients in F3 are proprietary and kept confidential by the manufacturers. Therefore, our current understanding of the composition and hazard profiles of F3 is derived from product SDSs that are either publicly available or have been shared through stakeholder engagement.

Furthermore, some substances in F3 are also present in PFAS-containing formulations, for example sodium decyl sulfate and sodium laureth sulfate. However, whilst PFAS-containing foams are effective with low PFAS component concentrations (typically 3% w/w), F3 require larger concentrations of active components in combination (typically 10 – 20% w/w) to be effective (ECHA, 2023a).

5.2.1 Human health hazards

F3 are reported to contain a range of substances, including solvents, stabilisers, and a variety of active ingredients from a range of chemical classes, including hydrocarbons, detergents (surfactants), proteins, and siloxanes (see Section 5.1.1).

The Agency looked at the components of seven F3 products on the GB market, from five manufacturers (see Annex D.2.3, Table D.7). The ingredients contained in these products were broadly similar to those identified by ECHA (2023a), with the exception of siloxanes, which do not appear to be currently available for commercial use in GB. Owing to the proprietary nature of the F3, information on the components of F3 is limited to those hazardous substances required to be included in SDSs. Additional substances commonly used in F3 products as listed in Jahura *et al.* (2024) and Wood (2020) were also included in the analysis.

To identify the human health hazard classifications for the substances contained in the available F3 products, the Agency consulted SDSs, ECHA's Classification & Labelling (C&L) Inventory and the GB MCL list. The Agency did not undertake an assessment of available toxicological data, nor do the sources indicate the availability of specific toxicological information for each substance, or lack thereof. If no relevant data were available, the substance would have no classification.

Of the 31 substances found to be in the seven F3 products, five had harmonised / mandatory classifications under EU and GB CLP (Table 5.1). Of the remaining 26 substances, 23 were self-classified by those placing them on the market, two were not classified, and one was not listed in ECHA's C&L Inventory or the GB MCL list. A summary of all the classifications found is presented in Annex D.2.3, Table D.7.

Table 5.1: Substances with mandatory classification used as alternatives to PFAS in firefighting products identified via stakeholder engagement.

Substance	CAS RN	Classifications (human health)
2-Butoxyethanol	111-76-2	Acute Tox. 3 (Inh): H331 Acute Tox. 4 (Oral): H302 Skin Irrit 2: H315 Eye Irrit. 2: H319
2-(2-Butoxyethoxy)ethanol	112-34-5	Eye Irrit. 2: H319
1-Butoxy-2-propanol	5131-66-8	Eye Irrit. 2: H319 Skin Irrit. 2: H315
N-Butanol	71-36-3	Acute Tox. 4: H302 Skin Irrit. 2: H315 Eye Dam. 1: H318 STOT SE 3: H335, H336
Ethanediol	107-21-1	Acute Tox. 4 (oral): H302 STOT RE 2: H373 (kidney) (oral)*
Amides, coco, N-[3-(dimethylamino)propyl], N-oxides **[cocamidopropylamine oxide]**	68155-09-9	Acute Tox. 4 (oral): H302* Skin Irrit. 2: H315* Eye Dam. 1: H318* STOT RE 2: H373 (liver, spleen) *

* Industry self-classifications are provided in Annex D.2.3. Table D.7)

The definition for Toxicity set out in Annex 13 of UK REACH for identification of PBT substances includes substances that meet the CLP criteria for carcinogenicity and/or mutagenicity in Category 1, reproductive toxicity in Category 1 or 2, or STOT RE in Category 1 or 2. None of the component substances listed in Annex D.2.3, Table D.7 had a classification for carcinogenicity, mutagenicity or reproductive toxicity (noting the caveat above regarding availability or otherwise of suitable data to assess these hazard end-points). Two substances, ethanediol (CAS RN: 107-21-1) and cocamidopropylamine oxide (CAS RN: 68155-09-9), were listed as being self-classified for STOT RE 2 (may cause damage to organs through repeated exposure).

The remaining classifications for the substances in the identified F3 products included acute toxicity (primarily in Category 4 for exposure by the oral route), narcotic effects after single exposure, and local effects comprising irritation of the skin, eye and/or respiratory tract. One substance, cocamidopropyl betaine (CAS RN: 61789-40-0), was self-classified for skin sensitisation (Skin Sens 1). These effects are also expected to be relevant for PFAS-based FFF, as many of these include either the same or similar substances as solvents and/or stabilisers. However, the classification of the products themselves depends on the concentrations of their components as well as their identified hazards. The classification of a substance is not carried through to that of the product where its concentration is below the relevant limit. As also noted above, whilst AFFF are effective with low PFAS component concentrations (typically 3% w/w), F3 require larger concentrations of active components in combination (typically 10 – 20% w/w) to be effective (ECHA, 2023a).

The hazard classifications of the seven identified F3 products, as stated in their SDSs, is shown in Section 5.2.3 below. One product was classified by the supplier as STOT RE 2 (kidney effects), with potential to cause damage to the kidneys through repeated exposure. The substance responsible for this classification, ethanediol, serves as an antifreeze that allows the foam to be used at extremely low temperatures. This substance is also found in some PFAS-based FFF products at concentrations that lead to classification of the product as STOT RE 2. The other F3 products were classified by their suppliers for skin and/or eye irritation / damage. These classifications for local effects are broadly consistent with most PFAS-based FFF products identified during stakeholder engagement. Specifically, five of the seven FFF products were classified by their suppliers for skin and/or eye irritation or damage, while the remaining two products were classified for skin sensitisation in Category 1.

5.2.2 Environmental Hazards

There are limited ecotoxicological data available for components of F3. Examples of known F3 components with ecotoxicological effects based on classifications from the ECHA C&L Inventory (C&L Inventory - ECHA) are listed in Table 5.2 (see Annex D.2.3, Tables D.7 and D.8).

Jahura et al. (2024) concluded that “most commercially available F3 are either equally or more toxic compared to C6 AFFF, particularly for aquatic species”. In contrast, IPEN (2018) maintains that there are only minor differences in acute aquatic toxicities between PFAS-containing foams and F3 and the more relevant characteristics are Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD).

Table 5.2: F3 components with environmental classifications (Sources: information direct from stakeholder, Jahura *et al.* (2024) and Wood *et al.* (2020))

Substance	CAS RN	EC No	ENV Classification from ECHA C&L Inventory
Alkylamidobetaine	147170-44-3	604-575-4	Aquatic Chronic 3
Amides, coco, N-[3-(dimethylamino)propyl]	68140-01-2	268-771-8	Aquatic Acute 1
(Carboxymethyl)dimethyl-3-[(1-oxododecyl)amino]propylammonium hydroxide	4292-10-8	224-292-6	Aquatic Chronic 3
N,N-dimethyl-1-tetradecanamine-N-oxide	3332-27-2	222-059-3	Aquatic Acute 1 Aquatic Chronic 2

1-Dodecanol	112-53-8	203-982-0	Aquatic Acute 1 Aquatic Chronic 2
Dodecyldimethylamine oxide	1643-20-5	216-700-6	Aquatic Acute 1 Aquatic Chronic 2
1-Propanaminium, 3-amino-N (carboxymethyl)-N,N-dimethyl-, N-coco acyl derivs., hydroxides, inner salts (-)	61789-40-0	263-058-8	Aquatic Chronic 3
1-Propanaminium, N-(3-aminopropyl)-2-hydroxy-N,N-dimethyl-3-sulfo-, N-coco acyl derivs., hydroxides, inner salt	68139-30-0	268-761-3	Aquatic Acute 1 Aquatic Chronic 2
Sodium decyl sulfate	142-87-0	205-568-5	Aquatic Chronic 3
Sodium dodecyl sulfate	151-21-3	205-788-1	Aquatic Chronic 3
Sulfuric acid, mono-C12-14-alkyl esters, compds. with triethanolamine	90583-18-9	292-216-9	Aquatic Chronic 3
1-Tetradecanol	112-72-1	204-000-3	Aquatic Acute 1 Aquatic Chronic 1
Triethanol ammonium- laurylsulfate	85665-45-8	288-134-8	Aquatic Chronic 3

Jahura *et al.* (2024) highlight how the environmental risks associated with F3 need further research to fill data gaps. Issues of concern include:

- Lack of available acute and chronic toxicity data (e.g. endocrine, reproductive, and developmental) for SDS-listed and proprietary components.
- Difficult to assess environmental fate and ecotoxicity impacts of complex chemical mixtures.
- The inclusion of degradable organic components such as hydrocarbons and proteins means that many commercial F3 have a high BOD, which could have a significant negative impact if released into aquatic systems. According to Jahura *et al.* (2024) newer F3 tend to have lower BOD and COD.

IPEN (2018) highlights that all PFAS-containing and F3 foams generally have high BOD and COD and “that in many cases there is no effective difference in BOD or COD values for the two types. The report states that the high BOD potential of all foams will be due to their high degradable organic component (e.g. solvents, detergents, hydrocarbons and proteins), which can rapidly reduce the dissolved oxygen concentration of receiving aquatic environments and damage aerobic biota. Some newer F3 formulations are solvent-free, which reduce the COD and BOD and “thus the potential for imposed oxygen stress on the receiving environment, by approximately 40%-60% compared to standard AFFF or F3 products” (IPEN, 2018).

Commercially available F3 are generally expected to be readily biodegradable and therefore significantly less persistent in the environment compared to PFAS substances (Jahura *et al.*, 2024). In contrast to PFAS-containing foams, which as previously described in Section 3.1.9 will not be fully degraded by WwTPs, F3 would be expected to undergo degradation in WwTPs (IPEN, 2018). However, as discussed earlier, one particular class of F3 are the siloxanes, some of which are known to have PBT/vPvB properties, although only limited numbers of commercially available products were identified (Wood, 2020).

5.2.3 Conclusions on the hazards of alternatives

The classifications applied by the suppliers for the seven F3 products are shown in the table below.

Table 5.3: CLP classifications identified in the SDS of F3 products available on GB market.

Product	Carcinogenic, mutagenic and toxic to Reproduction (CMR) Properties	PBT or vPvB	Other human health concerns indicated in the product SDS	Other Environmental concerns indicated in SDS
Re-Healing Foam RF3x3	No	No	May cause damage to organs through prolonged or repeated exposure (H373)	Avoid spillage into the aquatic environment as it contains substances potentially dangerous for this.
Expandol 3%	No	No	Causes skin irritation, eye irritation (H315, H319)	Chronic Aquatic Toxicity (H412)
Sthamex K1% F15	No	No	Causes skin irritation & serious eye irritation (H315, H319)	Can harm aquatic fauna when entering surface waters
Freegen SF-LV	No	No	Causes skin irritation (H315)	Harmful to aquatic life (H402)
SOYFOAM TF-1122	No	No	Causes skin irritation & serious eye irritation (H315, H319)	Aquatic toxicity – no data available
ReHealing RF1 1%	No	insufficient data	Causes skin irritation & serious eye damage (H315, H318)	No data available on ecotoxicity
3% Mil-Spec SFFF	No	No	Causes skin irritation & serious eye damage (H315, H318)	This product is not classified as hazardous to the environment. Keep product away from drains, surface and underground water.

The available information on components of F3 products indicates that none of the substances (and hence products) are currently classified for carcinogenicity, mutagenicity or reproductive toxicity. The remaining human health hazards are associated with ingredients used as solvents and stabilizers, which are also commonly found in FFFs, and therefore are not unique to F3 products. Overall, the F3 products have broadly similar or less severe human health hazard classifications to the FFF.

The ecotoxicological information for components of F3 products listed on the SDS indicate concerns for aquatic environmental release with several labelled as harmful and others lacking information. None are indicated as meeting PBT or vPvB classification, although one is listed as having insufficient data for assessment. However, regardless of whether a foam is fluorine-free or contains PFAS, all will have the potential to cause a negative environmental impact when released, and each should be assessed for its human health and environmental hazard and risk (ECHA, 2023a). Given the potential ecotoxicity concerns of F3 it is expected that manufacturers, formulators, distributors and operators will need to establish appropriate measures to control and minimise environmental releases and ensure appropriate disposal of waste streams, although it is recognised that this may not always be possible in live incidents.

5.3 Transitioning to F3, including training

This section considers the technical feasibility of alternatives to AFFF. It outlines some of the general performance-related considerations associated with replacing PFAS-containing FFF with F3, before discussing more specific concerns, successful transitions and uncertainties relating to F3 application in the various use sectors.

5.3.1 General Considerations

Rather than any firefighting performance benefit, the main drivers for moving away from AFFF are the potential reduction in human health and environmental risks associated with PFAS. Development of effective F3 is progressing, but they cannot be considered as direct replacements for PFAS-containing FFF in all firefighting scenarios because of “variations in their performance across different fuel types and test conditions” (Jahura *et al.*, 2024). In some cases, a change in equipment must accompany the switch to F3. It is worth noting that standardised firefighting tests usually represent an ‘ideal’ firefighting scenario, i.e., they involve ideal climatic conditions, trained and experienced fire crew, known accelerants / fuels and flat and unrestricted surfaces. These scenarios, and the associated foam performance may be different in live fire events such that modification of firefighting tactics and techniques will be required to address this (Farley *et al.*, 2023).

The Agency is aware that the firefighting services in Australia have transitioned to using F3. Environment Operations (General) Regulation 2022 (Chapter 9, Part 5) in New South Wales (NSW), banned the use of PFAS foams in stages, starting with training and demonstrations. There are exemptions for the use of PFAS-containing foams for watercraft in “relevant waters”, and their use remains permitted for “preventing or firefighting catastrophic fires by relevant authorities and exempt entities”. Catastrophic fires are defined as a fire involving a combustible accelerant, including petrol, kerosene, oil, tar, paint or polar solvents including ethanol.

Similar restrictions on the holding and use of PFAS-containing foams are seen in other Australian states, such as Queensland, where strictly monitored use of C6 foams are permitted in controlled circumstances. These include limits on impurities in the foam and capture of all firewater with no escape permitted directly into the environment. Here, PFSAs ≥C4 and precursors are not to be used, and foams containing PFCAs ≥C7 are to be withdrawn and disposed of (Operating Policy Environmental Management of Firefighting Foam, Queensland Government, 2021).

The permitted use of PFAS-containing foams in certain circumstances suggests an element of uncertainty of fluorine-free alternatives, and the Agency would welcome further information on efficacy of fluorine-free foams to inform regulatory decision making in GB to ensure a considered proposal can be made when restricting PFAS in firefighting foams.

Large-scale validation tests of F3 conducted by the US Navy (Farley *et al.*, 2023) found that even with optimised techniques, F3 typically took about 1.5 - 2 times longer than AFFF to extinguish the fires in most scenarios. The main differences between F3 and AFFF from these tests were summarised as follows:

> *“F3s are less forgiving than AFFF due to the absence of the film-forming component and the sole reliance on the bubble blanket to smother the fire.*
> *F3s generally work better when aspirated but aspirated foam is hard to throw far distances and doesn’t flow well around obstructions.*
> *F3s require better application techniques and some level of finesse to optimize performance and prevent plunging into the fuel and disruption of the foam blanket.*
> *F3s are effective in AR-AFFF type applications with the proper application techniques but typically take multiple application passes to control and extinguish the fire versus one for AFFF.”*

Currently available fluorine-free firefighting foam technology has not duplicated the resealing “film-forming” property of the PFAS surfactants (with the possible exception of some siloxane products) and any breaks or disturbance of the foam blanket can lead to vapour release and reignition (Back and Farley, 2020; FAA, 2023). Therefore, F3 rely heavily on cooling the fire and the integrity of the bubble structure to suppress fuel vapours and their use sometimes requires modified firefighting tactics.

The analysis of alternatives reveals specific international compliance standards for commercially available foams. However, current testing protocols often focus on PFAS-based foams, which may not be suitable for fluorine-free foams owing to different application methods and read-across between different burning fuels. Some stakeholders highlighted that comparing the two types purely based on certification is challenging. Some fluorine-free foams can meet standard firefighting certifications, as demonstrated by some airports and municipal fire brigades. The analysis highlights the need for more tailored testing protocols to reflect the firefighting ability of fluorine-free foams.

5.3.2 Application of alternative firefighting foams and implications for training and storage

The way that F3 are applied to a liquid fuel fire varies from that of traditional PFAS-containing foams. According to work carried out by the US Naval Research Laboratory, the standard technique of forceful application of foams to a fire can lead to significant fuel pick up into the foam, allowing the fire to continue to burn and holes being punched in the foam blanket at the site of application (Farley *et al.*, 2023). Further testing identified a “gentle” foam application works more effectively than a forceful one for F3. This technique is reflected in the testing of F3, where foams are applied to a backboard behind the pan so they can gently rebound and be dispersed over the fire (Farley *et al.*, 2023).

Effective training of firefighters on F3 application and blanket maintenance is essential. According to the FAA, application should ensure a proper ‘base sweep’ (i.e., level application directed at the base of the fire with a sweeping motion to spread the blanket) as opposed to a ‘plunging’ application where the angle is too steep and may cause mixing, or arching ‘raindown’ which may be not allow effective foam formation (FAA, 2023). Increased visual monitoring of the foam blanket and constant replenishment when it breaks down and becomes susceptible to reignition can be a more important consideration when using F3, due to the increased fragility of the blanket. Depending on the nature and layout of the fire (e.g. firefighting at a distance, large structures, obstacles and obstructions) it may also be necessary to utilise drones or unmanned aerial vehicles (UAV) and for additional crew to act as spotters and advise operators as they concentrate on the fire base, where the foam blanket is degenerating requiring further foam application (FAA, 2023; LASTFIRE, 2023). This is a particular safety issue, as the firefighting crew might have to move through the established foam blanket to reach the blaze, disturbing the blanket as they do so and risking reignition (FAA, 2023).

Whereas AFFF tend to have low viscosity, many available F3 display higher viscosity which can affect their application rate. A poor application rate may cause the foam blanket to breakdown. Therefore, appropriate discharge equipment is required e.g. aspirated discharge nozzles. This in turn can affect the reach or ‘throw’ distance of the foam. According to Jahura *et al.* (2024) “F3s typically require 1.5 to 3 times the application rates of C6 AR-AFFF to achieve comparable performance.” It has been suggested by some stakeholders that this means larger volumes of foam concentrate are required with implications for storage volumes and infrastructure for fixed systems particularly where storage space might be limited. The Agency would welcome further information on the potential need for increased foam storage capacity, especially from those who have already transitioned to F3.

5.3.3 Compatibility

Physiochemical properties of F3 products may mean that premixed concentrates (concentrate diluted with water) may be incompatible for different temperature extremes: i.e., if stored in very cold or hot climates. Similarly, it has been suggested that some F3 concentrates are incompatible with saltwater use, although the Agency is aware of F3 products which are compatible with saltwater.

Mixing of two different F3, for example from two different monitors at an incident may potentially impact the foam blanket formation and separate F3 concentrates should not be mixed without testing to ensure compatibility (FAA, 2023; Trazzi and Casey, 2023). Concerns were also raised regarding incompatibility when mixing different F3 concentrates and finished foam products as this may lead to the foam being inoperable and cause damage to the operating system. However, it was noted that this also applies to mixing different AFFF concentrates as well. It was stressed that stakeholders should ensure that their foams should be compatibility tested to see if they can be used in combination with other foam concentrates/ finished products (stakeholder meeting, FIA, Jun 2024).

Summary

Given that there are differences in the firefighting performance of the F3 alternatives compared with PFAS-containing foams, they are not a ‘like-for-like’ replacement. However, it is noted that to be suitable for use in the various sectors, all F3 will have been tested and demonstrated to meet the requirements of the relevant sector-specific standards.

5.3.4 Sector-specific use of firefighting foams and the suitability of alternatives

5.3.4.1 Fire & Rescue Services (FRS) including transportation

5.3.4.1.1 General Concerns

The Fire and Rescue Services (FRS) in GB have a responsibility for extinguishing fires and ensuring the safety of people and property. Responsibilities also include rescuing and safeguarding individuals during road traffic accidents and crises, such as flooding (LGA, 2024). Under the Civil Contingencies Act 2004 (CCA, 2004) they have an obligation as a category 1 responder to attend all fires. Therefore, they attend most of the fires where foam is required, with the exception of some airports and industrial sites where the onsite industrial fire responders entirely tackle the fire on their own premises.

As outlined in Section 3.1.6.1, the FRS attend fires in a large variety of locations and cover different types of fires. The decision to use foam on a particular fire is made by the FRS on the scene with the aim to protect life and property and it must be able to extinguish any fire quickly. The NFCC raised concerns that F3 may not be as effective as AFFF in extinguishing large petrochemical tank fires, but there has yet to be an actual incident to test this.

Stakeholders contacted during preparation of this report indicated that currently most *training* activities with firefighting foam in GB are performed with F3. This has not always been the case. One stakeholder the Agency met during preparation of this Annex 15 report indicated that about 3 – 4 years ago (i.e., before around 2020 – 21), fluorine-based foams were used for training and no specific measures were taken to prevent exposure of firefighters to substances in the foam (stakeholder meeting, JOIFF, June 2024). Some sites may have transitioned at a later date. DWI (2022b) indicates that at the Duxford airfield, transition to PFAS-free foams did not take place until March 2022.

5.3.4.1.2 Call for evidence

The NFCC advised the Agency of a survey they had undertaken of all 52 UK FRS regarding their stocks of firefighting foams (Call for evidence, NFCC, 2024). Of the 29 who responded, 3 held approximately 21,500L of PFOA-containing foam and had plans in place for disposal and replacement before the July 2025 deadline, as mandated under the POPs Regulations. This type of foam had not been used in the previous two years, and plans were also in place to procure an alternative foam. Seven FRS held stocks containing PFHxA totalling approximately 711,400L, of whom 4 had used 4,100L in the two years leading up to the survey. The remaining 19 FRS had already transitioned to fluorine-free foam.

Separately, in the Agency’s call for evidence, Norfolk FRS confirmed their transition away from PFAS by the end of 2022. London Fire Brigade and West Sussex FRS both held some AFFF. Both indicated they are in the process of transitioning to F3.

The NFCC expressed concerns regarding the efficacy of alternatives as there had not been a fire of the magnitude of Buncefield extinguished by fluorine-free foams to provide such a test. However, the alternative foams had all passed the appropriate testing, e.g. BS EN 1568 part 1-4. The NFCC also suggested that fluorine-free foams may need increased application rates, and raised concerns about increased fire risks, compatibility of FFF in the existing equipment operated by the FRS, and whether new equipment may need to be purchased. These concerns have been detailed above in Section 5.3. The NFCC has since suggested that a phased transition may be necessary to allow for the use of foams subject to future restrictions (NFCC, 2024).

The Agency is lacking in information on the quantities of foam used by many FRS and the NFCC expressed concern regarding potential decontamination of existing equipment and foam storage.

5.3.4.1.3 Successful transitions

Several FRS have published responses to FOI requests in 2022, identified using an internet search with the search terms: fire rescue service PFAS free foam FOI requests UK. Of the 13 responses from FRS, 4 indicated that transition to fluorine-free foams has already occurred:

- West Midlands FRS confirmed that while they previously used Angus Fire Tridol 3-3 C6 in their bulk foam carrier and a C6 fluorinated foam in their pump rescue ladder vehicles, they have replaced them with fluorine-free (WMFS, 2022).
- North Yorkshire FRS stopped using fluorinated foams in 2020 (NYFRS, 2022).
- Lincolnshire FRS do not use fluorinated foams, as confirmed by Lincolnshire County Council (LCC, 2022).
- Humberside FRS moved away from PFAS-containing foams in 2011 (HFRS, 2022), despite having a number of large chemicals complexes on the banks of the river Humber, for example Saltend Chemicals Park (2025).

The remaining 9 FRS were either still using fluorinated foams or were planning on transitioning within the next year:

- Cheshire FRS responded saying that they did use fluorinated foams at that time and had a project team who were working on finding a fluorine-free replacement (CFRS, 2022).
- Cumbria FRS used PFAS in 2022 but planned to replace it with fluorine-free by the end of 2022 as confirmed by Cumbria County Council (Cumbria CC, 2022).
- The London Fire Brigade confirmed in 2022 that they did use PFAS-containing foams and were working on a foam replacement project to replace all fluorinated foams by 2025 (LFB, 2022).
- Staffordshire FRS used a variety of fluorinated foams and at the time of the response were in the process of disposal and replacement (Staffordshire FRS, 2022).
- Shropshire FRS gave details of their environmental policy on the use of foams, explaining that they were moving from PFAS foams to Moussol FXS FF 3/6 F-5, a PFAS free foam. At the time five of their frontline appliances had already been transferred and the remaining 23 appliances were ongoing (Shropshire FRS, 2022).
- Dorset and Wiltshire FRS (DWFRS, 2022), South Wales FRS (SWFRS, 2019), Royal Berkshire FRS (RBFRS, 2022) and Northamptonshire FRS (NFRS, 2022) all used PFAS foams and at the time of the FOI did not have a policy to transition to fluorine-free.

Norfolk FRS stated in the call for evidence that they had exhausted their stocks of fluorinated foams in 2022 and had transitioned to Sthamex K 1%, Freegen SF-LV 3% and Expandol.

In summary, 5 of the 14 FRSs described above had already transitioned at the time they responded to an FOI request (mostly in 2022), and a further 5 had plans to move away from PFAS foams at the time of the FOI requests. The alternatives identified in the FOI requests were: Dr Sthamer Sthamex-K 1%, Freegen SF-LV 3%, Expandol and Moussol-FF 3/6 F-15.

The Agency does not have any information on whether any vehicles or equipment had to be changed, as a consequence of transition, by those FRS who have successfully transitioned (NFCC, 2024).

5.3.4.1.4 Transition periods

In their recommendation to restrict PFAS in firefighting foam, ECHA, recommended a transition period of 18 months for FRS generally (ECHA, 2023e). As discussed in Section 5.3.4.1.2 the NFCC has indicated that time is required for this sector to transition, rather than any immediate prohibition. It is also noted that while the FRS train and attend smaller fires, they also attend fires at COMAH sites where they would be able to benefit from the longer transition period proposed for this sector.

5.3.4.1.5 Considerations for FRS response at transport locations

The following locations are areas where the FRS generally attends fires and that are not addressed under the analyses given for other sectors later in this section. The Agency believes particular challenges surrounding the use of firefighting foams within various scenarios in the transport sector may occur and therefore has focussed on them here.

5.3.4.1.5.1 Ports/docks

Firefighting in port buildings and infrastructure is provided by the FRS, with emergency action plans in place (see Section 3.1). No information was received with specific mention of ports or harbours in the Agency’s call for evidence and the types of foams or quantities used at port facilities is so far unclear.

ECHA recommended ports designated as Seveso III (Upper or Lower tier) should be given a transition period of 10 years; any other ports not covered by this definition would have a transition period of 5 years, as with “all other uses” (ECHA, 2023e).

In the absence of contradictory information regarding the efficacy of alternative foams deployed in ports and docks, the Agency assumes that the complexities of fighting fires here will be similar to those at COMAH sites or offshore, except for the use of tug-based monitors with sea water rather than potable water. Therefore, where alternatives are considered to be efficacious when partitioned with sea water, there should be no situation where the foams would face a challenge different to those experienced in the offshore, marine, and COMAH sectors.

5.3.4.1.5.2 Rail transportation

During the call for evidence, one comment was received from DG Rail Consultants relating to railway maintenance trains. This highlighted that 2 flammable liquids (diesel fuel and hydraulic fluid) require the use of AFFF with the non-aspirated fire suppression system in place. Testing was carried out with a manufacturer to assess if alternative chemistries could be used, but because the tested alternative chemistries lacked film-forming properties, it was concluded a suitable alternative was not available (lack of adequate fire suppression). Dry powder was not considered as an alternative as this was viewed unsuitable for work in tunnels (Call for evidence, DG Rail Consultants). The stakeholder stated that aspirated systems and large volumes of foam are impractical.

In the consultation held by ECHA, stakeholder concerns were raised around the outdoor storage of portable fire extinguishers containing fluorine-free foam (EUROFEU), given that ambient temperatures may be outside the recommended range for efficacious storage and use (ECHA, 2022c). Whilst this concern is not limited to rail transportation, the comment was made in relation to numerous settings, including rail transportation.

There was also a concern that ongoing testing and the efficacy of the F3, with differing application of the foam in comparison to the PFAS-containing foams, may affect firefighting capability in both the road and the rail sector (comment 3546, comment 3593). Comment 3564, from a German company stated they had F3 for mobile operating systems for smaller (than storage tank) fires which would include use in rail and road operations. A similar comment was received by a non-governmental organisation (NGO) in Belgium, stating that alternatives were available and useable for all types of fuel (comment 3595) and whilst larger quantities may be required, this does not disqualify their viability (ECHA, 2022c).

In their recommendation to restrict PFAS in firefighting foam, ECHA described how high temperatures can be relevant for some transport scenarios but also that heat resistant fluorine-free foams are reported to be available and during transportation, volumes of hazardous material are expected to be lower than tank farms or chemical storage facilities (ECHA, 2023b).

ECHA did not propose specific transition periods for the transport sector, rather that this should be covered by municipal fire brigades.

The Agency expects that firefighting complexities will be similar to those faced at COMAH sites, and generally by the Fire and Rescue Service. Therefore, if alternative foams are found to be efficacious in these situations, the Agency believes there is no known situation for rail transportation where the efficacy of the foams would face a challenge that differs to the FRS or COMAH sites. The suitability of alternatives to control fires on railway maintenance vehicles is uncertain, and without further information in this unique situation, it is unknown if a viable alternative could be found to be efficacious.

5.3.4.1.5.3 Tunnels

There are no known uses of fixed firefighting foams in tunnels in the UK, except for firefighting measures in the Channel Tunnel (discussed in Section 3.1.6). The Channel Tunnel has foam firefighting capabilities in emergency sidings (on the English side of the tunnel), as well as foam-based systems within the tunnel and onboard rolling stock (stakeholder meeting, ORR, June 2024). There are currently ongoing works to replace the tunnel fixed firefighting system with a water drench system.

After the publication of the EU REACH Annex 15 technical report a request for derogation for the use of PFAS-containing firefighting foams in the Channel Tunnel was submitted during the public consultation (personal communication, Office of Rail and Road, June 2024). This was based on the complexities of firefighting in the Channel Tunnel itself.

ECHA received stakeholder comments that included cases of effective fire suppression in both road and rail tunnels. Antwerp harbour tunnel is a rail tunnel fitted with a fluorine-free foam suppression system, designed to extinguish any fires arising from the carriage of hazardous goods from the port area (ECHA, 2022c).

Fluorine-free foams are also installed in a road tunnel in Germany (Jagdberg) where in 2016, a fire in the tunnel which had arisen from a collision between 2 lorries was quickly and effectively suppressed.

The Agency concludes that where needed, suitable alternative fluorine-free foams are available to ensure adequate fire protection in tunnels, based on the evidence provided to ECHA. However, the need for this technology in the UK is unclear as all the tunnels with fire suppression systems (excluding the Channel Tunnel) known to the Agency deploy water mist systems.

5.3.4.1.5.4 Road vehicle fuel stations

Fuel stations contain moderate volumes of flammable liquids. Relevant legislation includes the Regulatory Reform (Fire Safety) Order (2005) including the obligations of premises to provide firefighting equipment in accordance with the British Standard BS 5306-8. The Dangerous Substances and Explosive Atmosphere (DSEAR) Regulations (2002) also cover risks arising from the delivery, keeping and dispensing of petroleum spirit and other motor fuels (such as liquefied petroleum gas), and the PEGL Petrol filling station guidance known as The Red Guide has been published to assist site operators in compliance with DSEAR (2024). Additionally, the FIA issued guidance for filling station forecourts (FIA, 2022) pulling together legislation and regulations applicable in GB. It is currently unknown if foam firefighting provisions are required. Firefighting using powders, as opposed to foams, are predominantly recommended as they can extinguish a number of different classes of fire.

The FRS extinguished a fire at a petrol station in North Yorkshire using foam (BBC, 2024). Given that the North Yorkshire FRS apparently transitioned from using PFAS foams in 2020 (see Section 5.3.4.1.3), it is assumed this fire was brought under control using fluorine-free alternative foam. This is unlikely to have been an isolated case, as the FRS attends many such incidents involving relatively small volumes of flammable liquids (compared to large storage tanks).

5.3.4.1.5.5 Electric charging points

Electric vehicles are powered using lithium-ion batteries, which, if a fire arises, may require the use of foam-based firefighting to extinguish. During the stakeholder engagement meeting with the ORR (ORR, June 2024) firefighting in this situation was discussed. Currently, a defined approach to tackling car battery fires across the fire brigades of the UK is lacking, although it appears that some FRS do use foam as a means of controlling such fires.

It is unclear if there are any requirements for firefighting foams in settings such as underground charging facilities, where there could be business or residential use of buildings. No information is known to be available on the use of alternative fluorine-free firefighting foams in this scenario, for example in fixed, firefighting foam systems integrated into building infrastructure.

5.3.4.1.6 Summary and conclusions for FRS and Transport sectors

The Agency notes that several FRS have already transitioned to fluorine-free foams, including in Humberside and Norfolk, where a number of different chemical complexes are located. Therefore, the alternatives have been deemed to be effective by these FRS. In line with ECHA’s recommendations for the EU REACH restriction, and with no evidence to indicate otherwise, the Agency proposes that a transition period of 18 months for fires attended by the FRS would be sufficient to allow adequate time to transition from PFAS-containing foams to fluorine-free alternatives.

From the information assessed, the Agency believes fluorine-free foams are available for the effective suppression of fires in the transportation sector with the possible exception of railway maintenance. One stakeholder reported the fluorine-free alternative(s) trialled so far were not suitable. Ports covered by COMAH regulations (Upper and Lower tiers) are proposed to have a transition period of ten years (Section 5.3.4.2), with other non-COMAH ports and transport hubs transitioning within five years along with all other uses.

ECHA considered concerns that extremes of temperature could reduce the efficacy of alternative foams, however heat-resistant fluorine-free alternatives are reportedly available

(ECHA, 2023b). Overall, taking into account all the comments received, ECHA did not propose that the extended transitional period for FRS to respond to incidents at Seveso III sites be applied to the whole of the transportation sector (ECHA, 2023b). There are expected to be suitable fluorine-free foams available to control fires in these situations that are proven to perform to internationally recognised performance standards.

The Channel Tunnel, passing through both GB and France, may require compliance with both EU and UK REACH restrictions. With this in mind, the Agency considers that relevant GB transition periods align with the ECHA proposed transition periods for the above uses.

5.3.4.2 Petrochemical, chemical and industrial sites

5.3.4.2.1 General Concerns

The chemical/ petrochemical industry was identified as the highest use sector of PFAS-based firefighting foams in the EU by ECHA with around 60% of sales to establishments in this sector (Wood, 2020). In contrast, data on sector specific usage for fluorine-free firefighting foams indicate around 30% of the EU market for these foams relates to use in the chemical and petrochemical industry (Wood, 2020). No such data are available for the GB market, however information gathered during the preparation of this report suggests that around 70% of the foam market (AFFF and F3) are sales to tank facilities and aircraft hangers (stakeholder meeting, JOIFF, Jun 2024), relating to the storage of petrochemicals.

Information received in the Agency’s call for evidence suggests there are COMAH sites that have transitioned to fluorine-free firefighting foams. It is unclear what percentage of the sites have transitioned, or what percentage of the F3 market supplies the chemical and petrochemical sector. During discussions with the FIA, one of their members estimated that 80% of their customers could transition to fluorine-free alternatives (stakeholder meeting, FIA, Jun 2024).

The chemical and petrochemical sector covers a vast array of sites where foams might be needed to suppress fires. Many of these sites are classified as COMAH sites, the definitions of which are found in Section 3.1.6.2. They hold a diverse range of substances, often with multiple substances held on each site. Efficacy of fluorine-free alternatives in this sector is a major concern due to this diversity and the evident risk of serious industrial fires, exemplified by the fire at Buncefield in 2005. It is widely reported that the presence of polar solvents can cause difficulties when tackling fires, with gentle application of alternative foam critical. However, PFAS-containing foam also suffered similar performance difficulties to those seen with alternative fluorine-free foams and likewise, gentle application was recommended (stakeholder meeting, LASTFIRE, June 2024, Call for evidence, LASTFIRE). It appears therefore that fires in which polar solvents are present can be effectively controlled with alternatives, as long as good practice is adhered to and appropriate training is given.

Issues tackling fires in high ambient temperatures (around 40°C) as well as the temperature of the foam solution and fuel temperature have been highlighted as an area of concern for foam performance with all foam types (AFFF and F3), with LASTFIRE suggesting further work is required to optimise operating in such environments (Call for evidence, LASTFIRE). The use of salt water rather than potable water can lead to concerns surrounding efficacy, however, this was also problematic for AFFF and not an issue unique to fluorine-free alternatives. Some accreditations consider the use of seawater as well as potable water, for more information see Section 3.1.5.2. The Agency is uncertain as to the extent of the use of sea water in these circumstances, but as numerous industrial and petrochemical sites are located in close proximity to the sea it may be of concern in establishments such as ports designated COMAH sites.

Mixing of the fluorine-free foam products to tackle fires has been highlighted as a concern, for example where a large industrial fire is being tackled by multiple appliances. The foams need to be compatible and not cause an unacceptable reduction in protection or cause reduced efficacy. During stakeholder meetings with the FIA, the mixing of foams was discussed, with the conclusions that the mixing of foam concentrate within the tank is not advised, however the finished foams (when combined with water) can be used to tackle the same fire (stakeholder meeting, FIA, Jun 2024). Manufacturers are cautious regarding the mixing of foams, there is an agreement that finished foams can be mixed but compatibility testing is advised. Likewise, LASTFIRE have tested mixing of products with success, however this could be product specific and so testing of the efficacy is critical prior to use (stakeholder meeting, LASTFIRE, June 2024). The concerns around mixing foams are not specific to the petrochemical, chemical and industrial sector, however due to the volumes of flammable liquids on sites, this is the most likely situation where large scale firefighting provisions would be needed, and mixtures of foams may be used due to availability of stock of foam concentrate. To contextualise the requirements, it may take around 100 L of concentrate to tackle a small fire attended by the FRS, but industrial fires can require in excess of 150 tonnes of concentrate (stakeholder meeting, JOIFF, June 2024) and if this exceeds the availability from the immediate area, other foam concentrate can be drafted in, a practice known as mutual aid.

There is some evidence to suggest that establishments such as distilleries can use water mist technology to suppress fire and not rely on foam (CIBSE, 2018) and that water mist technology can be used to assist in the extinguishing and prevent re-ignition of class B fires (Johnson Controls, 2024).

Due to the broad and diverse nature of the substances covered by the COMAH Regulations as well as large volumes, consideration of the firefighting needs of the industries covered needs careful examination to ensure risks to human health and the environment are not compromised in transitioning away from any existing PFAS-based firefighting systems to fluorine-free alternatives. Information provided in the call for evidence has been used to better understand the requirements and concerns of COMAH, petrochemical and industrial stakeholders and the responses received have been summarised below.

5.3.4.2.2 Call for evidence

Overall, around 20 responses from stakeholders linked to the COMAH & Petrochemical industries were received during the call for evidence, including from distributors and suppliers, as well as users of foam.

Themes of responses included:

- Current landscape of foam use at COMAH sites and in the petrochemical industry, including firefighting systems operative in COMAH sites, products used and in some instances quantities and information on frequency of use.
- Efficacy in niche applications, other industrial uses and incompatibility with some substances.
- Costs of transitioning.
- Requirement for guidance for transitioning including threshold levels of PFAS in firefighting systems and guidance on clean out.
- Waste disposal of PFAS-containing foams and rinsate.

- Positivity around the transitioning from PFAS-containing foams.
- Information on industries that have transitioned successfully to fluorine-free alternatives.

5.3.4.2.3 Market analysis

Numerous stakeholders reported using C6 and other PFAS-based foams, including AR-AFFF and fluoroprotein foams. There were indications from some stakeholders that transition away from PFAS-containing foam was being considered, and in some cases all of their sites had transitioned to fluorine-free alternatives or were in the process of doing so.

One importer of foam products reported supplying around 50 tonnes of foam concentrate to the UK market, with the majority of the foam being alcohol resistant synthetic fluorine-free foam (SFFF-AR) (Call for evidence, Hawkes Fire). They report seeing a shift amongst major UK-based oil companies from PFAS-based foams to SFFF-type foams. The importer suggested that there has been a slower transition for smaller companies as there has not been a push from regulators to transition, in spite of some foams such as those containing PFOA being subject to the POPs Regulation.

Specific information from Fuels Industry UK, an industry association who represent eight of the main oil refining and marketing companies operating in the UK reported AFFF are the predominant foams used in UK refineries and terminals (Call for evidence, Fuels Industry UK). Significant stocks of these foams are held on sites as required in COMAH regulations and their use is of particular importance in the extinguishment of alcohol/ethanol fires. CHEM trust (an NGO) state in their information that Equinor, BP, ExxonMobil, Total, Caltex, Gazprom, Bayern Oil, JO Tankers and ODFJEL have already transitioned to fluorine-free alternatives (Call for evidence, CHEM trust).

The FIA reported all new projects they undertake offer non-fluorinated foams, as well as undertaking transitioning projects from PFAS-containing foams to non-fluorinated foam alternatives (Call for evidence, FIA). Use of PFAS foams was reported in the paper industry (Call for evidence, CPI) (industrial but not COMAH use) but it is currently unclear if PFAS-based firefighting foam is required, or if transitioning to alternative fluorine-free foams can be achieved.

5.3.4.2.4 General concerns raised by stakeholders

There are comments raised by industry suggesting that legislative certainty would be well received to aid the transition. In particular, industry are currently unclear about the extent that existing equipment must be cleaned and decontaminated, if concentration limits for residual PFAS are to be proposed after transitioning to F3 (Call for evidence, Recticel Insulation UK Ltd, Fuel Industry UK, CIA). There is a reported reluctance for companies to transition to alternative foams and all the associated costs and downtime for the business to allow the adoption of fluorine-free foams, to then find they may be out of compliance when the legislation is applied.

5.3.4.2.5 Efficacy of fluorine-free alternatives

The FIA and Fuel Industry UK state that for most situations, fluorine-free foams have acceptable levels of performance, with Fuel Industry UK asking for time to ensure effective alternatives are optimised to dispersal systems, to allow for successful transition (Call for evidence, FIA, Fuel Industry UK). Some stakeholders report incompatibility of the alternative fluorine-free firefighting foams to their chemical products (Call for evidence, ITW, CIA). The CIA highlighted that there are concerns around the release of toxic gas from fires such as hydrogen chloride (HCl) release from chlorosilane fires if fires are not effectively controlled and harmful combustion products are released into the air. It is unclear in some instances from the information provided which substances are incompatible with the fluorine-free foams. The CIA are asking for site-specific exemptions where this is an identified problem to ensure effective firefighting measures are in place (Call for evidence, CIA).

Further comments from industry state a reliance on foams that have surfactant properties, able to repel fuel and provide chemical vapour sealing (Call for evidence, Ineos). They report substantial variability and vulnerability in testing of fluorine-free foams to gasoline and alternative foams not being equivalent to C6 performance, particularly at lower expansion rates and on more volatile fuels containing aromatics (crude oils) demonstrated in two named US studies. They also comment that testing of alternatives have shown little evidence of effectiveness against large tank fires.

Concerns were raised by the CIA that fluorine-free alternative foams work best with aerated sprinkler systems, which will incur further costs to sites that do not have these systems in place currently (Call for evidence, CIA).

One stakeholder from the petrochemical sector provided information that the fluorine-free foam they use conforms to BS EN 1568:2008 part 1-4 and the product was required to have an effective response to hydrocarbon and polar solvents (Call for evidence, EET Fuels). The product has similar dilution characteristics to previous fluorinated foam as well as minimum effective operating temperature requirements and one of their two sites successfully transitioned to fluorine-free alternatives.

5.3.4.2.6 Successful transitions

LASTFIRE reported very few concerns with transitioning to fluorine-free alternatives, many tests having achieved fire suppression in under 2 minutes (stakeholder meeting LASTFIRE, June 2024). In summary of their extensive testing programme, LASTFIRE indicated stated that "*PFAS-free foam has been subjected to greater levels of testing than previous generation foams, allowing the opportunity to build a firmer database upon which to build system design principles and possibly optimise foam structure and application* (Call for evidence, LASTFIRE)". This provides confidence in the scrutiny of the testing of fluorine-free alternatives.

It was acknowledged by LASTFIRE that alternative foams may not be as efficient as AFFF, are not oleophobic and do not have film-forming properties, as well as requiring a more careful application. However, LASTFIRE stated that "they do work well" (stakeholder meeting, LASTFIRE, June 2024). Not all PFAS-containing foams are equally effective; for example, a reduction in performance of some C6 PFAS–containing foams was seen in comparison to C8 PFAS-containing foams as companies previously transitioned away from C8 foams (Call for evidence, LASTFIRE).

The FIA found that by analysing the risk, original design, application rates, foam tank, proportioning system and discharge devices, they could achieve transition to alternatives in every case (Call for evidence, FIA). Examples of sites that have undergone transition to fluorine-free alternatives include aircraft hangers and chemical plants. Most of the existing pipework can be re-utilised by selecting foams with lower application rates, however, discharge devices and proportioning equipment require upgrading. EETFuels also report successful transition to fluorine-free foams at one of their sites (Call for evidence, EETFuels) for which a replacement of infrastructure and concentrate storage facilities was also undertaken.

LASTFIRE have shown fluorine-free foams can achieve virtual extinguishment with an acceptable margin of safety factor, above the standard required for NFPA 11, an international firefighting foam testing standard (see Standards Section 3.1.5). Any flickering observed was also seen with PFAS-containing foams. Polar solvent fires required gentle application, both with PFAS-containing foams, or with alternative fluorine-free foams and the application technique was critical, but extinguishment could be achieved within the requirements of safety standards. When applied to gasoline, E15 and ethanol, testing demonstrated that "*fluorine-free foams can work on hydrocarbons and polar solvents at rates in accordance with NFPA11* (Call for evidence, LASTFIRE)". Crude oil fire extinguishment was also achieved in similar times to PFAS-containing foams using fluorine-free alternatives.

Fluorine-free foams have been developed by numerous companies that conform to the performance standards set out in Section 3.1.5 above, such as:

- BS EN 1568 Part 1-4 - (Respondol ATF 3-6%, produced by Angus Fire; Solberg Re-Healing Foam RF3x6 ATC, produced by Solberg Scandinavian, Norway; and Ecopol Premium, produced by BIOEX SAS, France),
- LASTFIRE - (Ecopol Premium; Orchidex BlueFoam 3x3, supplied by Orchidee in Belgium; Solberg Versagard 1X3),
- UL 162 - (Universal®F3 Green 1%-3% AR-SFFF by National Foam, in the US, and Ecopol Premium, BIOEX SAS))

This is not an exhaustive list and foam concentrates may be assessed to comply with multiple performance standards. One stakeholder commented that a full portfolio of foams, including 1%, 3% and 6% concentrates are available as well as alcohol-resistant foams that are fluorine-free alternatives, covering most if not all use scenarios of firefighting foams (stakeholder meeting, FIA, June 2024). The Agency does not have data on the quantities of the alternative foams used in this sector or details of the limitations of fluorine-free foams in every possible application.

5.3.4.2.7 Transition periods, including ECHA transition periods for Seveso III establishments

ECHA recommended a 10- year transition period for establishments covered by the Directive 2012/18/EU (Seveso III) Upper and Lower tiers (equivalent to COMAH sites in GB (European Commission, 2012)). They documented how the oil and petrochemical industries are prominent users of PFAS-containing firefighting foams and successful testing of alternative foams has happened in some settings. However, also, some adaptations to alternatives or their application and methods were still required to improve the safety margin in specific applications. They referenced large tanks of crude oil and the risk of boil over as an example where adaptations are required. The length of the proposed transition period aimed to ensure "*an orderly, practicable and cost-effective efficient transition, that can take advantage of scheduled maintenance downtimes and similar practices that guarantee the safety of on-site activities*" (ECHA, 2023e).

ECHA used the definition of Seveso III sites as an approximation to encompass establishments that would require a longer transition period. They intended that only Seveso III establishments with dangerous substances of the hazard classes P2 (flammable gases), P3a, P3b (flammable aerosols) and P5a, P5b and P5c (flammable liquids) (involving flammable liquids) should be subject to this transition period by requiring

PFAS foams only be used for fires involving flammable liquids and not other classes of fires. Where PFAS-containing firefighting foams are required, ECHA recommended that local management plans must be put in place to ensure there is justification for their use.

Municipal fire brigades in charge of industrial fires of Seveso III establishments were also given a 10-year transition period, for this use only. ECHA also recommended that this period could also cover port facilities, which would either have the 10-year transition period (Seveso III establishments) or 5 years, as with other onshore oil/gas/chemical manufacturing or processing facilities not covered under the Seveso III definition. Portable extinguishers on Seveso III establishments would be subject to a 5-year transition period – specific to fire extinguishers across sectors – under the ECHA proposals.

ECHA recommended a review of availability of alternatives for Seveso III installations at the end of the time-limited derogation to reduce remaining uncertainty about unwanted impacts of the restriction in terms of fire safety (ECHA, 2023b).

5.3.4.2.8 Uncertainties and remaining concerns relevant to the technical assessment

There are no reports available to the Agency of fluorine-free alternative foams being used in live fire situations within this use sector and therefore no evaluation of the efficacy of these foams in real-life situations has been undertaken. Whilst it is probable that industrial fires have been suppressed by fluorine-free foams since their introduction, information of their use in live fire situations would allow the Agency to fill gaps in knowledge and evaluate where alternatives have not been successful or, alternatively, have effectively suppressed/ extinguished fires.

Whilst there are some situations fluorine-free foams are thought to be unsuitable for use, the Agency cannot confirm that every use scenario has been captured. Linked to the point above, further information would be valuable to the Agency in order to assess situations where PFAS-containing foams are currently in use and no known viable alternatives have been found.

Concerns highlighted by stakeholders (call for evidence) which merit consideration when considering transition periods include:

- Chlorosilane vapour suppression (Call for evidence, CIA)
- Costs and practicalities of transitioning to fluorine-free alternatives (including associated down time for business whilst fire safety is compromised).
- Alcohol/ethanol fires and concerns surrounding efficacy in very small number of uses with certain substances.
- Mixing of fluorine-free foam concentrates providing less efficacious foam.
- Disposal of PFAS foam stock.

5.3.4.2.9 Summary for the COMAH & Petrochemical sectors

Chemical substances and volumes used in this sector are diverse, and a range of foams are required to effectively control fires, dependant on the type of flammable liquid, including alcohol resistant foams for polar solvents. Fluorine-free foams have been developed for a large range of fire scenarios and have undergone extensive trials where they appear to effectively control fires in test situations, meeting approved international standards for efficacy.

There is evidence to suggest that transition to fluorine-free foams has happened at some sites, with more sites reportedly in the process of transition, often to coincide with planned downtime and maintenance as this reduces cost of taking a site out of production and fire safety being compromised. Stakeholders have suggested that whilst there are ongoing trials into fluorine-free foams in some niche applications, they are currently not sufficiently efficacious to ensure a suitable level of fire safety. These include suppression of some vapours in chemical plants, but there may be other uses that require PFAS foams where transition may compromise safety that the Agency is unaware of.

ECHA recommended a transition period of 10 years, with a further review before the end of this time (ECHA, 2023b). ECHA's intention was to limit the use of PFAS foams to class B fires only (reducing the number of establishments able to benefit from this transitional period) and this recommendation did not cover port facilities, onshore oil/gas/chemical manufacturing sites or processing facilities not described specifically elsewhere. A 5-year transition period was recommended in these instances. The Agency believes that a similar recommendation would be appropriate for GB, to allow time for review and refinement of foams to meet sufficient safety standards to protect human life and ensure that all sites can safely use fluorine-free foams as needed.

5.3.4.3 Offshore

5.3.4.3.1 General Concerns

There are concerns within the offshore sector that fluorine-free replacements are not as effective as PFAS-containing foams, are incompatible when mixed with salt water and that F3 alternatives are only tested with fresh water. Compatibility with low temperature (-18°C) requirements is also a concern. Additional concerns relate to the costs of replacing equipment (i.e., not being able to decontaminate existing systems and reuse), which is seen as extremely expensive with significant issues around increased storage space requirements, installation(s) downtime and associated costs, and transporting stocks and old equipment back to shore after transition (personal communication, HSE Offshore, May 2024).

5.3.4.3.2 Call for Evidence

Offshore Energies UK (OEUK), the UK based trade association for offshore energy organisations highlighted the following concerns relating to F3 use in the offshore sector (stakeholder meeting: OEUK June 2024):

- Fluorine-free foams have not yet passed low temperature, sea water UL162 accreditation. The US Navy issued a statement indicating that F3 foams for application in seawater are "*not authorised for US Navy shipboard use.*"
- A Swedish study (Dahlbom *et al.*, 2022) indicated that, in general, seawater negatively impacts fire test performance.
- Viscosity issues with F3 at low temperatures.
- Compatibility issues with mixing different F3, preventing its use in 'mutual aid' and/or supply chain issues.
- Compatibility issues between F3 and dry powder extinguishing agents.
- Difficult, complex and expensive decontamination with integral equipment *"not easily removed, cleaned, or replaced"*, leading to excessive installation downtime and loss of fire protection coverage.
- Costly retrofit of F3 systems into mid- /end- of life stage assets and limitation of space where F3's require larger volumes for storage and effective fire control than the PFAS foams, particularly as there is currently no 1% F3 Concentrate on the market. *"As the majority of offshore operators utilise 1% AFFF concentrate in their foam-enhanced deluge systems and helideck fire protection systems, this would*

require a substantial increase in foam concentrate storage space due to the increased proportioning rate and increased application time to ensure fire control and extinguishment."

- Retrofit of F3-compatible proportioning equipment and associated pipework leading to downtime and lack of fire protection coverage. Any requirement to collect all discharged foam solutions would need suitably sized collection tanks to be installed downstream of the proportioning equipment. Training foams comparable with PFAS-containing foams could be used as a measure to reduce PFAS discharge, but would require retrofit of additional tanks, pipework and directional valves again leading to downtime and lack of fire protection coverage.
- Uncertainty of effectiveness of non-aspirated systems utilising seawater especially in extreme/windy conditions.
- Uncertainty regarding fire safety performance of F3 is magnified when coupled with low temperature and seawater compatibility issues.

Given the greater risks found for offshore personnel, OEUK argued that offshore sites should be regarded in the same way as ECHA has recommended for Seveso III installations. They should be subject of a review before the end of the proposed 10-year transition period to establish availability of alternatives. Oil Technics Ltd (a formulator and distributor) which provides C6 PFAS AFFF for low temperatures raised issues regarding F3 performance, stating that there is no drop-in fluorine-free alternative for the offshore sector (stakeholder meeting, FIA, Jun 2024). Oil Technics summarised the disadvantages of transitioning to F3 for the offshore sector:

- Current evidence confirms F3 are not capable of effective operation at temperatures of -18°C using seawater with non-aspirated delivery devices required offshore to overcome wind, and because of reduced proportioning accuracy/reliability due to viscosity issues.
- The reduced performance increases the risk of fire escalating out of control and potential for a catastrophic event with significant risks to human lives and the environment.
- Potential for incomplete fire control (e.g., smouldering, edge flickering) with F3 may increase the risk of reignition and structural failure particularly with composite materials (e.g., carbon fibre). [NB, it is not known by the Agency to what extent composite materials are used in the offshore sector].
- Incompatibility with dry chemical powder applications, particularly on helidecks for engine fires.
- Disproportionate costs to allow transition to F3 requiring shut-down, including system flushing and decontamination, re-engineering, retro-fitting equipment, recommissioning and retraining, particularly "*when increasing decommissioning of UK and EU offshore installations are scheduled around 2030"* (Call for evidence, Oil Technics).

The Agency followed-up with some platform operators, with communication facilitated by OEUK as the representative trade organisation. The China National Offshore Oil Corporation (CNOOC) stated that it has considered F3 for use in its offshore installations but concluded that no suitable drop-in alternative was available without extensive system modification. CNOOC further stated that it had no major concerns with decontamination of equipment that previously held PFAS-containing foam, but the transition would be expensive and would require considerable down time of systems during decontamination. Furthermore, the replacement equipment required would be expensive and the transition would *“require additional system modifications to incorporate additional storage capacity and possibly testing facilities,”* again with significant system down time. CNOOC felt the main cost implication would be the *“requirement to change out proportioning equipment, increase storage tank capacity and provide winterisation heating for storage tanks and concentrate supply pipework.”* Installation of additional test facilities would be required to produce test foam *“to assure ongoing induction accuracy of equipment.”* Whilst the company did not think additional training would be required it considered that potential higher application rates associated with F3 use would require increased nozzle sizes, proportioners, storage tanks and potentially distribution pumps and pipework (Call for evidence, CNOOC).

OEUK, responding on behalf of their members, also described how Shell had stated that it does not use F3 offshore as *“it does not meet the requirements for operating in the North Sea.”* Shell considered that a foam meeting the required specifications is at least 10 years away but did not think additional training or alternative equipment (e.g. nozzles, monitors) would be required (Call for evidence, OEUK).

Responding to the Agency’s stakeholder questions, LASTFIRE stated that research has indicated F3 to be less effective when used with seawater; however, such foams may still be used but might require longer application depending on the circumstances. LASTFIRE considered that fire situations that are inappropriate for F3 uses would also be those where PFAS-containing foams were also unsuitable (e.g. water reactive products, running spill fires, very high volatility fuels) (Call for evidence, LASTFIRE).

Angloco Limited, an importer and formulator of foam products that began providing fluorine-free foams in 2007, stated that "*we now provide PFAS-free to all market sectors of fire and there is at least one PFAS-free foam for every application or scenario. There are no sectors where PFAS is still required - only legacy users who are reluctant to change"* (Call for evidence, Angloco). Angloco further clarified that they provide a full range of 1 %, 3 %, 6% foams, IMO (International Maritime Organization) foams and saltwater-compatible foams, demonstrating there are a full range of foams available to the UK market for transitioning (stakeholder meeting, FIA, Jun 2024).

5.3.4.3.3 Successful Transitions

Equinor, an operator representing 80 % of all oil production on the Norwegian continental shelf, successfully replaced PFAS-containing foams in about 40 offshore installations and five onshore facilities within 8 years (stakeholder meeting, Equinor, Oct 2024; IPEN, 2019; Wood, 2020). In 2012, Equinor successfully developed a suitable F3 foam in collaboration with Solberg Scandinavian. The replacement F3 required compatibility with the following specifications:

- certified according to BS EN 1568 - standard for extinguishment and burnback;
- no fluorine or other halogens;
- suitable for sub-zero conditions; and
- complete human health and environmental documentation.

Challenges included application to -18°C and viscosity.

The product selected was Solberg’s Re-healing RF1, 1% foam. It was not necessary to use larger volume tanks for the replacement foam (stakeholder meeting, Equinor, Oct 2024; Equinor, 2024). Substitution was completed on 40 offshore installations during scheduled maintenance stops, with 300 tonnes of firefighting foam substituted from 2013 – 2016 at a cost of approximately £ 1 - 2 million (stakeholder meeting, Equinor, Oct 2024; IPEN, 2019); equating to approximately *“£ 3 per litre (2014 prices) including handling/destruction of old foam”* excluding working hours (stakeholder meeting, Equinor, Oct 2024). Subsequently, Solberg modified Re-healing RF1, 1% foam for a version with lower viscosity compatible with low temperatures and better environmental properties called RF1-AG. This product went into operational use in 2018 for all new fields (IPEN, 2019). It is reported that the transition to F3 has reduced an annual release of 3 to 4 tonnes of PFAS into the environment to effectively zero tonnes (stakeholder meeting, Equinor, Oct 2024). No emergency responses have occurred since the implementation of the substitution. However, fluorine-free foam is used for training and systems testing (stakeholder meeting, Equinor, Oct 2024; ECHA, 2023a).

In 2014, the Norwegian authorities required The Harmonised Offshore Chemical Notification Format (HOCNF) under the OSPAR (Oslo-Paris) Convention 1992 documentation for all high-volume firefighting foam. The product, Solberg Re-healing RF1 was required to be reported under HOCNF, making it clear to other companies that a viable alternative was available, potentially resulting in pressure on the rest of the Norwegian market to transition. As a result, it was asserted that the majority of operators on the Norwegian Continental Shelf currently use F3 in their offshore installations (stakeholder meeting, Equinor, Oct 2024; IPEN, 2019).

For a few installations where there is risk of methanol fire, Solberg Re-Healing Foam RF3x6 ATC (alcohol resistant foam) is used (ECHA, 2022d). However, in the Stakeholder Engagement Meeting of 8 October 2024, Equinor confirmed its policy is to use PFAS-free firefighting foam as standard, unless there is a significant operational challenge to justify exception (stakeholder meeting, Equinor, Oct 2024). The example of Rosebank was given where the FPSO vessel contains large volumes of methanol and ethanol to prevent hydrate formation in the extracted hydrocarbon. AFFF is more effective on polar solvent fires, and Solberg RF-1 is not recommended, nor was their sufficient storage capacity for a 3% foam concentrate and so the option to use F3 was discounted at an early stage of the design process. Equinor are trying to develop a 1% polar solvent appropriate foam (stakeholder meeting, Equinor, Oct 2024).

A further challenge was dealing with contamination from previous PFAS present in tanks and distribution lines. According to ECHA (ECHA, 2022d), Equinor found that costs of decontamination of equipment were not significant and no firefighting equipment or storage tanks were replaced; the storage tanks were emptied and the PFAS-based foams handled as waste (for destruction/incineration). Equinor confirmed that it would not be possible to drain some of the pipelines, but in these cases residual PFAS would be displaced and discharged during the next deluge test (stakeholder meeting, Equinor, Oct 2024). Dilute PFAS concentration wash water/rinsate was discharged to the sea or wastewater treatment plants. It was considered that these small discharges were insignificant compared with continuous use of PFAS (stakeholder meeting, Equinor, Oct 2024; ECHA, 2023a).

5.3.4.3.4 Transition periods for the Offshore sector

ECHA's stakeholders highlighted that many offshore installations are due to be decommissioned before 2030. ECHA agreed that for such installations the cost of transition would indeed be disproportionate. Considering the specific challenges affecting the transition to fluorine-free foams in the offshore sector, ECHA (ECHA, 2023b) recommended the phasing out of PFAS foams within *"10 years after entry into force for installations belonging to the offshore oil and gas industry and a review of the substitution status shall be implemented before the end of the transitional period to address the uncertainty about the successful implementation of alternatives."* ECHA considered the reviews important to maintain safety where fires may have high impacts on the environment and human health (ECHA 2023e).

- The ECHA (ECHA, 2023b) also recommended: Collected PFAS-containing waste resulting from cleaning of firefighting equipment, where the concentration of total PFAS is > 1 mg/L to be handled for adequate treatment.
- Collected PFAS-containing waste resulting from cleaning of firefighting equipment shall be handled for adequate treatment where the concentration of total PFAS is > 50 mg/L for the offshore oil and gas industry and > 1 mg/L in all other uses/sectors.

As derogations, OEUK requested a 10-year transitional period: for the offshore oil and gas industry (where not covered by the Seveso III definition); for the use of PFAS foams in the offshore exploration and exploitation of minerals, including hydrocarbons; and, for transportation of flammable liquids either in pipelines or by road, rail, or ship. Additionally, OEUK requested a derogation for offshore helipads and a higher decontamination limit value of 50 ppm for offshore equipment already installed.

5.3.4.3.5 Uncertainties and remaining concerns relevant to the technical assessment

There is a lack of data regarding the use, quantities and performance of F3 in live incident situations in the offshore sector. Provision of data relating to successful/unsuccessful fire suppression at live incidents may allow the Agency to further evaluate performance of F3 alternatives.

There is conflicting evidence from stakeholders regarding the availability of F3 compatible for use in the offshore sector, with some responding that appropriate F3 do not currently exist and others directly contradicting this either as a supplier or having already transitioned to F3 in the sector. Further information may be forthcoming during the commenting period and consultation with Norwegian regulators.

5.3.4.3.6 Offshore Summary and Conclusion

It is evident that F3 are available for the offshore sector, given that the Norwegian oil producer Equinor and apparently most operators in the Norwegian Continental Shelf have successfully substituted out PFAS-containing foams for F3 alternatives for the majority of installations. However, the Agency is unaware of any serious live fire incidents occurring in the Norwegian offshore sector resulting in deployment of substituted F3 to demonstrate its effectiveness.

Nevertheless, there are concerns within the GB industry related to seawater and low temperature compatibility, disproportionate costs of substitution, decontamination and disposal, retrofitting and resulting downtime and lack of fire protection coverage during downtime. For similar reasons, ECHA recommended a 10-year transition period and a review of the available alternatives before the end of the transitional period to *"address the uncertainty about the successful implementation of alternatives."* On the available evidence, the Agency concludes that a similar approach for GB might be appropriate.

5.3.4.4 Marine Sector

5.3.4.4.1 General Concerns

As with the offshore sector, considerations for the application of F3 concentrates in the marine sector are that they must be able to produce effective foam blankets when proportioned with seawater and to do so at a range of temperatures including extremely low temperatures. There are additional concerns regarding corrosion and the compatibility of fluorine-free foams for on-board storage and deployment (e.g. tanks, proportioners, pipes and nozzles etc), with some foams requiring stainless steel or resistant plastic and others compatible with 'black-steel' (i.e. non-galvanised steel with a hardened iron-oxide / magnetite coating) (Wood, 2020).

Currently PFAS-containing foams and even PFOS-containing foams are still in use in maritime vessels. In relation to the latter, in March 2022 the IMO sub-committee on Ship Systems and Equipment (SSE) 8th session finalised prohibition of the use of PFOS from new ships from 1 January 2026 and to phase out the substance from existing ships and ensure safe disposal ashore no later than five years from the date of this requirement coming into force (BIMCO, 2022; IMO, 2022). Additionally, ECHA found indications from their stakeholders there were PFAS foams used in the marine sector further to the foams identified in the initial survey by Eurofeu. The components of those foams included carboxymethyldimethyl-3-[[(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl)sulphonyl]amino]propylammonium hydroxide (CAS number: 34455-29-3) and 6:2 FTS (Wood, 2020).

EU stakeholders commented to ECHA that civilian maritime vessels can carry wide-ranging bulk flammable fuel cargos including hydrocarbons and polar solvents, which may change with different voyages. Additionally, it may be difficult to refill at the next harbour after a fire at sea since different fluorine-free foams cannot be mixed (ECHA, 2023e). It was also stated that forceful non-aspirated application of firefighting foam is often necessary due to effects of wind, which conflicts with the appropriate well-aspirated application of F3 (ECHA, 2023e).

5.3.4.4.2 Successful Transitions

Fluorine-free foams are currently available that have the accreditation to the relevant IMO standards and the ability to work in fresh and sea water conditions at low, medium or high expansion rates and low ambient temperatures. According to ECHA, marine applications use around 16% of the identified market which equates to around 1,100-1,400 tonnes of fluorine-free foam per year on the European market (Wood, 2020).

Wood assesses some examples of fluorine-free foams currently in use including:

- Angus Fire: Respondol ATF 3-6 %.
- Dr Sthamer, Germany - FOAMOUSSE® 3 % F-15, a protein-based product, a low expansion foam typically used in non-polar hydrocarbon fires. This is well established as a fluorine-free alternative, developed before the regulatory drive towards PFAS-free foams. It has compliance to BS EN 1568 part 3 (Wood, 2020).
- BIOEX SAS: Ecopol Premium, which conforms to BS EN 1568 1-4 at the highest level as well as IMO 1312, and is *"effective on class B hydrocarbon fires using gentle or forceful application with slow drainage time. Intended for alcohol fires (water-immiscible liquids), it covers all class B risks of fires encountered on ships, and also makes it possible to use it as High Expansion to drown ships' holds or engine rooms"* (BIOEX, 2024; Wood, 2020).

Other examples of fluorine-free foams applicable for use in the marine sector include: Bio Foam (supplied by BIOEX) - low, medium and high expansion foam, with the latter designed to flood large volumes such as ships holds, and Dafo Fomtec AB: Enviro SEA 1, 3, 6 %) and Enviro USP (both supplied by Dafo Fomtec AB in Sweden).

5.3.4.4.3 Transition periods for the Marine sector

It has been suggested that marine applications in particular should be prioritised for a swift transition due to the potential for retention of runoff, challenges regarding clean-up after incidents, and established alternatives being available (Wood, 2020). The marine sector was identified as having an *“average potential for fire-safety risks from using alternatives”* (Wood, 2020). At the same time the PFAS risk reduction potential is identified as very high as the sector has the *“lowest potential for retention of run-off and clean up after incidents”.* Therefore in using alternatives there is potentially an immediate and significant reduction of PFAS emissions, notwithstanding any environmental risks associated with the F3 alternatives (Wood, 2020). A short transition period for marine applications of 3 years based on the market availability of alternative products and limited ability to contain foams during use is recommended (Wood, 2020).

ECHA concluded that transition for the marine sector appears less difficult compared with the offshore sector, noting that some of their stakeholders had advised that *“even a 3-year transitional period would be suitable in their case.”* However, they recommended a 5-year transitional period for the marine sector, following further stakeholder engagement (ECHA, 2023b).

5.3.4.4.4 Uncertainties and remaining concerns relevant to the technical assessment

There is a lack of data regarding the use, quantities and performance of F3 in live incident situations in the marine sector. Provision of data relating to successful/unsuccessful fire suppression at live incidents would allow the Agency to further evaluate performance of F3 alternatives.

From consultation with Eurofeu, there is uncertainty regarding breakdown of foam tonnages by user sector. “*Generally, “chemical/petrochemical” is expected to include offshore oil and gas platforms (in addition to refineries and other facilities storing, processing or transporting flammable liquids) while “marine” applications refers to the shipping industry. However, due to the above uncertainty some of the tonnage for marine applications may also reflect use in offshore oil and gas platforms”* (Wood, 2020). The Wood report estimates the marine sector (which may or may not include offshore and gas platforms) accounted for 12% of the sales of PFAS-based firefighting foams and 16% of the sales of fluorine-free foams. The sector uses and amounts used in the UK are as yet unknown (Wood, 2020).

The Agency considers that an important regulatory and policy consideration for the marine sector relates to regulation of vessels operating within different maritime zones e.g., territorial water, contiguous zones, exclusive economic zones etc. Whilst it might be more straightforward to restrict PFAS-containing FFF for GB-owned and/or registered vessels, there could be issues with implementing, monitoring and enforcing such a restriction. Environmental and human health risks from continued use of PFAS-containing foams will be the same for all vessels, size-depending regardless of their origin. A restriction could be possible for GB owned and/or registered vessels, but the Agency acknowledges that other international vessels may be equipped with PFAS foams when they enter GB territory. This will be considered further during the opinion development phase.

The Merchant Shipping (Marine Equipment) Regulations (UK Government, 2016b) regulate marine firefighting and safety. Also, ECHA’s recommendation noted that, in the civilian marine sector, certain uses of firefighting foams are regulated by IMO rules under Directive 2014/90/EU (European Commission, 2014). This directive transposes IMO requirements “and makes them applicable on vessels flying the flag of an EU Member State”. ECHA noted that a similar measure at IMO level would be needed for the application of a restriction under EU REACH on firefighting foams to all sea-going ships calling at EU ports. As directive 2014/90/EU is implemented in UK Law, the Agency considers a restriction under UK REACH could also require similar measures at IMO level for ships calling at GB ports.

5.3.4.4.5 Marine summary and conclusion

Some fluorine-free firefighting foams capable of effectively extinguishing class B fires are currently available for the marine sector. However, similar concerns to the offshore sector regarding saltwater and low temperature compatibility, use in high wind conditions and potential to cause corrosion, as well as compatibility between different F3 and for different cargos are acknowledged.

For the proposed EU restriction, a 3-year transition period for the marine sector was initially proposed. This aimed to address the higher risks relating to direct emission to water. Further to this, following stakeholder engagement, ECHA recommended a 5-year transition period given the sector’s requirement for transport of bulk flammable fuel cargos including hydrocarbons and polar solvents, variety of cargo between voyages, and logistical difficulty with refilling and compatibility between different foams. The Agency considers that these issues would be relevant for GB and therefore a similar recommendation for a 5-year transition period would be appropriate. The European Commission appear to suggest a 10-year transition period for existing vessels in the recitals of their draft restriction. The Agency will consider this further during opinion development.

Application to this sector of any restriction, given the international nature of maritime shipping, will also require further consideration during the opinion development stage.

5.3.4.5 Aviation Sector

5.3.4.5.1 General Concerns

Concerns have been raised regarding the comparative performance of F3 to AFFF foams, and extensive testing has been undertaken. Trials conducted to US Military Specification MIL-PRF-24385F and International Civil Aviation Organization (ICAO) Level C standards for extinguishment time, burnback resistance, and drain down time amongst others; and additional live fire tests with modified parameters, e.g., fuel type, application method, and pre-burn duration found that in general none of the F3 *“evaluated had an equivalent extinguishing performance to AFFF”* (Back and Farley, 2020; Casey and Trazzi, 2022; Hinnant *et al.*, 2020).

It is evident that extinguishing performance will vary between different F3 with different fuel fire types, and with discharge devices and proportioning systems (Back and Farley, 2020; Casey and Trazzi, 2022; Hinnant *et al.*, 2020). The 2020 Fire Protection Research Foundation (FPRF) report (Back and Farley, 2020) concluded that F3 *“are not a “drop in” replacement for AFFF. However, some can be made to perform effectively as an AFFF alternative with proper testing and design (i.e., with higher application rates/densities).”*

The FAA stated that currently available F3 tend to take longer to suppress a fire, require larger volumes of foam to maintain the blanket, and are more likely to result in reignition if it is disturbed or the foam structure collapses more quickly (FAA, 2023). F3 may also be miscible with the fuel allowing formation of low burning flames across the blanket; and, contamination of the foam with the fuel will likely lead to faster degradation of the foam structure (FAA, 2023).

5.3.4.5.2 Call for Evidence

Oil Technics asserted that foam testing standards have not been varied for F3, *"except perhaps ICAO, which changed from a 60 second extinguishment criteria to a 60 second control and 120 second extinguishment criteria in 2014"*. Oil Technics claim this was to allow F3 to be certified because they were unable to extinguish the test fires within 60 seconds. Oil Technics also asserts that the US MILSPEC standard was 'weakened' for F3, *"by aligning it closer to ICAO Level B fire test criteria, not the higher ICAO Level C criteria, which is nearer the original US AFFF MILSPEC"* (Call for evidence, Oil Technics).

Oil Technics also asserted *"Extensive independent fire testing shows on average there is a need for higher F3 volumes to extinguish a flammable fuel (same quantity of fuel) fire compared to AFFF. Particularly when gasoline or E10 (gasoline with 10% Ethanol added) fuels are involved.*" Further, fires may more easily re-ignite using F3 during a major incident, in particular with jet fuels and composite materials used in aircraft-structures, Oil Technics citing the A350 fire in Tokyo (Wilson, 2024), and that *"composite materials are making fires harder to control."* Oil Technics asserted that it is unaware of any major aircraft fire incident to date *"where F3 has worked rapidly, effectively and reliably to verify its functionality under challenging fire conditions"* (Call for evidence, Oil Technics).

Churches Fire Security maintained PFAS firefighting foam systems at British Airways maintenance hangers at Heathrow Airport, Cardiff Airport and Gatwick Airport and Airbus at Broughton and Filton. The company confirmed that it is looking at their removal and replacement with fluorine-free alternatives. As the use of fluorinated foams was stopped in 2016 on assets controlled by Heathrow Airport Ltd, and Churches is working on the transition of the British Airways hangers based at Heathrow, This indicates that separate commercial entities within different airports and at least at Heathrow may not yet have fully transitioned (Call for evidence, Churches Fire Security).

Highlands and Islands Airports Limited (HIAL) confirmed that it is still using PFAS-containing foam (Angus Petroseal C6 3%) across the 11 HIAL airport locations but had a live tender for supply and ongoing testing of a fluorine/PFAS-free foam to replace its current stocks (22,000 litres) (Call for evidence, HIAL).

JOIFF (The International Organisation for Industrial Emergency Services Management) confirmed that high hazard industry and aviation sectors are by far the biggest consumers of firefighting foams comprising approximately 70% of sales (stakeholder meeting, JOIFF, Jun 2024). JOIFF confirmed that significant progress in the development of fluorine-free foams has been made in the last 10 years, driven by large investment due to the push away from PFAS-containing foams and that fluorine-free foams are rigorously tested. JOIFF stated that non-fluorinated foams are now equivalent to AFFF foams and whilst there are application differences between fluorinated and non-fluorinated foams, there is no barrier to transition to alternatives other than the cost (stakeholder meeting, JOIFF, Jun 2024).

The FIA stated that at airports that have transitioned, there is little desire to move back to AFFF as there are clear performance benefits to fluorine-free alternatives e.g., less burnback and ability to use non-aspirated monitors which increase the distance the foam can travel (stakeholder meeting, FIA, Jun 2024). It was the opinion of some of the FIA members that derogations would just allow for delays in transitioning, and they are not necessary (stakeholder meeting, FIA, Jun 2024). IPEN (2018) reflects a similar viewpoint stating *"there is absolutely no need for any exemptions, whether conditional, i.e., derogations, or otherwise, allowing the continued use of existing or new stocks of fluorinated foams (including those containing free PFOA, its salts, or PFOA precursors) as the local regulatory legislation of almost all jurisdictions has more than adequate* *provisions to permit transition to best practice with controls, milestones and timelines appropriate to the particular circumstances."*

5.3.4.5.3 Successful Transitions

The CAA reported that an airport Rescue and Firefighter service survey found that 71% of licensed aerodromes in the UK use fluorine-free and organohalogen-free foam concentrate (stakeholder meeting, CAA, Jun 2024). The survey only included large aerodromes and there was no information on smaller/general aviation aerodromes (gliding centres, private airstrips) for F3 use. Information on the number of sites surveyed or whether all sites responded to the survey was not provided. The CAA also expressed concerns that the surveyed aerodromes may have sold their PFAS AFFF stock to the smaller sites. The CAA stated that larger sites that have not transitioned are hesitant due to the costs of changing their infrastructure and the disposal and storage of legacy PFAS AFFF.

The CAA does not mandate the type of foam used, only the quantity of foam, discharge and performance level (ICAO levels) required for different sizes of aerodrome. ICAO level C is regarded as the most optimal performance standard due to it requiring the least amount of foam concentrate to provide the highest quantities foam when mixed. This can reduce the size of vehicles needed and number of personnel needed, reducing cost (stakeholder meeting, CAA, Jun 2024). The CAA highlighted an example where one of the transitioned runways had an incident where F3 was used and 1 hour after this the runway was fully clear and ready to be used again. In contrast, PFAS-containing foam would have required cleanup, storage and incineration costs. Similarly, it is possible to train with the same F3 foams as will be used in any live incident, without required cleanup, storage and incineration costs of PFAS-foams. These points may be juxtaposed with the anticipated costs of transitioning (stakeholder meeting, CAA, Jun 2024; IPEN, 2018).

A significant number of airports within the UK (including: MAG group - Manchester, London Stansted and East Midlands; Heathrow; Gatwick; London Southend; London City; Newcastle; Birmingham; Leeds; and Bradford) and internationally (e.g., Copenhagen, Stockholm, all of the 27 major airports in Australia, Auckland, Dubai, Dortmund and Stuttgart) have already transitioned to F3 (IPEN, 2018; Wood, 2020) on the assets that these airports control. Transition on all of these airports may not be complete as some of the companies who maintain assets such as hangers on these airports, such as British Airways on Heathrow and Gatwick are currently transitioning, as shown by the information submitted by Churches Fire Security in the call for evidence. F3 meeting the ICAO standards include Solberg Re-healing Foam RF3x6 ATC used in Copenhagen, Orchidex BlueFoam 3x3 (Incendin) in Germany and Moussol FF 3x6 (Dr Sthamer) in Sweden and Heathrow (Wood, 2020).

In the US, manufacturers are able to submit new F3 for MILSPEC qualification by the Department for Defence (DoD). Once MILSPEC-qualified, the foam is placed on the DoD Qualified Products Database (QPD) (US DoD, 2024a). The FAA has confirmed that once an F3 has passed the military performance standards MIL-PRF-32725, and been listed on the QPD, it meets FAA requirements and use of the specified F3 complies with its regulations (Code of Federal Regulations Title 14; Aeronautics and Space (14 CFR part 139)) for use at Certificated Part 139 airports (FAA, 2024). By April 2024, the US Department of the Air Force was committed to purchase more than 270,000 gallons of the new F3 at a cost of approximately $8.55 million and replacing stocks of AFFF in fire and emergency services vehicles with F3. Overseas installations were the first to transition to the new F3 (Miller, 2024). As of October 2024 (US DoD, 2024a), there were four entries for F3 meeting MIL-PRF-32725 listed on the QPD for Type 3, 5, 55 and 265 gallon for use in military and civil aviation:

- National Foam INC
    - AVIOF3 GREEN MIL 3% NSN: 4210-01-723-4452 (5-GAL CONT.)3AVIOF3 GREEN MIL 3% NSN: 4210-01-723-4435 (55-GAL CONT.)3AVIOF3 GREEN MIL 3% NSN: 4210-01-723-4442 (265-GAL TOTE)3BIOEX INC 3ECOPOL A3+ MILSPEC NSN: 4210-01-714-8276 (5-GAL CONT.)3ECOPOL A3+ MILSPEC NSN: 4210-01-714-8284 (55-GAL CONT.)
    - ECOPOL A3+ MILSPEC NSN: 4210-01-714-8267 (265-GAL TOTE)
- Perimeter Solutions LP
    - SOLBERG 3% MIL-SPEC SFFF (ESP) NSN: 4210-01-713-4370 (5-GAL CONT.)
    - SOLBERG 3% MIL-SPEC SFFF (ESP) NSN: 4210-01-713-4366 (55-GAL CONT.)
    - SOLBERG 3% MIL-SPEC SFFF (ESP) NSN: 4210-01-716-2476 (265-GAL TOTE)
- Perimeter Solutions LP
    - SOLBERG 3% MIL-SPEC SFFF NSN: 4210-01-713-4370 (5-GAL CONT.)
    - SOLBERG 3% MIL-SPEC SFFF NSN: 4210-01-713-4366 (55-GAL CONT.)
    - SOLBERG 3% MIL-SPEC SFFF NSN: 4210-01-716-2476 (265-GAL TOTE)

These products are not authorised for use on board US Navy ships, are not intended for use on polar solvents, and are not to be pre-mixed. (US DoD, 2024a).

5.3.4.5.4 Transition periods for the aviation sector

When discussing potential transition periods Wood (Wood, 2020), acknowledged that whilst *“alternatives are considered feasible and have been implemented by many users”* there is a concern that *“if the use of alternatives caused any increased fire-safety risks, the potential damages could be significant and would likely include danger to human life”*.

ECHA recommended a transition period of 5 years for civilian aviation for the restriction of PFAS foams after entry into force of an EU REACH restriction (ECHA, 2022b). ECHA acknowledged that the aviation sector is one where there could be significant detrimental impact to human life if a foam did not perform well, but also considered there could be significant, continued environmental impacts of PFA foams associated with the difficulty of containment of firewater. In concluding on the proposed 5-year transition period, ECHA stated that it is *“therefore especially important that the transitional period applied is neither too short nor unnecessarily long”* but that a compelling case for a shorter transition period was not presented (ECHA, 2023e).

In contrast, foam product manufacturer Oil Technics suggests extending the transition period to 10 years for the aviation sector (Call for evidence, Oil Technics) due to their concerns over inferior performance and increased application rates, in particular for new composite aircraft. This is in contrast to the experience of a number of large airports who have already transitioned to F3.

5.3.4.5.5 Uncertainties and remaining concerns relevant to the technical assessment

There is a lack of data regarding the use, quantities and performance of F3 in live incident situations in the aviation sector. Provision of data relating to successful/unsuccessful fire suppression at live incidents would allow the Agency to further evaluate performance of F3 alternatives.

5.3.4.5.6 Aviation summary and conclusion

Fluorine-free firefighting foam alternatives already exist. They are used by major GB airports and internationally. Stakeholders consider that whilst non-fluorinated foams require different firefighting techniques and design, they can be equivalent to PFAS-containing foams in their ability to extinguish fires. Additionally, there are advantages in terms of post-incident clean up and runway turnaround with use of fluorine-free firefighting foam, as well as reducing liability for environmental and human health impacts associated with PFAS use. However, the Agency also recognises the potential for significant risk to human life if fluorine-free foams fail to be effective.

The Agency considers on this basis that a similar transition period to that recommended by ECHA of 5 years would be appropriate for a restriction under UK REACH. Perhaps even a shorter period of 3 years could be justified, given 70% of "surveyed" aerodromes have transitioned (and the ECHA restriction may have been in force already). This will be considered further during opinion development.

5.3.4.6 Military/Defence

5.3.4.6.1 General Concerns

As noted in Section 3.1.5, this sector relates to use of FFF on land either owned by the Ministry of Defence (MoD), or where the MoD has rights to the land or assets owned by or operated on behalf of the MoD.

Due to the overlap of uses of FFF in the defence sector with other sectors, many of the concerns relating to alternatives are the same as those highlighted elsewhere. Concerns on air bases are similar to those in the aviation sector, the navy has encountered issues similar to those of the marine and offshore sectors regarding F3, dedicated municipal fire services for military bases have similar concerns to the civilian municipal sector, and bulk fuel storage sites on MoD-owned land has similarities to the COMAH sector. In addition, potential proximity to munitions and use of FFF during live training or combat scenarios, including use at extreme temperatures pose unique challenges for this sector. (Darwin *et al.*, 2005; 2017)

5.3.4.6.2 Call for evidence

During the call for evidence, the Agency engaged with representatives from the MoD. Although the specific information gathered during this consultation is confidential, it was evident that there has already been considerable transition to F3 across the MoD in accordance with the Defence Fire & Rescue Structural Fire-fighting Regulations (2024). These stipulate how “foam products should be free of PFAS, or any derivative that is persistent in the environment” (Defence Safety Authority, 2024). This is considered defence regulatory advice, where alternative approaches may be utilised where the outcome is as good as the regulation.

The MoD expressed concerns regarding any potential requirement to either fully replace or decontaminate current foam storage tanks and equipment, although this is likely based on the EU restriction requirement to ensure the levels PFAS is not present above 1 mg/L, rather than any ability to decontaminate more broadly.

The Agency is aware of instances in which there are challenges in transitioning to F3, particularly for naval vessels, where it is suggested current products are not viable. The US DoD’s MILSPEC certification, which looks to certify PFAS AFFF and F3 that are viable for military applications, indicates that F3 products assessed are “not to be authorised for US Navy shipboard use” (MIL-PRF-32725). However, this may be related to the scope under which the certification was created – for installations and not vessels – rather than specific deficiencies with F3 products.

5.3.4.6.3 Transition Periods

Given that this sector overlaps significantly with other sectors, it follows that a suitable transition period for the military/defence sector could be based on the transition period for the most challenging sector. However, given that this overlap includes COMAH sites, it also may be difficult to justify a 10-year period for the whole sector, where other parts of the sector could transition much sooner.

ECHA suggests that the readiness to transition varies greatly between individual nations (ECHA, 2023e). Accordingly, making use of the Article 2(3) defence exemption in EU REACH was seen to be beneficial, however could be arduous to administrate across Member States and pose particular challenges in providing a harmonised level of protection across the EU. With UK REACH only applying to a GB, it may be simpler to make use of this exemption where appropriate. As such, it could be useful to propose a shorter transition period – in line with marine or aerospace uses, and have relevant stakeholders use the Article 2(3) exemption where necessary, for example if greater time is needed for defence COMAH sites.

The Agency will continue to engage with MoD during opinion development. Since there has already been some transition to F3, in the absence of further information, a transition period in line with that suggested by ECHA – 5 years – should be sufficient.

5.3.4.6.4 Certifications

The MoD have firefighting standards that are adaptations of the civilian counterparts for a specific sector, including the ICAO for the Air Force and IMO for Naval vessels. The exact details are confidential.

In addition to the European standards and sector-specific civilian certifications, there have been a variety of international test standards designed specifically for military testing and applicability of FFF. In the US, for example, the DoD standard MILSPEC indicates approval of foam for use by the military, except for use on board navel vessels. Both Ecopol A3+ and Solberg 3% have met the standard.

The company 3F have a synthetic fluorine-free foam concentrate marketed under the name Freedol, which has met multiple performance standards, appears to have been assigned a NATO stock number. However, there is limited information publicly available on this and it is unclear what the specific requirements are to obtain this classification listing. The Agency has found no other foams listed in this way, and that includes MILSPEC certified ECOPOL products. Further, stakeholder engagement confirmed that this is likely not relevant to MoD and it therefore appears it may be an arbitrary classification by the manufacturer.

5.3.4.6.5 Summary and conclusion

Use of FFF by MoD resembles several civilian sectors, including aviation, marine and transport, with the added hazard of a fires proximity to explosives or munitions. This variety within the sector makes transitioning the entire sector to F3 complicated and multifaceted. Airbases will contend with same risks as the civilian aviation industry, where much transition away from AFFF has already occurred and alternative foams are readily available. Most bases also have a dedicated fire and rescue service, similar to civilian municipal fire and rescue, that services the MoD site and the surrounding residential areas in cases of emergency. As for civilian airports, alternative foams are readily available and transition to alternatives appears viable.

There are MoD sites that house large fuel storage areas, similar to COMAH sites, and uncertainty over the efficacy of F3 to tackle a large tank fire exists. However, this is mostly founded in F3 not having been tested in such a real-life scenario.

Naval bases are situated in coastal areas in the UK and, similarly to ports and docks, are serviced by municipal fire services that use integrated foam systems with fresh water. Naval vessels operate across the globe in a variety of conditions, including sub-zero temperatures, and their integrated foam systems use seawater. Similarly to the offshore and marine sectors, low temperatures, seawater and strong winds offer significant challenges for foam products to overcome.

The Agency is not currently aware of viable alternatives for handheld portable extinguishers that are used by the military in sub-zero temperatures, or for portable extinguishers from 90 to 150 L in size. However, viable alternatives are available for 3, 6 and 9L extinguishers. A more extensive consideration of portable extinguishers follows in the next sub-section of this report.

The Agency will continue to engage with MoD during opinion development – particularly regarding use on naval vessels and portable fire extinguishers. Until further information is received, the Agency suggests a 5-year transition period in line with that suggested by ECHA, with further consideration of a 10-year transition period for existing military vessels as suggested by the European Commission (2025).

5.3.4.7 Ready-to-use

5.3.4.7.1 General Concerns

According to BS EN3-7, a portable fire extinguisher is defined as a fire extinguisher which is designed to be carried and operated by hand and which in working order has a mass of not more than 20kg. The ready-to-use category also includes mobile extinguishers up to 150 litres (BS EN 1866; wheeled units) and spray-can extinguishers (BS EN 16856).

Integrated “wet” foam sprinkler systems are also defined as ready-to-use. However, they are far less widespread, being reserved for large areas considered at a high risk of a liquid based fire (e.g. aircraft hanger). They work by housing a foam concentrate and deionised water in a storage tank that combines and is deluged over the affected area automatically upon detection of a fire/activation. According to Eurofeu, the integrated “wet” systems are extremely rare compared to the handheld units (ECHA, 2023e). In view of this, and because “wet” systems are used across a variety of sectors and have unique uses and challenges, this analysis of alternatives for ready-to-use products will focus primarily on the handheld portable units. Information for the integrated “wet” systems can be found in the sector specific sections where appropriate.

Fluorine-free portable fire extinguishers are generally readily available on the GB market, with standard spray can 3, 6 & 9L extinguishers (BS EN 16856) retailing at similar prices to their PFAS counterparts. These cover the majority of use in this sector and are utilised at airports, COMAH sites, maritime vessels, in the defence sector and premises covered by

BS EN 5306-8 (shops, offices, garages, warehouses, flats and entertainment complexes). The feasibility of spray-can extinguishers at low temperatures is a concern that was highlighted through stakeholder engagement with the MoD and ECHAs public consultation. Both naval and civilian maritime vessels may be impacted, however current research and development is ongoing and industry expects a viable solution within 5 years. Further concerns over the availability of wheeled units (BS EN 1866) on the GB market have been highlighted through an information search by the Agency. Fluorine-free versions of these larger units (up to 150L), do not currently appear to be available in GB. It is unknown whether operators currently using PFAS-containing wheeled units can replace the contents with fluorine-free foam upon full discharge, either after live use or 5 yearly testing under BS 5306-3: 2017. This will be considered further during opinion development.

5.3.4.7.2 Call for evidence

The UK figures are currently unavailable, however in the EU a total of approximately 6 million portable extinguishers are sold annually. Of these, 35% (2.1 million) are foam extinguishers (AFFF) with the most common size being 6 & 9 litres and other popular sizes including 2 & 3 litre units (mainly used for transport vehicles). The UK uses far more foam extinguishers, rather than dry powder, than EU countries due to concerns over low visibility during escape from buildings and inhalation of powder particles in confined spaces (IPEN, 2018). Preliminary discussion with Britannia Fire Ltd, a UK-based manufacturer and distributor of fire equipment, has given some insight into the quantity of PFAS foam they currently supply annually (~30 tonnes). Britannia Fire Ltd also supply high quantities of fluorine-free foam that meets their own requirements for ratings, life and corrosion resistance. The manufacturer is Uniteq (Belgium) and their fluorine-free foam product is ASX.

The FIA provided an estimate for the number of portable fire extinguishers supplied by their members as 2 million units, and these would be supplied to any premises covered by BS 5306-8 (shops, offices, garages, warehouses, flats and entertainment complexes) (Call for evidence, 2024).

Fluorine-free portable extinguishers, usable on class-B fires, are readily available in the UK. Britannia Fire manufacture and supply the P50-ECO fire extinguisher (Britannia Fire, 2025), which is fluorine-free and does not require professional annual servicing. Safelincs, a UK based fire extinguisher supplier, stocks and supplies the 6L version of the P50-ECO for £220.79 per single unit (Safelincs, 2025). A comparable 6L AFFF portable extinguisher is retailed at £182.39. Both are marketed for Class-A, -B and electrical fires up to 1000V, however the fluorine-free extinguisher can also be used to tackle Class-F fire risks. Similarly to AFFF extinguishers it is not made clear the exact constituents of the foam, therefore it is difficult to conclude exactly which fluorine-free alternatives have been deemed appropriate and are currently available in ready-to-use products.

CheckFire Group are another portable fire extinguisher supplier based in the UK, providing both AFFF and F3 products. In the call for evidence, they highlighted that they have recently released a new range of 3, 6 and 9L fluorine-free extinguishers in 2024 and further investigation revealed they are currently phasing out their PFAS-containing AFFF range. The F3 extinguishers retailed around 30% more than their AFFF counterparts with the 9L AFFF at £51.00 and the 9L F3 at £65.00 (Hartson Fire Ltd., 2025).

5.3.4.7.3 Transition periods

BS 5306-3:2017 outlines the following testing and maintenance for portable extinguishers. The annual basic service consists of checking the extinguisher for use or tampering, its location is still optimal for any relevant hazards, the media and propellant are within allowances, it is still safe and fit for purpose and that it will work adequately if required for use. An additional extended service is carried out every 5 years on selected extinguishers, including water based foam extinguishers, that involves full discharge of the media to ensure it will work when operated. The discharged extinguisher is then refilled or replaced if necessary.

ECHA proposed a transition period of 6 months for the formulation and placing on the market of AFFF ready-to-use products and 5 years for their use. This 5 year timeframe coincides with the full service required on units, which requires full discharge and refilling to ensure adequate functionality. During this service the units can be refilled with F3 or replaced altogether. In addition, stakeholders with concerns over the use of ready-to-use products at sub-zero temperatures have suggested a 5 year transition period for technology meet the requirements. The suggested 5 year transition period is feasible in the UK, but may be dependent on any minimum concentration thresholds of PFAS that are included in the restriction. Full replacement will incur higher costs to users, which can be particularly high when using the larger wheeled units.

Stakeholders have queried ECHAs proposal for restricting the formulation and placing on the market of PFAS-containing portable fire extinguishers, most significantly regarding the availability of technically feasible alternatives for use on alcohols and polar solvents (AR-FFF) and at low temperatures (ECHA 2023d). However, alcohol-resistant F3 are already available, and according to ECHA and our own public consultation, F3 that are capable of being used at extremely low temperatures are nearing the end of their development phase. A single stakeholder suggested an 18-month transition period due to concerns over the fairness of global market conditions that could arise with a shorter transition period. Considering these issues, ECHA finally recommended an 18-month transition period for AR-FFF extinguishers.

The European Commission agreed with ECHA on an 18 month transition period for AR-FFF and suggested a 12 month period for all portable extinguishers, to allow appropriate time and capacity for stakeholders to obtain the required certifications in all member states (European Commission). This would not be a requirement for GB stakeholders.

Consultation with GB stakeholders has highlighted the reliance on the EU for a large proportion of its FFF supply (OilTechnics). Furthermore, any restriction implemented by the agency would likely enter into force after that of an EU restriction, which would allow time for the development of alcohol resistant F3 that can be utilised at sub-zero temperatures and sufficient saturation of these products on the market before a transition period has begun in GB. The agency is considering a 6 month transition period for the formulation and placing on the market of PFAS-containing AFFFs in all portable extinguishers.

5.3.4.7.4 Certifications

Ready-to-use products are independent of the major sectors such as aviation or petrochemical, although they may still be used within these settings, such as administrative office buildings or communal buildings and amenities. Due to this they are subject to generalised standardisations and certifications.

BS EN 1568 tests the extinguishment and burnback time for firefighting foams. Parts 1 & 2 are concerned with testing medium and high expansion foams against water-immiscible liquids in a test or fail capacity, whereas parts 3 & 4 tests the capability of low expansion foams against both water-immiscible (heptane) and -miscible (acetone or isopropanol) liquids based on a grading system for both extinguishment time and burnback resistance.

BS EN 13565 is a directive that covers the requirements and test methods for components of integrated “wet” systems and is split into 2 parts (EN 13565-1 & 2). Part 1 covers the required accuracy of the proportioning system and stipulates that the resulting foam shall be “not less than the rated concentration” and “not more than 30% above the rated concentration or 1 percentage point above the rated concentration (whichever is less)”. Part 2 covers the design, construction and maintenance of the system and stipulates that “A test of the proportioner and associated fittings” shall be done annually “by competent and trained foam laboratory personnel” and “the accuracy of the foam proportioning system shall be in accordance with the tolerance given in BS EN 13565-1”.

The BS 5306 Section 3 gives more general information on the maintenance, servicing, overhaul procedures and recharges of portable fire extinguishers.

The BS 5306 Section 8 gives guidance on the selection and positioning of portable fire extinguishers. It highlights the importance of environmental considerations, the type and number of extinguishers required and the operational temperature ranges.

NFPA 11 is an internationally recognised US standard for Low-, Medium- and High expansion firefighting foam. NFPA 11: 2021 is the most recent revision and covers the design, installation, operation, testing and maintenance of fixed foam systems.

5.3.4.7.5 Uncertainties and remaining concerns relevant to the technical assessment

There are uncertainties over the quantities of foam and number of portable fire extinguishers in use in GB and the figures from the ECHA consultation may not be as applicable as other sectors. The EU totalled ~6 million units sold annually, with 35% (2.1 million) being spray can extinguishers at 6 or 9 litres. However, according to Eurofeu, the UK uses a higher proportion of foam extinguishers over dry powder due to concerns over visibility issues during building evacuation.

Further uncertainties reside over the availability of wheeled units, from 45 to 150L, containing fluorine-free foam that are sold in the UK. An information search revels that retailers in the UK only stock the smaller handheld units. Larger wheeled units are available for purchase internationally.

5.3.4.7.6 Summary and conclusion

The ready-to-use sector refers to portable fire extinguishers up to 150L, including spray can (EN 15856) and wheeled (EN 1866) extinguishers. These are used across a variety of other sectors where the risk of a class B fire is present but does not require large amounts of foam (e.g. offices, kitchens, small fuel storage areas on board civilian and military ships, at airports, at COMAH sites) and are utilised at premises covered by BS 5306-8 (shops, offices, garages, warehouses, flats and entertainment complexes). Integrated fixed systems, although defined as ready-to-use, are not within the scope of this sector and will be covered where necessary in the individual sector specific sections. Fluorine-free alternative spray can extinguishers appear to be readily available in the UK, the cost per unit is currently ~10-30% higher for F3 products at retail price, however this may be due to the added utility of tackling electrical fires. These suppliers and retailers identified do not have a fluorine-free version of the larger wheeled units currently listed. ECHA have proposed a 6-month period to cease the formulation and placing on the market of most PFAS-containing portable extinguishers, with 18 months being allowed for alcohol-resistant foams. The Commission have allowed 12 for most PFAS-containing extinguishers to allow for Member State certification, which would not be required in GB. ECHA also suggested 5 years for the use of all PFAS-containing AFFF in portable fire extinguishers. Based on the 5-yearly service, including full discharge and refilling under BS 5306-3:2017, these transition periods for use would be reasonable for GB. Since the EU restriction will likely have been in force for at least 12 months before a GB restriction, the Agency considers that the additional 18 month allowance for the placing on the market of AR-FFF extinguishers would not be necessary.

5.4 Analysis of Alternatives Overall Summary

There is one key issue regarding the functionality and perceived efficacy of fluorine-free foams: they are not film-forming. Without an additional fluorinated film layer to help contain the volatile vapours and seal them from access to oxygen, the fire-suppressing action must come from the foam alone.

Most of the concerns that the Agency has heard from stakeholders stem from this one issue:

- It can take longer to extinguish fires, and more foam is required to maintain sufficient foam coverage.
- F3 must be applied differently and more discriminately than AFFF.
- To maintain a more substantial foam, and perform better, they may need to be aspirated. However, this compromises the range from which they can be applied.
- It can be easier to break the foam blanket, resulting in re-ignition, so greater care or a modified approach to firefighting must be taken.
- They may not perform as well as AFFF in testing, or a test may require modification to account for a different application method.

Concerns were also raised about the inability to mix F3 from different manufacturers or with AFFF. However, this is not exclusive to F3 and has also been a consideration for AFFF. Furthermore, stakeholders have informed the Agency that compatibility testing should be undertaken to ensure the correct products are used.

A need for training with F3 has also been cited as a concern by industry. Conversely, with a greater understanding of how to apply F3, appropriate training could also be seen as the solution to a number of the concerns listed above. Indeed, a number of comments the Agency has received as ‘concerns’ are solutions to the consequences of switching to F3:

- More vigilant visualisation of the fire and progress of suppression.
- Requirement for different application rates, methods and tools.

The main issue is that these solutions come at a cost and require time to implement, train and transition.

There are some other issues which can result from formulating foam products without PFAS, including increased viscosity, incompatibility with seawater and lowered resilience to extreme temperatures. However, the Agency is informed of examples where these issues have been overcome and there has been a full operational transition to F3 foams, such as Equinor on the Norwegian continental shelf.

Despite issues and concerns from stakeholders that are yet to transition, **there are examples of successful transition away from AFFF to F3 across each of the analysed sectors**.

Such a transition comes with a cost to those stakeholders. Beyond the financial and time costs to train responders to combat fires using F3, there may be:

- Additional equipment costs in the requirement for new partitioning educators, tanks, hoses, pipes and nozzles.
    - For industrial sites in particular, these changes may be more challenging, expensive and time-consuming, possibly needing plant redesign before retrofitting new equipment.
- The costs of downtime whilst infrastructure changes are made. Whilst these can be mitigated in some instances by taking advantage of scheduled maintenance, that would require a longer time period for transition.
- Costs related to the decontamination of existing equipment and the appropriate disposal of contaminated rinse solvent.
    - These could be exacerbated if a very low concentration limit would be required to ensure compliance at the point of use.

Nonetheless, stakeholders across each sector have clearly determined that F3 are a viable alternative to AFFF, worth the investment to switch, and transitioned.

The Agency still has some information gaps, arising from contradictory or unclear information from stakeholders, which we would be particularly interested in addressing during the commenting period.

- Whilst there is some information suggesting that appropriate mixing of foams can occur (compatibility testing required), and that mixing has historically been an issue for AFFF, the extent to which F3 are unable to mix with each other or AFFF is unclear:
    - Does this relate to mixing in the tank or mixing upon application?
    - How much mixing or contamination is required to see an effect?
    - To what degree is this a problem if the foams are deemed to be “compatible”?
- There is a general industry concern that F3 cannot be used on all fuel types or in challenging conditions. It is clear that different foams are required for polar and non-polar solvent fires, with AR foams typically able to be used on both. However, foam suppliers have asserted that they have a product for every use case; every sector displays examples of successful transition.
- It is often suggested that more foam may be required to extinguish fires. It is unclear if this is always in relation to a greater volume of foam solution, or if it is

conflated with a requirement for more concentrate at a higher proportioning percentage.

  - How much would this apply to fixed systems due to how foam is delivered through these systems and included safety factors?
  - To what degree would increased tank sizes be required at COMAH sites? I.e., if a greater volume of foam is not actually required.
- The general uncertainty from some stakeholders around the efficacy of F3 drives a larger concern about potential increased risk to life from an inferior firefighting product. However, these F3 products are often marketed as having passed international test standards, such as those within BS EN 1568:2018. Stakeholders undergoing transition are expected to have ensured that substitute products are suitable for their individual needs.

The Agency considers that alternatives are broadly available and viable and that the primary barriers to transition are cost and time. The Agency will seek to further and more fully assess and document the technical and economic feasibility of alternatives following, and informed by, responses to the public consultation on this report. Based on the initial findings in this report, the Agency considers the following substitution timeframes to be reasonable for switching to alternatives to AFFF, taking account also the findings of ECHA and the European Commission in their draft regulation in this respect:

Table 5.4: Sector specific substitution timeframes

	Sector/use	Suggested substitution timeframes
1	Portable fire extinguishers (defined by BS EN3-7, BS EN-1866 and BS EN-16856)	5 years
2	COMAH sites; except for those already covered by the arrangements for aviation (see point 6)	10 years
3	Training and testing[#]; except testing of firefighting systems for their function.	18 months
4	Fire and rescue services; except for those also responsible for attending industrial fires for establishments covered by COMAH, where the 10 year transition period will apply for **use at these establishments only** (see point 2).	18 months
5	On board civilian boats	5 years
6	Civilian aviation sites	5 years

	Sector/use	Suggested substitution timeframes
7	Defence[*]; except for military vessels where a 10 year transition period will be applicable	5 years
8	Offshore oil and gas installations	10 years
9	All other uses[$]	5 years

[#] A separate transition period is considered appropriate for training with FFF compared to their use during live incidents. Given that most training takes place under controlled conditions and measures are already in place to use PFAS-free foams for such purposes, a relatively short transition period is considered appropriate. Likewise for testing (e.g., testing foams to establish suitability), a shorter transition period is considered appropriate. An exception should be made for the testing of fixed firefighting systems to ensure they can continue to comply with required safety standards until the end of the sector-specific transition periods.

*Defence is considered to include sites on land either owned by the Ministry of Defence (MoD), or where the MoD has rights to the land or assets owned by or operated on behalf of the MoD. An exception should be made for use on military vessels, where a longer transition period is considered appropriate to account for specific defence requirements and to allow for any refitting.

[$] There may be other uses that are not covered by the sector specific transition periods in points 1 to 8. For such cases, the Agency suggests a 5 year transition period which is in line with the requirements for most sectors. Other uses could, for example, include chemical manufacturing facilities not classed as COMAH sites.

6 Socioeconomic Analysis

6.1 Rationale for intervention

The market for firefighting foams has a number of potential “failures” which may justify government intervention.

Firstly, there are negative externalities (costs) associated with the release of PFAS into the environment from these foams.

PFAS are stock pollutants. As outlined in the hazard / risk assessment, an initial PFAS precursor can go through a number of transformations before becoming a PFAA arrowhead. PFAAs are highly stable in the environment so can persist for a long time (potentially years, decades or longer). As such, they can essentially be thought of as *permanent* stock pollutants, i.e., pollutants for which no counterpart degrading capacity exists in the environment.

Precursors, intermediary transformation products, and arrowheads may or may not be toxic depending on the particular substances. Eventually, over the *very* long term, these arrowheads will likely all degrade to trifluoroacetic acid (TFA), an ultra-short chain PFAA. Although, this specific final transformation may take many hundreds to thousands of years.

Accordingly, the negative externality under consideration arises from the use of PFAS -containing firefighting foams resulting in direct emissions into the environment of permanent stock pollutants, that are persistent and mobile in their own right and/or when degraded. Available evidence on their terminal degradation products indicates that these have toxic properties compatible with the T criteria under UK REACH. These released substances and their degradation products can contaminate drinking water sources and, owing to their persistence, their concentrations are expected to increase over time and contribute to PFAS exposures at the population level, resulting in potential harm to humans and the environment with associated damage costs.

The combination of persistent, mobile and toxic properties is also concerning because it can result in environmental stocks which could be difficult, if not impossible, to reverse.

The market price paid for PFAS-containing firefighting foams does not account for these external costs i.e., costs incurred by third parties or society as a whole. As such, there is excess consumption/production of these foams relative to the level that would occur if their price also reflected the harm they may inflict on society. Externalities could also be relevant to any potential remediation of legacy pollution associated with the uses in scope of this restriction, for instance if this is funded through taxation on those who had no relation to/did not benefit from the releases of PFAS.

Additionally, there is likely another market failure in the form of information failure. Knowledge surrounding the potential for environmental and human health risks associated with the use of PFAS-containing foams is lacking or unevenly distributed amongst all of those potentially affected by the use of PFAS in FFFs. This is most notable when humans are exposed via the environment who are likely unaware that this is happening and so cannot take any measures to limit this occurrence. Institutions as well as individuals may also be unaware of risks.

These market failures may warrant government intervention, whereby regulation can result in an increase in societal wellbeing relative to doing nothing.

The Agency considers it unlikely that any negative externalities in the form of potential risks to human health and the environment associated with the use of PFAS-containing FFFs will be adequately addressed in the absence of government intervention. Although a significant transition has already occurred away from PFAS-containing foams (and this may continue to some extent over time), there are heterogeneous costs associated with transition and apprehension about the performance of alternatives in certain sectors, such as offshore uses of FFFs. Those who have already transitioned are likely those who face the lowest costs of doing so. This consideration is expanded further throughout the socio-economic analysis (SEA).

6.2 Approach to the Socioeconomic Analysis

The socioeconomic analysis (SEA) seeks to understand the costs and benefits of a regulatory intervention via a UK REACH restriction and conclude upon the proportionality of any such intervention. Within the SEA, the costs of restriction are largely estimated in monetary terms. Costs are more readily quantifiable and monetisable than the benefits of restriction, where a significant degree of data limitations and uncertainty exists in assessing the risk posed by PFAS in firefighting foams.

As such, monetised costs are primarily compared to a qualitative exploration of potential restriction benefits. A quantitative estimate of the avoided emissions associated with restriction is also outlined. This allows for the avoided future releases of PFAS under restriction, relative to the baseline, to be compared to the associated restriction costs. Here, the magnitude of avoided emissions acts as a proxy for societal benefits, albeit one which is not commensurable with costs.

However, cost-effectiveness ratios can be derived from these estimates, allowing for measures of the *£/unit of abatement* to be compared with other chemicals regulations that have been undertaken/proposed. This is not an ideal appraisal approach as the risk posed by different pollution scenarios from different substances can vary drastically. As such a measure such as *£/tonne of substance* does not always allow for a meaningful comparison. Nonetheless, in light of the analytical challenges due to the complexity of PFAS risks, it may aid in helping the decision maker understand and contextualise the impacts of regulation. It is complemented by a qualitative outline of potential benefits.

The geographical scope (policy standing or accounting stance) of analysis is the UK, as per HM Treasury’s Green Book (HM Treasury, 2022). As mentioned in Section 3.1.2, Northern Ireland (NI) falls under EU REACH jurisdiction. This means that a UK REACH restriction would address use in GB and not NI. Nonetheless, if restriction in GB does impact the wellbeing of people in NI, this should be considered. Furthermore, because of their high mobility and long-range transport potential, transboundary issues are also relevant to the analysis. That is to say that releases of FFF in GB may result in PFAS contamination elsewhere in the world. However, whilst such impacts outside GB should certainly be noted, they are typically difficult to reliably assess.

All GB emissions abated as a result of restriction are included in the analysis, irrespective of whether the ultimate impact of these under the baseline would have occurred within the UK or not. In this regard, the standing is likely to extend beyond the UK when considering the benefits of abatement.

A 30-year appraisal period is used when modelling impacts, with 2026 assumed for the purposes of the SEA analysis to be the first full year of entry into law, although in reality this may be later due to legislative processes. Irrespective, this will not affect the conclusions of the analysis. PFAS are highly persistent substances. As such, their regulation touches upon questions of intergenerational equity. For these reasons, the Agency considers a longer appraisal period than perhaps typical in economic appraisal (HM Treasury (2002) note that an appraisal period of 10 years is suitable for many government interventions) to be appropriate to capture the duration of impacts. Here, the Agency considers 30 years to be an appropriate timeframe.

Due to the high persistence of PFAS, harm associated with releases today may extend well beyond 30 years. However, the longer the appraisal period the greater the uncertainty associated with modelling future impacts. A greater number of unforeseen future changes in parameters are expected as the appraisal period grows longer and so a trade-off exists in the choice between capturing changes in intergenerational welfare and accuracy. The EU Restriction analysis similarly opted for a 30-year appraisal.

Impacts are presented in present value (PV) terms, using the Green Book (HM Treasury, 2022) recommended discount rate of 3.5%. All values presented in the SEA have a price base year of 2024, calculated using HM Treasury GDP deflators (HM Treasury, 2024). Present-value figures are discounted to 2026 values, in line with the assumption that this is the year that any proposed restriction would come into force, but as noted earlier a later entry into force will not affect the conclusions.

A ’partial equilibrium’ approach is taken within the economic appraisal that underpins this socioeconomic analysis. This means that impacts are investigated in the small number of markets that are considered to be directly affected by restriction. This is in contrast to a ‘general equilibrium’ approach, which would seek to model impacts across the entire economy through the inter-connectedness of markets. General equilibrium modelling is more challenging to undertake and typically considered disproportionate for a regulatory scenario like this where impacts are mostly confined to an individual or small number of markets.

Within this SEA (and as is typical within economic appraisal), the term ‘cost’ will refer to any impact that results in a loss of wellbeing, whereas the term ‘benefit’ refers to an impact that results in a gain in wellbeing. Where costs are estimated these are measured in terms of opportunity cost (the value of the foregone alternatives) associated with employing factor inputs (labour and capital).

Where quantitative estimates are provided for impacts, these are underpinned by modelling parameters, with Table 6.10 in Section 6.4.5 outlining a list of key parameters. The values of these parameters are uncertain to differing degrees depending on the data source and assumptions made. The Agency's current SEA is based on what it considers to be the 'best estimate' of these parameters with the data that is currently available. A large number of data gaps exist and the SEA relies largely on parameter estimates extrapolated from the EU restriction. In future iterations of the SEA, additional sensitivity/uncertainty analysis will be undertaken, and the Agency will seek to gather more GB specific data. In line with this uncertainty, **the Agency recommends that current quantitative estimates are treated as an order of magnitude exercise** as a significant degree of uncertainty remains. Exploring the impact of the uncertainty on the Agency's proposals is a priority for future versions of the SEA.

In terms of structure, an options analysis is first undertaken, where potential risk management options are examined to identify the most appropriate option for addressing the identified risks. The section then provides an assessment that a restriction is the most appropriate measure in terms of the criteria outlined in Annex 15 of UK REACH. Following this analysis, the Agency proposes a **restriction on the sale and use of PFAS in FFFs.** Discussion around the proportionality of this restriction can be found in Section 6.4.4.

6.3 Options analysis

6.3.1 Baseline for Analysis of Options

Section 4 concluded that the use of PFAS in FFFs results in risks that are not adequately controlled. In response to the identification of this risk, the Agency has conducted an analysis of risk management options (RMOs) to identify the most appropriate option for addressing the identified risks, including a REACH restriction. Measures already taken within the UK along with any changes that will take place in the absence of any further risk management measures are first briefly described below as this represents the baseline for analysis, before then considering the various further risk management options.

The existing regulatory measures noted in Section 4.2 and Annex F are included as part of the baseline scenario, under which no further risk management measures are implemented under UK REACH. As outlined in Section 5, it seems that significant transition away from PFAS-containing foams has recently occurred (to varying degrees across sectors). The Agency understands the majority of GB foam usage to now be PFAS-free although this is unevenly split between sectors of use.

In spite of this, the Agency considers further transition unlikely to occur without regulations that mandate this. In particular, this is because differences in the costs of transition are expected across sectors, in addition to certain users demonstrating hesitance to switch to alternatives out of concerns around their efficacy. As a result, the Agency does not believe that sufficient incentives exist for these users to transition in the absence of government intervention and so does not consider any further change in use to occur under the baseline ‘do nothing’. That being said, market changes at the international level may induce some further transition, though the Agency currently has little information on this and will seek to gain further understanding when developing future iterations of the SEA

6.3.2 Analysis of Risk Management Options

Based on the conclusion from Section 4 that there is a risk that is not adequately controlled and that action beyond the measures already in place is necessary, the Agency considers a restriction under UK REACH (Article 69(3) of UK REACH) to be an appropriate risk management option (HSE, 2023).

The UK has left the EU and is no longer bound by decisions made by the EU, however the Agency has taken the EU restriction proposal as a starting point for this analysis (European Commission, 2025).

The restriction option is assessed qualitatively against the criteria outlined in Annex 15 of UK REACH:

- Effectiveness: The restriction must be targeted to the effects or exposures that cause the risks identified, capable of reducing these risks to an acceptable level within a reasonable period of time and proportional to the risk (also with regards to the costs).
- Practicality: the restriction must be implementable, enforceable and manageable;
- Monitorability: it must be possible to monitor the result of the implementation of the proposed restriction.

Other potential risk management options that may be appropriate to reduce these risks have also been considered and are set out in Section 6.3.2.2.

6.3.2.1 REACH restriction option (RO)

6.3.2.1.1 RO1:A restriction on the placing on the market and use of PFAS-containing firefighting foams with sector specific transition periods.

This restriction option would be a ban on the placing on the market of PFAS-containing FFF and a ban on the use of PFAS as a constituent in FFF in GB. Sector specific periods would apply to ensure an effective transition to PFAS free alternatives whilst still accounting for the needs of different sectors. The option would also include concentration limits for the levels of PFAS in the foam placed on the market and used, giving consideration to the issues associated with decontamination of existing equipment (refer to Section 6.4.2.11). Time limited exemptions or derogations for specific sectors/users (e.g., for sites where measures are in place to fully capture and treat emissions to the environment) could also be considered.

The restriction option has been assessed against the Annex 15 criteria to determine its appropriateness.

Effectiveness

The restriction would target all PFAS-containing FFF use, and all those which are placed on the GB market. This would result in a complete reduction of any additional PFAS-containing FFF being placed on the market or used and therefore avoid the risks of any future PFAS emissions in GB occurring from the use of FFF. As the restriction would cover the use of PFAS as a constituent in FFF, formulation of PFAS-containing foams would also be prohibited in GB.

The potential to set derogations/exemptions, or different transition periods for specific sectors/users, means that this restriction option can be designed so that it is proportional to the risk faced by each sector. For example, longer transition periods could be given to industries and sectors that may require a longer period due to any technical, economic or logistical challenges.

Ultimately, such a restriction would prevent on-going releases of PFAS from FFF, and as such is an effective risk management measure. As discussed above, the level of abatement that it results in over a given period of time will depend on how the different elements of a restriction are designed.

Practicality

As outlined in Section 5, the Agency considers that suitable alternatives to PFAS-containing FFF exist and are available, albeit with necessary caveats (see Section 5.3.4.3.5) as they generally have not been tested on extreme events. Indeed, a significant transition has already occurred to date across multiple sectors, demonstrating that those affected have the capability to comply, and that as well as suitable alternatives existing the associated techniques for the application of these foams have also been developed. The restriction could be implemented in the most practical way possible through careful consideration of appropriate transition periods to account for issues raised around timescales needed for full transition in certain sectors (see Section 5.4) and potential derogations where socio-economic considerations call for this. It could also be enhanced by other elements considered in this assessment, such as, communication campaigns including case studies etc. These could assist with managing any challenges which may occur during the transition period.

Regulatory bodies will be able to verify compliance in a number of ways. Concentrates could be tested analytically, in addition to audits of purchase documentation and evidence of decontamination. Compliance visits could take place at both user and formulator/producer sites, in addition to tracking online sales of foam concentrates. Consideration will be given to appropriate concentration limits to account for rebound of PFAS from existing equipment. The need for a management plan, and for this to be made available to any enforcing body would also help to be able to document transition, where PFAS FFF are still in use and the management of any potential emissions.

Overall, the Agency considers this to be a practical option.

Monitorability

The foam stocks of users could be monitored to understand the constituents (i.e., verify they are PFAS-free). Concentrates could be tested analytically to check for compliance, in addition to audits of purchase documentation. Monitoring could occur on sales from domestic formulators in addition to any potential imports.

Environmental monitoring may also be used to analyse levels of PFAS within environmental media within catchments (ambient monitoring) or at various sites which require the use of firefighting foam (site-specific monitoring). This allows for background or baseline concentrations of known PFAS to be understood, to determine whether these levels are increasing at different locations and how it is moving through the environment. However, this may be a less desirable approach because of the possibility of PFAS rebound (See Section 3.1.7), meaning that a user may be using FFF in compliance with the concentration limit in the restriction, in spite of environmental monitoring showing small releases of PFAS.

Ultimately, the restriction would be designed with these considerations in mind, and in any case the Agency considers this option to be monitorable.

Authorities will be able to verify when a user is not in compliance with the restriction requirements. Compliance visits could take place at both user and formulator/producer sites, in addition to tracking online sales of foam concentrate. If designed to require compliance at end-of-pipe (i.e., a rebound limit is set on firefighting foam outputs), environmental monitoring could also be undertaken to aid enforcement. This could be further aided by a record-keeping requirement on the continued use of PFAS FFF, e.g., as part of a management plan.

Overall, this RO is considered to meet the Annex 15 criteria for effectiveness, practicality and monitorability.

Inclusion of additional complementary measures within the suggested restriction option:

During opinion development, the Agency will also consider whether the restriction could include additional complementary measures during any transitional periods to contribute to the minimisation of emissions, so far as is reasonably practicable. Such measures may include, for example:

- A requirement for users of firefighting foam products, which contained total PFAS at greater than 1 mg/L when placed on the market, to document and maintain a management plan addressing how they:
    - use PFAS-containing firefighting foam, including an assessment of the technical and economic feasibility of alternatives

  - seek to minimise PFAS release to the environment from the use of such foams

  Such a plan would be kept up-to-date and available for inspection by the relevant enforcing body on request.

- Labelling requirements that apply to the packaging of firefighting foam containing total PFAS at greater than 1 mg/L when placed on the market. Such a label would alert users to the presence of PFAS and support proper handling of these materials during the transition periods.

6.3.2.2 Other risk management options than restriction (RMOs)

6.3.2.2.1 RMO1: Economic Instruments

As discussed in Section 6.1, negative externalities arise from the production and use of PFAS-containing foams. This means that their production and use are associated with costs on external third parties that are not reflected in the price for which they are sold on the market. Economic instruments, such as taxes, subsidies or quota/‘cap-and-trade’, allow for market prices to be corrected to account for the external costs otherwise ignored

The extent to which economic instruments are effective at controlling risks associated with PFAS-containing foams depends largely on their design. In the case of taxation, there is theoretically a level of taxation that would eliminate all risk, as no user would be willing to pay the resulting elevated price. Subsidies on alternatives, from a theoretical perspective, could achieve the same result, as would a cap-and-trade style regime which mandated zero emissions.

There would be significant difficulties in establishing appropriate taxation levels that took account of the variety of typical use volumes, emissions, the nature and extent of the harm caused, appropriate deterrent levels, etc. Quota/permit systems could circumvent this, but also contain drawbacks due to stockpiling and the very long service life of the products.

In line with the above, the Agency does not consider this as an appropriate risk management measure and it will not be considered further.

6.3.2.2.2 RMO2:Stewardship programme

This option entails encouraging producers or users of PFAS-containing FFF to join a stewardship programme with the intention of committing to reducing their use of PFAS-containing firefighting foam by a particular amount, by a particular date.

In the USA, the US EPA (2024f) implemented a PFOA Stewardship Program in January 2006. The program asked the eight major companies in the PFAS industry to commit to reducing PFOA emissions and product content by 95 percent by 2010, and to work toward eliminating PFOA from emissions and product content by 2015. All companies invited committed to the program and all participating companies state that they met the program goals. In the case of PFOA, whilst the voluntary agreement was successful, it was in part because the suppliers had a viable alternative in the form of C6 perfluoro compounds to replace the C8 compounds in PFOA.

If members enact their voluntary pledges, this restriction option could reduce emissions of PFAS within a reasonable timeframe. However, ultimately it would be a voluntary process and with the extended number of users and sites within scope of this proposal it would be difficult to get a voluntary agreement. As such, there is no guarantee that this would lead to a full transition or that transition would occur at an appropriate rate. As such, the Agency does not consider this to be an appropriate risk management option and has not considered this further.

6.3.2.2.3 RMO3: Communication with users and labelling of PFAS FFF

This option would include communicating with users of PFAS-containing firefighting foams to provide them with more information regarding the risks of continued use of these foams, and with information regarding the availability and performance of alternative fluorine-free foams. This may also include labelling requirements for firefighting foams to ensure users are better informed. This would aim to ‘nudge’ a change in behaviour such that users would choose to transition to alternative foams. To increase the likelihood of engagement and successful transition, it could be possible to tailor the level, depth, or style of communication depending on the users. Communication campaigns could also be run through key stakeholder associations in partnership with the appropriate government body. The effectiveness of such an option is difficult to determine.

However, as with the previous option, this would essentially be a voluntary process with limited evidence of effectiveness and there is no guarantee that this would lead to a full transition or that transition would occur at an appropriate rate. As such, the Agency does not consider this to be an appropriate risk management option and has not considered this further.

6.3.2.2.4 RMO4: PFAS specific legislation

This option focuses on the introduction of legislation, additional to that described in Section 4.2 and Annex F, which is specific to the regulation of PFAS generally but would include those PFAS substances which are used in FFF and included in the scope of this Annex 15 report. This would aim to regulate PFAS substances across their life cycle so could include prescriptive approaches on emissions, waste and disposal, segregation and phase out by use, and even include measures for the submission of information to allow use to be permitted in certain circumstances. This could also include a responsibility to analyse all products in use (whatever the tonnage) to ensure all PFAS used in GB are tracked.

As the scope of any legislation could be flexible and not required to meet the bar of “risk not adequately controlled” and the justification test set out in Annex 15 of UK REACH (see Section 6.3 above) then this could cover multiple substances, groups of substances and uses. Additionally, this would also not be limited by the scope of the UK REACH legislation, this could seek to cover all uses of PFAS in all sectors, this could also seek to control and prescribe measures to manage and track waste - creating a cradle-to-grave management of PFAS.

As this legislation would be primarily environmentally focused, but would be wider than UK REACH in scope covering all areas of sale, use, disposal and waste of PFAS, this is not something that the Agency is able to take forward to scope and/or plan. It would require additional legislation to be made and the associated legislative process to be followed. This is beyond the scope of Agency functions, and beyond the scope of the restriction request by the Appropriate Authorities, therefore whilst this remains an option and one that may be effective to manage the risk from PFAS, the Agency is unable to take this forward under our responsibilities in UK REACH, and will not be assessed further.

6.3.2.3 Conclusion on Risk Management Options

The use of PFAS-containing firefighting foams results in direct emissions to the environment of substances that are persistent and mobile in their own right and/or when degraded. Available evidence on their terminal degradation products indicates that these have toxic properties compatible with the T criteria under UK REACH. These released substances and their degradation products can contaminate drinking water sources and, owing to their persistence, their concentrations are expected to increase over time and contribute to PFAS exposures at the population level. The use of PFAS-containing FFF is therefore considered to pose a risk to the environment and to human health via the environment.

The Agency considers that these risks are not adequately controlled by measures already in place (see Section 4.2 and Annex F) and has suggested a restriction on the placing on the market and use of PFAS-containing FFF.

Risk management options other than restriction have been assessed (Section 6.3.2.2), but are not considered to be as effective as a restriction under UK REACH or, in the case of PFAS specific legislation, cannot be assessed further by the Agency in the context of this report. Therefore, a restriction under UK REACH on the placing on the market and use of PFAS-containing FFF is considered to be the most appropriate option and has been taken forward for economic appraisal.

6.4 Economic Impact analysis of Proposed Restriction

6.4.1 Baseline Use

Prior to appraising the impacts of the proposed restriction option it is necessary to outline the assumed baseline scenario in terms of the actual current use of PFAS-containing firefighting foams. This relates to how the use of PFAS-containing FFFs is expected to behave in the absence of any intervention- i.e., the ‘do-nothing’ scenario.

Below are the annual tonnages of FFF concentrate that the Agency assumes to be sold in the UK per year, reproduced from Section 3.1.2 where greater detail is outlined on the methodology behind the estimates. Here, and elsewhere in the analysis, a range of values may be presented for parameters in order to account for uncertainty. Analysis is currently based on ‘central’/best estimate values. As discussed in Section 6.2, future iterations of the analysis will be updated to include sensitivity testing where parameters will vary from their low-high values.

Table 6.1: Estimates of PFAS-containing foam concentrate sales

PFAS-containing foam concentrate sales (t/year)	
Low	1,300
Central	2,000
High	2,500

Table 6.2: Estimate of fluorine-free foam (F3) concentrate sales

Fluorine-free foam (F3) concentrate sales (t/year)	
Low	2,000
Central	2,900
High	3,600

For current purposes, these tonnages are held constant across the 30-year appraisal period, assuming that no further transition occurs under the baseline as per the considerations outlined in Section 6.3.1. Further, this assumes that the overall use of firefighting foams (PFAS and fluorine-free) will remain stable over time. Although it is possible that further transition away from PFAS-containing FFF may continue, particularly as other restrictions (i.e., EU REACH) presumably take place and induce general market transition, the Agency assumes that there will not be any significant change. The extent to which this actually occurs depends on how international the market is, an issue on which the Agency currently has little information and will seek to understand further when developing future iterations of the SEA.

To hold quantities constant across time results in a conservative estimate of costs (i.e., potentially exaggerates the costs of restriction), in addition to potentially overestimating the abatement that results from restriction. This, similarly, will be further considered for future iterations of the SEA.

The Agency has categorised FFF use into the following 7 sector-specific uses:

1) Fire and rescue services.

2) (Petro)chemical
3) Offshore
4) Marine
5) Aviation/airports
6) Military
7) Ready-to-use

Distinguishing between sector uses is important for understanding where the greatest sources of emissions can be expected, in addition to comparing these to sector-specific abatement costs (see later).

However, as is the case with the overall GB market, the Agency currently lacks sufficient actual data to estimate the magnitude of foam use associated with each of these sectors. As a result, ECHA’s apportionment across sectors will be assumed to also represent the distribution within the GB market, with the Agency endeavouring to elicit GB-specific data during the commenting period.

Wood (2020) and ECHA (2022a) estimate the following market breakdown:

Table 6.3: Sector-specific market share, Wood (2020) and ECHA (2022a)

Sector	PFAS-based foam concentrate	F3 foam concentrate
Aviation	9%	8%
Marine	12%	16%
Ready-to-use	1%	1%
Military	6%	2%
(Petro)chemical	59%	29%
Municipal Fire Brigades	13%	44%
Total	**100%**	**100%**

It should be noted that this is a slightly different grouping than that used by the Agency. ECHA appears to include offshore uses in their (petro)chemical sector though they note that due to uncertainty in estimating quantities “some of the tonnage for marine applications may also reflect use in offshore oil and gas platforms as well as use in harbours” (ECHA, 2022b, p.4). The transport use also appears to be represented by ‘municipal fire brigades’.

In line with the above, when estimating emissions (and also abatement costs), the Agency does not analyse the offshore and transport sectors in isolation, rather they are encompassed within the (petro)chemical and fire and rescue sectors, respectively.

Section 3.1.2 showed that the Agency estimates ~59% of the GB market to have already transitioned to PFAS-free foams. This transition will be at different stages across different sectors. For instance, in response to the call for evidence, the CAA reported that 71% of licenced aerodromes have transferred to F3 (though they note this survey to only reflect large aerodromes, who may have sold old FFF stocks to small aerodromes in transitioning) (Call for evidence, CAA). Conversely, due to concerns around the perceived effectiveness of alternatives, this percentage may reasonably be expected to be much lower in the (petro)chemical sector. The Agency does not hold data on sector-specific transition beyond the Aviation use. For present purposes, data from ECHA (2022a) is used for all sectors, and the Agency will explore this further in the consultation period.

Further details on aggregate and sector-specific emissions of PFAS can be found in Section 6.4.2.10. As previously noted, a list of key parameters and the sources/calculations underpinning them can be found it Section 6.4.5.

As with the assumed future tonnages of PFAS-containing and F3 foams, the Agency assumes that the relative prices of both foams will remain constant across time, under both the restriction and the baseline case.

The following prices are assumed:

Table 6.4: Estimate price of PFAS-containing foam concentrate

PFAS-containing foam concentrate (£/t)	
Low	3,330
Central	3,700
High	4,625

Table 6.5: Estimate price of fluorine-free foam (F3) concentrate

Fluorine-free foam (F3) concentrate sales (£/t)	
Low	3,600
Central	4,000
High	5,000

The central/best estimates for both PFAS and F3 foams come from personal communications between the Agency and a foam concentrate manufacturer. For the two types of foam, this best estimate is adjusted by a factor of 0.9 in the low case, and 1.25 in the high case; these are the adjustments made by ECHA (2022a, p.88) which they state to be confirmed by stakeholders.

Relative prices will fluctuate across time as a result of changes to demand and supply in the PFAS-containing FFF and F3 markets. These fluctuations can also be expected to differ in the case of restriction relative to the baseline: a price increase in F3 foams post-restriction/during transition may be expected as producers pass on some share of compliance costs to consumers. The longer-term trajectory of relative prices depends largely on the functional form of demand and supply in the two markets. The Agency's modelling relies on constant relative prices as a simplifying assumption in the absence of any robust forecast on how such prices will evolve over time.

6.4.2 Costs of Proposed Restriction Option

This section explores the costs of the proposed restriction option .

Costs are here defined as opportunity costs associated with resource and factor input use.

The analysis below explores the cost associated with a restriction on the placing on the market and use of PFAS-containing foams. The precise design of this restriction will affect the associated costs; for example longer transition periods should reduce costs (at the expense of reduced abatement), less stringent/no decontamination requirements do the same, as will less stringent concentration limits. These are discussed further within the following sections.

Current modelling assumes that sector specific transition periods are the same as those recommended by ECHA, highlighted in Section 6.4.2.10. Throughout the restriction proposal opinion making period the Agency will further consider the appropriateness of these for a GB context.

6.4.2.1 Foam Substitution/replacement

Users of FFF hold them in stocks such that they are readily available if and when required.

Any restriction imposed would have a transition period. If PFAS-containing foam stocks are not exhausted before the end of that transition period, any remaining stocks will require disposal. Stocks will then be replaced by fluorine-free foams, which are expected to be more expensive (see Section 6.4), and a larger stock may be required if a greater quantity of alternative foam is used for fighting any given fire (see Section 5). Similarly, whenever ‘top-ups’ to the stock are made, an additional cost would be imposed if fluorine-free foams are more expensive/a larger quantity is required. These costs of restriction (like any) are only material for users that would not have undertaken such behaviour under the baseline.

To estimate these costs, the Agency assumes an average annual quantity of firefighting foams used by each sector. From 2026, which for the purposes of this analysis is assumed to be the date when any proposed restriction would be announced, this average annual quantity is replaced with fluorine-free foams (accounting also for an increased quantity to reflect the potential need for more foam to be used to extinguish a given fire). That is to say that even before use of PFAS-containing FFFs is required by law to cease, any foam used in that time period will be replaced by fluorine-free foam. This is assumed because to replace the stock with PFAS-containing foam just prior to a restriction would increase the risk of requiring stock disposal (at a cost) and once again purchasing more foam to replace it, this time fluorine-free. The rationality of this decision would ultimately depend on the relationship between the transition period and the average stock duration in any given sector.

Based on estimates from ECHA (2022b), the Agency assumes that 6 %-18 % of foam stocks are used per year, with a best estimate of 12%. This annual usage rate will depend on the specific sector being considered; the Agency will assess whether further engagement with stakeholders during the commenting period is necessary to better estimate a sector specific rate, but for now this average figure is used across all uses.

Based on this, each sector is attributed an annual cost of replacing this used share of the stock during their transition (and beyond), in addition to the one-off cost of replacing any remaining stock not phased out at the end of their transition period. Costs are measured above and beyond what would have been replaced under the baseline, accounting for the assumed relative price increase of F3 foams (outlined in Section 6.4.1) and the fact that a greater quantity may be required, and so replacement of the stock necessitates a larger quantity of F3 be purchased relative to PFAS foams.

The Agency assumes F3 foam multipliers (i.e., the relative increase in the amount of F3 required to extinguish a given fire relative to a PFAS foam) of 1.25, 1.5 and 1.75, as the low, central, and high scenario, respectively. These are the assumptions used by ECHA (2022a) which they state to be verified by stakeholders.

The Agency estimates the cost of replacing foam stocks to total to £145.3m across the 30-year appraisal period. This is **£94.1m** in present value terms.

6.4.2.2 Disposal

Following on from the foam replacement cost, where stocks are not fully phased out during the transition period, users will be required to dispose of them in an appropriate manner. WSP (2023) report findings from an unpublished report by WSP (formerly Wood Group Ltd) (2022) which investigates different technologies to destroy PFAS in waste. Their report concludes that although alternative technologies exist, high temperature incineration remains the only technically and economically feasible technology currently available in the UK (see Section 3.1.9).

Based on ECHA (2022), the Agency assumes that foams have a shelf-life of 10-30 years, with a central estimate of 15 years. Paired with the assumed annual usage rate 6-18%, the Agency's model assumes only a small amount of disposal under the baseline would be required (i.e., close to all PFAS foams would have been used before their expiration date). Indeed, under a central and high scenario no premature disposal is required under the baseline because their average annual use rate means that all stocks are expected to be used up before expiry.

Under a scenario using the 'low' parameter values, an average annual disposal rate of 40% is estimated. This is calculated as follows: with a 6% annual use, it takes just under 17 years to exhaust a given stock. E.g., if 100 tonnes are held, and 6 tonnes are used per year (6%), the stock will be exhausted in the 17th year.

Given the range of 10-30 years as an expiry period, the low parameter is modelled as the combination of a ~17 year exhaustion period combined with a 10 year shelf life. In that scenario, 40% of the stock will be disposed of (and assumed replaced with new purchases) each year.

Through stakeholder engagement and literature review, Eftec (2019) estimated the cost of disposal of PFOA firefighting foams to range from £300-£700/tonne, with a best estimate of £433 (all 2019 prices). The Agency uses these values, inflated to 2024 prices, as the low, central, and high parameter values (£362, £522, £845, respectively).

This unit price is then multiplied by the volume remaining share of stock, if any, remaining at the end of the restriction transition period.

Using the central parameters, the Agency estimates this cost to total £2.1m across the 30-year appraisal period, equal to **£1.9m** in present value (PV) terms.

6.4.2.3 Technical equipment changes

ECHA (2022b) note that transition to alternative foams can cause complications with specific components of foam delivery systems, notably proportioner pumps and jets and nozzles for discharge. They note these challenges associated with transition to be due to the different foam viscosity. They assume the cost of technical changes to amount to EUR 500,000 for Seveso sites and EUR 5,000 for other sites, noting the larger costs associated with sites like oil refineries (hence the larger site cost for Seveso sites): *"the need for increased storage volume of foam concentrate and for the need to retrofit the bund areas in some tank farms to cover a significantly higher volume of liquids, associated with an emergency response action"* ECHA (2022b).

There is likely to be considerable heterogeneity in cost across sites. In their sensitivity analysis ECHA apply a factor of 0.5 and 3 to estimate low and high parameter values, respectively. The Agency uses ECHA's estimates (adjusted to £2024: £529,205 and £5,292 for COMAH and non-COMAH sites, respectively) and endeavour to seek more robust GB specific data for future iterations of the SEA.

WSP (2023) estimate there to be around 2,000-3,000 UK sites which use firefighting foams, with a best estimate of 2,500. They estimate ~400 of these to be COMAH sites. Using the estimated share of the market to have not transitioned (41%, see Section 3.1.2), the Agency assumes there to be between 653-1,061 non-COMAH sites, with a best estimate of 857, and 163 COMAH sites.

The Agency assumes that 100% of these COMAH sites are attributable to the petrochemical use sector. ECHA (2022a) estimates that 98% of petrochemical use sector sites are classified as Seveso and list no similar figure for the other sectors. As such the Agency assumes for the purpose of this cost assessment, that all COMAH sites fall within the petrochemical or offshore use sectors; the ECHA data seems to suggest that all Seveso sites fall within these uses, even if all of these use sites may not be Seveso.

Technical changes to equipment are assumed to happen in 2026 (year 0), such that the transition away from fluorine foams can begin. In reality, this is likely to occur over several years during the sectors' respective transition periods. Assuming this cost to be frontloaded is a conservative assumption (no discounting) and avoids the need to predict the time profile of kit replacement.

Based on the above, the Agency estimates the cost of implementing the technical changes required to transition away to total **£90.9m.** This one-off cost is assumed to all occur in year 0 (2026), meaning that the above figure represents both the discounted and non-discounted total.

6.4.2.4 Decontamination of equipment (if required)

As noted in Section 3.1.7, even after transitioning away from fluorine foams, discharges of PFAS can continue to occur due to ‘rebound’, where PFAS become attached to the interior surfaces of equipment and slowly leach into alternative foams overtime. If this is to be avoided, decontamination of kit is required between ceasing PFAS-based foams and beginning use of alternatives.

The design of any potential restriction proposal should be able to dictate whether or not this is a requirement. As part of restriction, an acceptable concentration threshold below which PFAS must be present in firefighting foams is likely to be specified. This allows for enforcement checks to take place.

This threshold could be set on inputs, for instance monitoring the products sold on the market, or checking the stocks of foam concentrate held by a user. It could also be set on outputs, e.g., monitoring the concentration of PFAS in the firefighting foam itself.

If a concentration limit is set on firefighting foam out of the pipe, rebound may cause users to exceed this threshold despite using foam concentrates that comply with the restriction. Where a GB restriction to operate in this way, decontamination of equipment would be expected to occur to mitigate the risk of violating restriction requirements. The consequence of this is that a restriction which does not require strict ‘end-of-pipe’ compliance is likely to result in lower compliance costs for users and subsequently a potential increase of emissions (through rebound) relative to one where decontamination is undertaken. Discussion of this trade-off can be found in Section 6.4.2.11.

Many different cleaning/decontamination approaches exist. These vary both in terms of their cost and their efficacy, which in turn also vary based on the type of site being decontaminated. As such, the cost associated with requiring decontamination if this were undertaken due to restriction depends closely on the threshold of decontamination required and where this decontamination takes place.

ECHA (2022b) assume that for a compliance threshold of 1 ppm, decontamination costs are EUR 200,000 for Seveso sites, EUR 50,000 for aviation and military sites, and EUR 20,000 per other site. They model ranges of -50% and +100% in their sensitivity analysis.

Several different decontamination procedures exist. From Table E.41. of ECHA (2022b), the cost estimates highlighted above appear to be based on the following three data points:

- PerfluorAd procedure: cost per vehicle (incl. wastewater handling): EUR 20,000-25,000.
- LfU (Bavarian State Ministry for the Environment and Consumer Protection)

procedure: cost per vehicle[1]: EUR 100,000-200,000 (permanently installed tank within vehicle is cleaned).

- WFVD (German Industrial Fire-Fighters Association): Cost per vehicle: ~EUR 4,000[2].

In the case of PerfluorAd, decontamination pertains to fire brigade vehicles and stationary extinguishing systems. For LfU it is tanks, for WFVD it is fire brigade vehicles. Due to the small number of data points, their variability, and the fact that they do not appear to represent all uses of foam within the scope of this restriction proposal, there is significant uncertainty surrounding the value this cost parameter should take.

For instance, ECHA also note that *“a large company in the chemical sector indicated that there would be costs of around €1 500 000 per installed system. However, in this case, no remaining PFAS-concentration was indicated”* (ECHA, 2022b). It is also not clear how representative this one petrochemical sector cost-estimate is.

ECHA (2022b) also note that costs for lower thresholds could be significantly higher, but that *“it is not possible to derive robust cost estimates for different concentration limits”* (ECHA 2022a). The Agency agrees with this; there is uncertainty around the rebound concentration that a given cleaning technique will result in (if any), in addition to this rebound varying over time. Ultimately, there is a finite quantity of PFAS attached to the insides of kit, and so this will not continue to be emitted indefinitely.

In the absence of more readily available GB cost estimates, the Agency uses the ECHA values in the current SEA but will seek to further clarify this assumption during the rest of the restriction proposal process.

These costs are assumed to be incurred at the end of each sector’s transition period, as is the case with the foam disposal cost. Based on the ECHA evidence applied to GB, the Agency estimates this cost to total £141.2m in undiscounted terms, and **£102.3m** in PV terms.

This is the greatest cost estimated in this impact assessment, and relative to the quantity of PFAS emitted under the baseline, is likely to result in a small marginal reduction of emissions. In Section 6.4.4, the Agency considers the proportionality of requiring decontamination of kit, in addition to the proportionality of any restriction proposal more generally.

---

[1] It is not explicitly noted whether these costs include wastewater handling, but given that this is explicitly stated for PerfluorAd (above), it is assumed that these costs do not include such handling.

6.4.2.5 Manufacture and formulation

The Agency is not aware of any evidence relating to the impact of the proposed restriction on formulators/vendors of PFAS foam concentrate. Information on this was not submitted during the call for evidence. Because the UK market is now predominantly fluorine-free, it seems unlikely that restriction will induce re-formulation costs; these are assumed to have already occurred. However, for the remaining share of the market yet to transition, there may be costs associated with this; capital and labour may be allocated towards this transition away from competing uses (opportunity cost).

The Agency will seek to further understand any potential impacts in this regard during the consultation period.

6.4.2.6 Familiarisation, research and training

As a result of restriction, a variety of stakeholders would need to spend time understanding the final restriction in addition to what it means for them/their organisation. Further, users of firefighting foam may need to undertake additional research about the efficacy of different foams and their suitability across the range of applications, as well as training with F3 that would not have occurred under the baseline. Costs are associated with this, notably with regard to foregone time and the cost of the foams and other material consumed during this research and training.

The Agency has not monetised these costs. It is not possible to know how much time will be required to understand any proposed restriction as this has yet to be formally finalised. Similarly, there is uncertainty surrounding the extent that different stakeholders will be required to undertake research on and re-train to use alternatives. For much of the industry the Agency understands that F3 are used for training anyway due to the lower costs of clean-up relative to PFAS.

WSP (2023) note that although consulted stakeholders did specify the need for training with alternative foams as a result of restriction, these costs were described as ‘minimal’ or ‘manageable’. ECHA (2022b) came to the same conclusion, noting these costs to be ‘comparatively small’.

The Agency agrees with this and notes that although these costs are anticipated, relative to the scale of other impacts, familiarisation and training costs are expected to be negligible. The Agency will seek to further understand costs in relation to research needs with respect to the use of alternatives during the consultation period.

6.4.2.7 Enforcement

A restriction would require enforcement to ensure that FFF users were complying with the regulation. Costs are associated with such enforcement, including staff costs from the relevant enforcement bodies across GB, in addition to market monitoring and undertaking analytical tests etc. if required.

No monetised cost has been attributed to enforcement in this impact assessment; the Agency will further explore this throughout the draft and final SEAs when any proposed restriction is designed in greater detail. In any case, it is unlikely to be significant in magnitude relative to other costs identified thus far.

6.4.2.8 Savings

Two notable direct cost savings to users may arise as a result of restriction. These relate to costs faced by users of foams, as opposed to wider cost savings, such as the potential for healthcare resources to be re-allocated if restriction avoids human health impacts.

First, as outlined in Section 6.4.2.2, disposal of PFAS-based foams may be occurring under the baseline if foams stocks are not used up before their expiration date. For some PFAS, such as those covered by the Stockholm Convention, expired foams should be sent to high-temperature incineration to break down the PFAS compounds. For others, they may be disposed of such that they end up in sewage treatment works where they are not likely to be broken down or removed.

However, were a restriction to come into place, the users who previously incinerated expired foam would no longer be required to because the Agency understands that alternative foams are suitable for disposal via standard drainage facilities.

As noted in Section 6.4.2.2, when using the central and high parameter values, no stocks expire under the baseline. When using the ‘low’ parameter values, roughly 40% of foams are estimated to expire annually.

Accordingly, the Agency models the cost saving under the situation where foams incinerated under the baseline no longer need to undergo this, as they are replaced with alternatives that do not require such treatment. Under the central scenario, there is estimated to be no cost saving. Under a low scenario, this is estimated to be £**<0.1m** across the 30-year appraisal period (PV).

A second, and perhaps more significant, cost saving may arise due to restriction avoiding the need to dispose of firewater and clean up any contamination in the area of use. Indeed, this cost saving alone appears to have already prompted transition for some users, notably airports.

6.4.2.9 Cost totals

The Agency estimates the total costs of restriction without decontamination to be £238.3m across the 30-year appraisal period. This is **£187.0m** in PV terms.

If decontamination is required (i.e., if restriction includes an end of pipe PFAS threshold that requires decontamination to meet), the total costs are estimated to rise to £379.5m, or **£289.3m** in PV terms.

Table 6.6: Estimate PV costs by type:

Cost type	PV estimate (30 years, million)
Foam substitution	£94.1
Incineration/disposal of unused stocks	£1.9
Capital replacement	£90.9
Decontamination cost (if relevant)	£102.3
Cost savings	<£0.1 (not including avoided clean-up costs)
Enforcement	Not quantified
Familiarisation	Not quantified
Cost to manufacturers	Not quantified
Total	**£187.0 (or £289.3 w/ decont.)**

In sector-specific terms, the above costs are estimated to break down as follows:

Table 6.7: Estimated PV costs per sector

Sector	Cost (30 years PV, million) Brackets denote cost where decontamination is undertaken.
Aviation	£10.0 (£14.0)
Marine	£14.6 (£16.9)
Ready-to-use	£1.1 (£1.3)
Military	£6.6 (£9.4)

Sector	Cost (30 years PV, million) Brackets denote cost where decontamination is undertaken.
(Petro)chemical	£138.1 (£228.4)
Fire and rescue services	£16.6 (£19.2)

From the above, one can see that roughly three quarters of costs relate to transition in the (Petro)chemical sector. This is for several reasons, notably the size of PFAS FFF use in the sector relative to others (assumed to be 59 % of GB consumption), but also in large part due to more expensive equipment changes being required for COMAH sites under restriction (see Section 6.4.2.3).

The next section explores the abatement that the Agency expects to occur under the restriction proposal, which will then allow for the proportionality of intervention to be considered. Abatement is compared with and without equipment decontamination.

6.4.2.10 Abatement

Under the central scenario, the Agency estimates annual emissions associated with the scope of this restriction to equal ~48 tonnes. This is estimated by multiplying the following four parameters below, with their respective central scenario estimates in brackets.

1) Annual sale of PFAS-containing foam concentrate (2000t)
2) Average share of concentrate which is PFAS (2.5%)
3) Share of releases which are not captured and destroyed/incinerated (currently arbitrarily assumed to be 95% in the absence of data)
4) Share of sales which are used, rather than incinerated (100%[3])

Because no further reduction in use is assumed in the current modelling, this estimated annual use is summed across 30 years to estimate a total baseline release of 1,425t.

---

[3] The best estimate (i.e. most likely value) of this parameter is considered to be 100% because it is a function of the average foam lifespan and the average time period over which stocks are used. The Agency's approach uses the best-estimates of these other two parameters (15 years and 8.3 years, respectively) to conclude that, on average, foams are used before they expire. In reality, there is likely to be significant heterogeneity across use sectors, and some users may be expected to incinerate expired stocks under the baseline. In further iterations of the SEA the Agency will investigate whether a more granular sector-specific set of parameters is feasible and proportionate to derive. The minimum value of this parameter is set to 0.6, derived similarly, where the minimum value for the average foam’s lifespan is 10 years, and this is contrasted with the assumption that the maximum time period over which foam stocks are used before exhaustion is 16.7 years.

To estimate the share of baseline emissions attributable to each sector, the Agency multiplies the annual sales of PFAS-containing foam by each sector’s estimated share of consumption (outlined in Section 6.4.1). Steps 2-4 above are then undertaken on this sector-specific foam consumption to estimate the following breakdown:

Table 6.8: Sector specific assumed annual baseline PFAS emissions

Sector	Assumed annual baseline PFAS emissions (tonnes, 1 decimal place)
Aviation	4.3
Marine	5.7
Ready-to-use	0.5
Military	2.9
(Petro)chemical	28.0
Fire and rescue services	6.2
Total	~48

Under restriction, the Agency adjusts emissions to account for sector-specific transition periods. These are in line with the substitution timeframes outlined in Analysis of Alternatives Section (Section 5) and shown as corresponding transition periods in Table 6.9 below. As noted in Section 5, the Agency considers these appropriate in allowing for technical aspects of transition. In terms of the economic considerations around transition periods, the Agency does not undertake specific analysis on this in the current SEA due to the limited availability of data. Further consideration of this will take place in future iterations of this impact assessment.

Table 6.9: Sector Transition Periods

Sector	Transition period (years)
Aviation	5
Marine	5
Ready-to-use	5
Military	5
(Petro)chemical	10

Sector	Transition period (years)
Fire and rescue services	1.5

Users of PFAS-containing foams are assumed to switch to the use of alternative foams when they exhaust the stock of PFAS-containing foams, or when their transition period ends, whichever comes first. As the Agency assumes that stocks across all uses last 8.3 years (see Section 6.4.2.2), it is only the (petro)chemical use sector who is assumed to cease use prior to their transition period finishing. All other sectors are assumed to have some PFAS-containing stock left at the end, which is sent to incineration. As noted above, the transition periods are currently based on technical considerations rather than economic ones. Revision to the proposals may occur as greater data is gathered by the Agency.

Subtracting the residual emissions under the restriction proposal from the baseline emissions, the Agency estimates a 30-year reduction in PFAS emissions of ~**1,120t**.

6.4.2.11 Decontamination

It is important to consider the implication of whether or not decontamination of kit is required as part of the restriction. It is also not a binary undertaking; there are different techniques available which will achieve varying results at different costs. As noted in Section 6.4.2.4, it is reasonable to assume that more stringent decontamination requirements entail greater costs. It is also noted that a detailed relationship between the extent of decontamination and the associated costs is not available at present. As such, the Agency has approached the issue in a binary sense: decontamination is either undertaken or it is not. Were it to not be required under restriction, no cost is attributed. If it is required a cost of **£102.3m** in PV terms is attributed.

As noted in Section 6.4.2.9, potential decontamination is the most significant cost identified in the impact assessment. It is undertaken to avoid ‘rebound’- the observed phenomenon that PFAS emissions can continue post-transition.

There is limited data available on the magnitude of rebound. As noted in Section 3.1.7 and Annex E.11, (Ross and Storch, 2020) found that 20 months after transition to F3 following dual water flushing of an aircraft hangar foam supply and delivery system, PFAS concentrations in the replacement foam varied from 60 µg/L (60 ppb) to 1,600,000 µg/L (1,600,000 ppb). The Agency uses these two estimates to form a lower and upper bound estimate of rebound, with the mean comprising the central estimate. In reality, the upper bound of 1.6 g/L seems an extreme case, and so the mean value is considered to lie much closer to the lower bound. The approach forms a conservative assumption.

The Agency assumes rebound to last 2 years post-cessation of PFAS-containing FFF. The true release pattern overtime is unknown. There is a finite quantity of PFAS which will have attached itself to the inside of equipment, meaning that rebound can only occur for a finite time period. The relationship of this release overtime cannot be determined; it may seem sensible to expect an exponential decay pattern where large releases initially occur, and then slowly tail off. However, it may also be the case that releases do not occur at first, and then a large spike occurs once PFAS become detached from the inside of the equipment after some period of alternative use.

In the absence of information of the above, the Agency assumes 2-years of constant rebound. In other words, anytime alternative foams are used during the 2 years-post transition, it is assumed that they contain 0.08% PFAS (compared to a best-estimate of 2.5% PFAS for PFAS-containing foams), where 0.08% is the mean of 0.000006% and 0.16%.

In the absence of decontamination, the Agency estimates that the modelled restriction is estimated to abate **1,121t** of PFAS across the 30-year appraisal period. Were decontamination to be stipulated, avoiding the rebound as outlined above, this estimation of abatement rises to **1,124t.** As such, the Agency's modelling suggests that some 3t of PFAS releases may be avoided through requiring users to decontaminate equipment in line with Section 6.4.2.4 before beginning use of alternative foams, at an estimated PV cost of £102m. Consideration of the proportionality of this requirement is outlined in Section 6.4.4.

6.4.2.11.1 Cost-effectiveness analysis

With estimates of the abatement occurring under restriction and the expected costs associated with this, the Agency can estimate cost-effectiveness ratios (CER). These can be estimated for restriction as a whole and for individual sectors. Crucially, one can estimate the incremental cost-effectiveness ratio (ICER) of a restriction which results in decontamination versus one that does not, which can aid the analysis of whether this is deemed a proportionate restriction measure. Once the CERs are derived, the Agency will explore (qualitatively) the benefits of restriction, before discussing and concluding upon the proportionality of restriction.

The estimated PV costs of restriction, across a 30-year appraisal period, are **£187.0m** in the absence of decontamination, and **£289.3m** if decontamination is required. Under the former, an estimated 1,124t of PFAS are abated. Under the latter, roughly 3t of additional PFAS emissions are assumed to occur due to rebound, resulting in 1,121t of abatement.

In the absence of decontamination, the estimated absolute cost-effectiveness ratio (CER) of the modelled restriction **is £167,000/t**. If decontamination is required, this rises to **£257,000/t**.

Both absolute CERs are significantly below (i.e., more favourable) the cost-effectiveness benchmark for PBT substances that Oosterhuis and Brouwer (2015) derive from previous chemicals policy interventions. In their study, the authors find that regulation on PBT substances with a CER below £1,628/kg or £1,628,000/t (converted from EUR 1,000 (2014 prices) to £2024) has been considered cost-effective from a decision-making standpoint, with CERs above this falling into a 'grey zone' (p.5). Of course, different substances have different impacts on humans and the environment and so an explicit £/weight threshold which is deemed ‘acceptable’ suffers from limitations, but this nonetheless provides useful context.

However, although both absolute CERs are below (more favourable than) the above ECHA-derived benchmark, the more appropriate insight relates to the incremental cost-effectiveness ratio (ICER) as opposed to the absolute cost-effectiveness ratio. This seeks to answer whether the incremental/marginal costs incurred from requiring decontamination are justified by the marginal reduction in emissions.

The ICER is calculated by:

$$\frac{Cost_{after} - Cost_{before}}{Abatement_{after} - Abatement_{before,}}$$

Where ‘before’ and ‘after’ refer to a restriction which does not require decontamination and one that does, respectively, and thus:

$$\text{ICER} = \frac{(£289.3m - £187.0m)}{(1{,}124t - 1{,}121t)} = \mathbf{£34.1m/t} \text{ (or £34,000/kg)}\mathbf{.}$$

The ICER is more than an order of magnitude above the ECHA-derived cost-effectiveness threshold, in what Oosterhuis and Brouwer (2015) refer to as the ‘grey zone’, where the costs of intervention have been deemed both proportionate and disproportionate depending on the case. Even if one were to assume that 1.6g/L of rebound (See Section 6.4.2.11) were to occur for two-years post transition (a highly conservative scenario), the ICER would roughly half to £17,000/kg (still an order of magnitude less favourable than the threshold derived by Oosterhuis and Brouwer (2015)).

As noted, there are many limitations to using the results of Oosterhuis and Brouwer (2015) as a firm threshold for demonstrating that a restriction is cost-effective. Nonetheless, it provides interesting context relevant to decisions that the European Union has previously made. Further discussion on the limitations are outlined in Section 6.4.3.

An ICER could similarly be estimated for every discrete step of restriction, for instance for each of the use sectors. This would be similar in design to a marginal abatement cost curve. The Agency does not derive this in the current SEA due to the uncertainty surrounding sector specific data. The Agency will seek to acquire greater evidence in this regard during the consultation period.

The Agency will now outline the benefits of restricting the use of PFAS in FFF. After this, and with the above cost-effectiveness analysis in mind, discussion around the proportionality of a potential restriction is outlined.

6.4.3 Benefits of proposed Restriction Option (RO1)

As noted in Section 4, the Agency considers that all PFAS used in FFFs are either PFAAs or degrade into PFAAs. All PFAAs have been shown to be very persistent (vP) and to have the potential to reach environmental compartments of concern (e.g. groundwaters and locations remote from the source) due to their mobility. Section 4 also noted that toxicity is associated with substances across both the PFCA and PFSA sub-groups of PFAAs, whilst also noting that given the unknown composition of PFAS-containing FFF, the PFAS present in any particular foam could degrade to a combination of various PFCAs and PFSAs. Section 3 concluded that releases to the environment can result in long term environmental exposure and potential contamination of drinking water. Consequently, exposure of humans via the environment constitutes the main health concern. These substances can remain in the body for a long time, up to several years in the case of some PFAAs, and continued exposure is expected to lead to increasing body burdens. Given the nature of the toxicity identified in Section 2, possible health effects associated with exposure to PFAS could include increased risks of cancers of various tissues, adverse effects on developing offspring and fertility, liver toxicity, immune system and metabolic effects.

The main economic impacts of these health effects are a decrease in the quality (and possibly quantity) of life of an individual impacted by one of these health issues (both the physical impact but also any additional mental health impact associated with having one of these health issues), as well as the increased demand for healthcare and the costs associated with the treatment required for these health issues.

In addition to the human health effects, there is the potential for damages associated with repeated and prolonged exposure of the environment and ecosystem services to PFAS. PFAS-contaminated ecosystems may provide less utility or welfare to users than they would if they had not been contaminated with PFAS due to the impacts on ecosystem goods and services. Whilst it is difficult to attribute such human health and environmental impacts directly to releases of PFAS-containing firefighting foams, such releases avoided as a result of a restriction will nevertheless contribute towards a reduction in the overall burden of PFAS releases in society.

The benefits of a restriction are thus predominantly the avoided losses in societal welfare associated with the potential human health and environmental risks posed by PFAS in FFF that society (current and future) would have incurred under the baseline but will no longer be incurred due to restriction. This is not the same thing as removing all future potential risks; legacy stocks will persist in the absence of other remediation measures.

Due to the combination of properties possessed by PFAAs, a non-threshold approach was taken in the risk assessment, with no quantitative estimate of risk undertaken. In exploring the benefits of the proposed restriction then, a non-threshold approach is taken in the absence of being able to estimate a threshold below which adverse effects would not be expected, due to the extreme persistence of PFAS, uncertainties around the effects of chronic and intergenerational exposure, and the irreversibility of exposure. Under this approach, any release of the substance is considered to pose a risk that is not adequately controlled.

This section provides an overview of academic and grey literature relating to both the benefits of avoided PFAS exposure and the costs associated with remediation (a proxy of benefits), noting that these typically stem from broad PFAS pollution scenarios and not just those relevant to this Annex 15 report. It should be noted that these often relate largely to PFOS and PFOA whose use in FFF is already regulated, and about which greater evidence and knowledge of hazards exists. Nonetheless, they can be useful to indicate preferences for avoiding such pollution.

No explicit monetised estimate for the benefits of restricting the use of PFAS in FFF is made due to the limitations in data regarding risks to human health and the environment, though the Agency will continue to explore this possibility throughout the rest of the restriction process.

6.4.3.1 Empirical research

The existing economic research literature related to the benefits of avoiding PFAS exposure is relatively small and can be categorised into the following groups:

1) Revealed preference studies
2) Stated preference studies
3) Impact pathway studies
4) Avoided cost studies (benefits proxy)

Much of the research outlined relates to the impact of legacy PFAS contamination. This is still useful in exploring the preferences that individuals may hold over avoiding the risk of exposure to PFAS stocks, however, it is likely unsuitable for informing a cost-benefit analysis within this Annex 15 report. Here, we are considering a restriction on future uses of PFAS in FFF which will not address the stock attributable to past uses of both PFAS in FFF and other uses. Moreover, most research seemingly relates to PFOS and PFOA, the use of which in FFF is already prohibited through the POPs Regulation.

Although these studies typically relate to other regulatory contexts and hence have limited application to the context considered in this report, the Agency still considers the existing literature useful to consider, as it nonetheless demonstrates that preferences are held over avoiding PFAS pollution more generally and hence are likely to held for avoiding PFAS in FFF.

Revealed preference

Marcus and Mueller (2024) estimated a large statistically significant decrease in house price values of about 31 % to 42 % on average attributable to the discovery of PFAS contamination within the Paulsboro water system service area relative to properties in the top 20 matched census tracts or other properties across New Jersey.

A similar study by Islam and Heintzelman (2023) estimated a smaller 1.5-2.8%[4] house price decrease attributable to drinking water contaminated with PFOS and PFOA above the EPA health advisories of 70 ng/L, in two counties of southeastern Pennsylvania. The authors note this contamination to be attributable to former US

---

[4] The authors report these values to be statistically significant at 5% and 1% level, respectively.

Department Of Defence sites where PFAS was released into surface and ground waters due to training exercises with AFFF.

Stated preference

There appears to be little in the way of available stated preference research on the benefits of reducing or avoiding exposure to PFAS. Albeit not without controversy in terms of the validity and reliability of results (e.g., see Hausman, 2012), stated preference studies have the advantage of being tailored to specific regulatory scenarios such as the restriction proposal within this Annex 15 report.

A recent Master's thesis from a student at the University of New Hampshire (Price, 2022) used a contingent valuation approach to value the economic benefits of a water filtration system that was presented as lowering the risk of adverse health consequences from PFAS exposure. The author estimates New Hampshire households are willing to pay an average of $13.07 per month on top of their existing water bill to avoid such exposure.

The restriction proposal would not achieve the same outcome as removing all PFAS from drinking water sources, and so this study is not considered suitable for use in a benefits transfer, before giving any further consideration to robustness. Nonetheless, it once again demonstrates positive willingness to pay (at least in New Hampshire) to mitigate potential risks posed by the substances.

Impact pathway

A study by the US EPA (2024e) modelled the costs and benefits associated with an enforceable National Primary Drinking Water Regulation associated with 6 PFAS substances: PFOS, PFOA, PFNA, HFPO-DA and its ammonium salt, PFHxS, and PFBS.

Through various quantitative approaches such as pharmacokinetic modelling, the EPA estimate quantitative benefits for reductions in PFOA and PFOS related birth weight, cardiovascular, and renal cell carcinoma effects, as a result of compliance with the regulation. Other benefits were explored qualitatively.

Another study published by the Nordic Council of Ministers (2019) investigated the human health and environmental impacts in the European Economic Area (EEA) associated with the life cycle of PFAS from manufacture to disposal. They estimate annual human health impacts associated with PFAS exposure and associated endpoints (kidney cancer, hypertension, low birth weight, infection, and all cause mortality) to sum to EUR 52-84 billion, which they consider to be a conservative estimate due to comprising "only a few of the health impacts linked to exposure of PFAS" (p.127).

Other statistical analysis

Other empirical economic research to estimate the societal costs of PFAS exposure includes a US working paper by Jacqz et al. (2024). This looked at the effect of proximity to a Navy fire training area (taken as a proxy of PFAS exposure) on infants' birthweight.

The authors found a statistically significant decrease in birthweights in counties exposed to fire training areas (FTAs) following the years of AFFF adoption relative to counties with military installations that did not have fire training areas. They also estimate that individuals born near installations with FTAs after the adoption of AFFFs earn $827/year less than cohorts born near other installations.

Avoided cost

There are many examples of PFAS remediation being undertaken which is related to contamination as a result of releases from uses such as firefighting.

The benefits of restricting future releases of PFAS via FFF use is not the same as the benefits of undertaking remediation. Similarly, the costs of undertaking remediation works may bear little relation to the benefits: remediation costs may be significantly higher or lower than the benefits of doing that remediation.

If it is plausible to assume that ongoing releases will lead to future remediation, that otherwise would not have needed to occur or would have required less resources, this can be used as a proxy of the benefits. If the assumption of remediation is correct (i.e., remediation takes place), this method results in a lower bound proxy, because it is possible that the benefits of the remediation could significantly exceed the costs that would have occurred from undertaking it.

Jacobs (2023) conducted an analysis for the Environment Agency which evaluated the economic burden of remediating PFAS from high-risk sites across England.

A review of evidence covering academic and grey literature on the unit costs and case studies of land-based remediation was undertaken, in addition to assessing potential health, environmental, and economic impacts relating to PFAS pollution. An expert elicitation exercise to validate cost information on remediation activities from specialists was also conducted.

The work found that average costs per site range from an estimated £400,000 to £29 billion due to the different levels of remediation required due to range of site type and size. The report estimates potential remediation costs across England of between £31 billion and £121 billion for 2,900 - 10,200 high-risk sites. These costs pertain to a wide range of PFAS uses and not just PFAS-containing FFF.

6.4.4 Proportionality and restriction design

As outlined in Section 6.4.2, the estimated PV costs of restriction, across a 30-year appraisal period, are **£187.0m** in the absence of decontamination, and **£289.3m** if decontamination is required. Under the latter scenario, an estimated 1,124t of PFAS are abated. Under the former scenario, roughly 3t of additional PFAS emissions are assumed to occur due to rebound, resulting in 1,121t of abatement. As previously noted, a large amount of parameter uncertainty exists which the Agency will seek to reduce during the consultation period and beyond, so these aggregate estimates should be interpreted with this in mind.

In the absence of decontamination, the estimated absolute cost-effectiveness ratio (CER) of the modelled restriction **is £167,000/t**. If decontamination is required due to the design of restriction, this rises to **£257,000/t**. The incremental cost-effectiveness ratio (ICER) associated with moving from a restriction which doesn't induce decontamination to one that does is **£34m/t**. Section 6.4.2.11.1 showed that although the two individual absolute CERs presented both fall within the cost-effective threshold derived by Oosterhuis and Brouwer (2015) (£1.6m/t), the ICER does not. In other words, using this threshold alone, the conclusion could be drawn that the costs of decontamination appear to be disproportionate to the associated reduction in risk.

<u>This is a crude measurement of proportionality</u>. The PBT classification used by the authors covers a broad range of risks and associated possible impacts and may be a poor proxy for judging preferences around avoiding PFAS risks. Further, the decisions taken under previous chemicals policy interventions on PBT substances, which in turn underpin the benchmark derived by Oosterhuis and Brouwer (2015), are not necessarily underpinned by economic efficiency; indeed, it is likely that most of them were, taken without regard to, or for reasons other than, a considered assessment of benefits and costs. Indeed, the same types of uncertainty surrounding costs and benefits are equally present for interventions related to PBT substances upon which the study was based, as are present in this report. Even if the decisions were based on economic efficiency, public preferences at the time (and therefore restriction costs and benefits) may not represent those of GB at the current moment.

Given the above discussion, the Agency is not able to quantitatively estimate the benefits of restriction. Nonetheless, it is clear from Section 6.4.3 that a range of possible environmental and human health risks may exist as a result of PFAS in FFF. There is significant uncertainty around future impacts, but there are potential scenarios where exposure to PFAS as a result of FFF releases leads to undesirable, irreversible and possibly intergenerational impacts. The likelihood and scale of this cannot be determined.

In light of this, a qualitative comparison of costs and benefits can be helpful: ultimately, the Agency concludes that alternatives to PFAS-containing FFFs are available and perform effectively in terms of technical requirements. Indeed, the Agency believes the majority of the market to already have transitioned away to alternatives voluntarily. Those who have not are likely to be those that face the highest transition costs and hence are unlikely to transition voluntarily. The most significant cost associated with a restriction appears to be decontamination of equipment to avoid 'rebound' post-transition. This would avoid a relatively small release of PFAS, perhaps as little as 3 tonnes across 30-years, compared to abating 1,120t as a result of restriction on just the use without decontamination. As such, restriction can be designed such that this cost is avoided, as it significantly reduces the burden of restriction whilst avoiding the vast majority of PFAS emissions from this source.

A quantified assessment of the risk that would be avoided as a result of restriction cannot be determined. The restriction proposal is thus based on a qualitative assessment of risk, which is both uncertain in magnitude and scope of associated impact. Proportionality cannot be explicitly demonstrated through means of a benefit-cost ratio. Nonetheless, a restriction on the sale and use of AFFF certainly does not appear disproportionate relative to other interventions taken, as per the benchmark in Oosterhuis and Brouwer (2015), though as discussed this benchmark is not necessarily a robust measure. The Agency's current analysis concludes, however, that the conclusion on proportionality cannot be said for measures that require decontamination before use of alternative foams (i.e., a restriction where a strict PFAS threshold is set on discharges, inducing costly decontamination protocols).

In line with the above, the Agency does not see a compelling case for concluding that restriction on the sale and use of PFAS in FFF would be a disproportionate risk management measure. This conclusion is based on the Oosterhuis and Brouwer (2015) benchmark rather than a fully quantified cost benefit assessment. Accordingly, **such a restriction is proposed as being an appropriate measure to address the risk, albeit one whose proportionality cannot be quantified at this stage. Further work will be done in this respect during the remainer of the restriction process**. As things stand, the Agency would not propose to include decontamination as an appropriate measure given that it considers this to likely be disproportionate. It is important to note that current proposals are draft, and subject to further consultation, so the proposal may change across the restriction process.

6.4.5 Sensitivity analysis

A large number of parameters are relevant and integral to the analysis outlined above. In the draft and final socio-economic analyses, the Agency will seek to incorporate extensive sensitivity analysis in order to address some of the uncertainties surrounding the analysis and their potential impact. Such analysis has not yet been included; the Agency endeavours to improve the data upon which this impact assessment is based, and a thorough sensitivity analysis will be undertaken alongside this improvement in data.

Table 6.10 below contains key modelling parameters used by the Agency in the Annex 15 SEA. **The Agency welcomes responses during the consultation period where consultees have expertise in or information pertaining to particular parameter values below (or other evidence that can be used in the economic analysis e.g., benefits assessment), the use of which may allow for a more precise estimate of the socio-economic impacts of restriction.**

Table 6.10: Key Modelling parameters used in the Socioeconomic Analysis

Parameter number (px)	Parameter description	Minimum value	Most likely value	Maximum value	Source(s)/approach
1	Annual UK purchase and use of PFAS-containing foam (t)	**1,300**	**2,000**	**2,500**	WSP (2023)
2	Annual UK purchase and use of PFAS-free foam (t)	**2,000**	**2,900**	**2,500**	WSP (2023)
3	Share of foam concentrate which is PFAS	**0.02**	**0.025**	**0.03**	ECHA (2022a)
4	Share of releases not captured and destroyed (not including those never released due to incineration at expiry point)	**0.90**	**0.95**	**0.99**	Currently an arbitrary assumption
5	UK total stock of PFAS-containing foam stockpile (t)	**7,222**	**16,667**	**41,667**	Estimated by dividing p1 by p57.
6	UK total stock of PFAS-free foam stockpile (t)	**11,111**	**24,167**	**60,000**	Estimated by dividing p2 by p57.
7	Total UK foam concentrate stock (t)	**18,333**	**40,833**	**101,667**	Estimated by summing p5 and p6.

Parameter number (px)	Parameter description	Minimum value	Most likely value	Maximum value	Source(s)/approach
8	Market price of PFAS foam concentrate (£/t) (assumed constant across appraisal period in real terms)	**3,330**	**3,700**	**4,625**	Central estimate from manufacturer in call for evidence, low and high are adjusted by -10% and +25% as in ECHA (2022a)
9	Price of alternative foam concentrate (£/t) (assumed constant across appraisal period in real terms)	**3,600**	**4,000**	**5,000**	Central estimate from manufacturer in call for evidence, low and high are adjusted by -10% and +25% as in ECHA (2022a)
10	Potential increased quantity of alternative foam needed for any given event relative to PFAS	**1.25**	**1.5**	**1.75**	ECHA (2022a)
11	Foam lifespan (i.e., natural expiration, years)	**10**	**15**	**30**	ECHA (2022a)
12	share of PFAS foam not disposed of/incinerated under baseline	**0.60**	**1.00**	**1.00**	This represents the baseline share of stocks which are used and not incinerated. Calculated as ((p58-p11)/p58)
13	Incineration/disposal cost of stocks (£/t)	**362**	**522**	**845**	eftec (2019)
14	Cleaning cost for typical COMAH site (rounded to nearest £1,000)	**106,000**	**212,000**	**423,000**	ECHA (2022a)

Parameter number (px)	Parameter description	Minimum value	Most likely value	Maximum value	Source(s)/approach
15	Cleaning cost aviation/military (rounded to nearest £1,000)	**26,000**	**53,000**	**106,000**	ECHA (2022a)
16	Cleaning cost other (rounded to nearest £1,000)	**11,000**	**21,000**	**42,000**	ECHA (2022a)
17	Cost of technical changes-Seveso/COMAH (rounded to nearest £1,000)	**265,000**	**529,000**	**1,588,000**	ECHA (2022a)
18	Cost of technical changes-other (rounded to nearest £1,000)	**3,000**	**5,000**	**16,000**	ECHA (2022a)
19	No. UK COMAH sites which have not transitioned to alternatives	**163**	**163**	**163**	WSP (2023)
20	No. UK ‘other’ sites which have not transitioned to alternatives	**653**	**857**	**1,061**	WSP (2023)
21	Aviation share of PFAS market (and therefore assumed sector split of PFAS stocks)	**0.09**	**0.09**	**0.09**	ECHA (2022a)
22	Marine share of PFAS market (and therefore assumed sector split of PFAS stocks)	**0.12**	**0.12**	**0.12**	ECHA (2022a)

Parameter number (px)	Parameter description	Minimum value	Most likely value	Maximum value	Source(s)/approach
23	Ready-to-use share of PFAS market (and therefore assumed sector split of PFAS stocks)	**0.01**	**0.01**	**0.01**	ECHA (2022a)
24	Military share of PFAS market (and therefore assumed sector split of PFAS stocks)	**0.06**	**0.06**	**0.06**	ECHA (2022a)
25	(Petro)chemical share of PFAS market (and therefore assumed sector split of PFAS stocks), including offshore	**0.59**	**0.59**	**0.59**	ECHA (2022a)
26	Fire and rescue services share of PFAS market (and therefore assumed sector split of PFAS stocks), including transport use sector	**0.13**	**0.13**	**0.13**	ECHA (2022a)
27	Aviation share of alternatives market (and therefore assumed sector split of PFAS stocks)	**0.08**	**0.08**	**0.08**	ECHA (2022a)
28	Marine share of alternatives market (and therefore assumed sector split of PFAS stocks)	**0.16**	**0.16**	**0.16**	ECHA (2022a)
29	Ready-to-use share of alternatives market (and therefore assumed sector split of PFAS stocks)	**0.01**	**0.01**	**0.01**	ECHA (2022a)

Parameter number (px)	Parameter description	Minimum value	Most likely value	Maximum value	Source(s)/approach
30	Military share of alternatives market (and therefore assumed sector split of PFAS stocks)	**0.02**	**0.02**	**0.02**	ECHA (2022a)
31	(Petro)chemical share of alternatives market (and therefore assumed sector split of PFAS stocks), including offshore	**0.29**	**0.29**	**0.29**	ECHA (2022a)
32	Fire and rescue services share of alternatives market (and therefore assumed sector split of PFAS stocks), including transport use sector	**0.44**	**0.44**	**0.44**	ECHA (2022a)
33	Aviation concentrate stockpile: PFAS (t)	**650**	**1,500**	**3,750**	Calculated by multiplying p21 by p5.
34	Marine concentrate stockpile: PFAS (t)	**867**	**2,000**	**5,000**	Calculated by multiplying p22 by p5.
35	Ready-to-use concentrate stockpile: PFAS (t)	**72**	**167**	**417**	Calculated by multiplying p23 by p5.
36	Military concentrate stockpile: PFAS (t)	**433**	**1,000**	**2,500**	Calculated by multiplying p24 by p5.
37	(Petro)chemical concentrate stockpile: PFAS (t)	**4,261**	**9,833**	**24,583**	Calculated by multiplying p25 by p5.
38	Fire and rescue services concentrate stockpile: PFAS (t)	**939**	**2,167**	**5,417**	Calculated by multiplying p26 by p5.

Parameter number (px)	Parameter description	Minimum value	Most likely value	Maximum value	Source(s)/approach
39	Aviation concentrate stockpile: alternatives (t)	**889**	**1,933**	**4,800**	Calculated by multiplying p21 by p6.
40	Marine concentrate stockpile: alternatives (t)	**1,778**	**3,867**	**9,600**	Calculated by multiplying p22 by p6.
41	Ready-to-use concentrate stockpile: alternatives (t)	**111**	**242**	**600**	Calculated by multiplying p23 by p6.
42	Military concentrate stockpile: alternatives (t)	**222**	**483**	**1,200**	Calculated by multiplying p24 by p6.
43	(Petro)chemical concentrate stockpile: alternatives (t)	**3,222**	**7,008**	**17,400**	Calculated by multiplying p25 by p6.
44	Fire and rescue services concentrate stockpile: alternatives (t)	**4,889**	**10,633**	**26,400**	Calculated by multiplying p26 by p6.
45	Aviation share of own stock: PFAS	**0.44**	**0.44**	**0.44**	Calculated as (p33/(p33+p39)
46	Marine share of own stock: PFAS	**0.34**	**0.34**	**0.34**	Calculated as (p34/(p34+p40)
47	Ready-to-use share of own stock: PFAS	**0.41**	**0.41**	**0.41**	Calculated as (p35/(p35+p41)
48	Military share of own stock: PFAS	**0.67**	**0.67**	**0.67**	Calculated as (p36/(p36+p42)

Parameter number (px)	Parameter description	Minimum value	Most likely value	Maximum value	Source(s)/approach
49	(Petro)chemical share of own stock: PFAS	**0.58**	**0.58**	**0.58**	Calculated as (p37/(p37+p43)
50	Fire and rescue service share of own stock: PFAS	**0.17**	**0.17**	**0.17**	Calculated as (p38/(p38+p44)
51	Aviation share of own stock: alternatives	**0.56**	**0.56**	**0.56**	Calculated as (1-p45)
52	Marine share of own stock: alternatives	**0.66**	**0.66**	**0.66**	Calculated as (1-p46)
53	Ready-to-use share of own stock: alternatives	**0.59**	**0.59**	**0.59**	Calculated as (1-p47)
54	Military share of own stock: alternatives	**0.33**	**0.33**	**0.33**	Calculated as (1-p48)
55	(Petro)chemical share of own stock: alternatives	**0.42**	**0.42**	**0.42**	Calculated as (1-p49)
56	Fire and rescue service share of own stock: alternatives	**0.83**	**0.83**	**0.83**	Calculated as (1-p50)
57	Total market average share of stock used annually	**0.06**	**0.12**	**0.18**	ECHA (2022a)
58	Time period over which concentrate stocks are exhausted	**5.6**	**8.3**	**16.7**	Calculated as (p7/(p57*p7))

Parameter number (px)	Parameter description	Minimum value	Most likely value	Maximum value	Source(s)/approach
59	Aviation share of COMAH sites	**0**	**0**	**0**	See explanation on p64.
60	Marine share of COMAH sites	**0**	**0**	**0**	See explanation on p64.
61	Offshore share of COMAH sites	**0**	**0**	**0**	See explanation on p64.
62	Ready-to-use share of COMAH sites	**0**	**0**	**0**	See explanation on p64.
63	Military share of COMAH sites	**0**	**0**	**0**	See explanation on p64.
64	(Petro)chemical share of COMAH sites	**1.00**	**1.00**	**1.00**	ECHA (2022a) assume that 98% of oil/petrochemicals category is Seveso vs non-Seveso. The Agency currently assumes that all COMAH sites belong to (Petro)chemical use.
65	Fire and rescue services share of COMAH sites	**0**	**0**	**0**	See explanation on p64.
66	Aviation share of other sites	**0.22**	**0.22**	**0.22**	Calculated by assuming that all (Petro)chemical sites are COMAH, and the remaining sites are distributed by use sector on the basis of their volume of foam stock.

Parameter number (px)	Parameter description	Minimum value	Most likely value	Maximum value	Source(s)/approach
67	Marine share of other sites	**0.29**	**0.29**	**0.29**	See explanation of p66.
68	Ready-to-use share of other sites	**0.02**	**0.02**	**0.02**	See explanation of p66.
69	Military share of other sites	**0.15**	**0.15**	**0.15**	See explanation of p66.
70	(Petro)chemical share of other sites	**0**	**0**	**0**	See explanation of p66.
71	Fire and rescue services share of other sites	**0.32**	**0.32**	**0.32**	See explanation of p66.
72	rebound potential (ug PFAS/L foam)	**60**	**800,000**	**1,600,000**	Ross and Storch (2020) for minimum and maximum value. Most likely value is taken as the mean of these.

Note: monetised figures are adjusted from initial source values to £2024.

7 Conclusions

Emissions of PFAS to the environment have been demonstrated from all uses of PFAS-containing firefighting foams in GB.

Once PFAS enter the environment, transformation processes eventually lead to the formation of highly stable fluorinated substances, referred to as terminal degradation products. The Agency concludes that the terminal degradation products that arise from PFAS contained in firefighting foams are very persistent. These terminal degradation products are also sufficiently mobile to reach environmental compartments of concern, including those remote from sources. In particular, their mobility in water means that they can contaminate water sources, including drinking water.

Following exposure of people, PFAS can remain in the human body for a long time, and continued exposure is expected to lead to increasing body burdens. Some terminal degradation products and other PFAS are suspected carcinogens, cause harm to the developing child and can cause effects in organs such as the liver or in the immune system.

Owing to their extreme persistence and resistance to conventional environmental remediation measures, continued emissions of PFAS from the use of firefighting foams are expected to lead to increasing concentrations of PFAS in the environment over time, contributing to PFAS exposures at the population level.

Whilst existing measures are in place to manage certain PFAS, these do not control emissions of PFAS into the environment from their use in firefighting foams. Therefore, the Agency concludes that the use of PFAS in firefighting foams presents a risk to the environment, and human health via the environment, that is not adequately controlled by measures already in place.

The Agency notes that numerous, technically feasible, fluorine-free alternative firefighting foams exist. However, the challenges of transitioning with regards to cost and efficacy compared to PFAS-containing foams are recognised, particularly in the petrochemical industry and at offshore installations. It is also noted that there are a limited number of robust reports of alternative firefighting foams being used in real fire incidents. However, the Agency considers that there are examples of successful transitions across all sectors considered in this report.

Therefore, as alternatives are broadly available to replace PFAS in firefighting foams across the assessed uses, the Agency is proposing a restriction on the placing on the market and use of PFAS as a constituent in firefighting foam. The proposed restriction includes sector/use specific transition periods to support an orderly transition and ensure that users can adapt to suitable alternatives without jeopardising safety. These transition periods have been determined using those derived in the EU restriction on FFF as a basis and supplementing with GB-specific information gathered during the development of this report.

The Agency also concludes that a restriction on the placing on the market and use of firefighting foam does not appear disproportionate relative to other interventions, though it has not been possible to undertake a fully quantified cost benefit assessment at this stage.

For the purpose of the restriction, PFAS will be defined as any substance that contains at least one fully fluorinated methyl (CF_3) or methylene (CF_2) carbon atom without any hydrogen, chlorine, bromine, or iodine atom attached to it. The Agency concludes that adopting a broad definition will minimise potential for regrettable substitution with PFAS not currently known to be used in firefighting foams, but which have the same risks as those already identified.

Further details of the suggested restriction are provided in the opening summary section.

8 References

Ahrens, L., Norstrom, K., Viktor, T., Cousins, A. P. & Josefsson, S. (2015). Stockholm Arlanda Airport as a source of per- and polyfluoroalkyl substances to water, sediment and fish. *Chemosphere,* 129, 33-38. https://doi.org/10.1016/j.chemosphere.2014.03.136

Angus Fire (2025a). Foam concentrates: Trainol 3*.* Angus Fire. Available at: https://www.angusfire.co.uk/products-catalogue/trainol-3-6

Angus Fire (2025b). Foam concentrates: Trainol 6*.* Angus Fire. Available at: https://www.angusfire.co.uk/products-catalogue/trainol-6

Ankley, G. T., Cureton, P., Hoke, R. A., Houde, M., Kumar, A., Kurias, J., Lanno, R.*, et al.* (2021). Assessing the ecological risks of per- and polyfluoroalkyl substances: Current state-of-the science and a proposed path forward. *Environmental Toxicology and Chemistry,* 40(3), 564-605. https://doi.org/10.1002/etc.4869

Aro, R., Carlsson, P., Vogelsang, C., Karrman, A. & Yeung, L. W. (2021). Fluorine mass balance analysis of selected environmental samples from Norway. *Chemosphere,* 283, 131200. https://doi.org/10.1016/j.chemosphere.2021.131200

Arvaniti, O. S., Andersen, H. R., Thomaidis, N. S. & Stasinakis, A. S. (2014). Sorption of perfluorinated compounds onto different types of sewage sludge and assessment of its importance during wastewater treatment. *Chemosphere,* 111, 405-411. https://doi.org/10.1016/j.chemosphere.2014.03.087

ATSDR (2021). Toxicological profile for perfluoroalkyls. Department of Health and Human Services Public Health Service, Agency for Toxic Substances and Disease Registry. Atlanta, USA. http://dx.doi.org/10.15620/cdc:59198

Back, G. G. & Farley, J. P. (2020). Evaluation of the fire protection effectiveness of fluorine free firefighting foams. [FPRF-2020-01]. Fire Protection Research Foundation, National Fire Protection Association (NFPA). USA. Available at: https://www.nfpa.org/education-and-research/research/fire-protection-research-foundation/projects-and-reports/evaluation-of-the-fire-protection-effectiveness-of-fluorine-free-firefighting-foams

Backe, W. J., Day, T. C. & Field, J. A. (2013). Zwitterionic, cationic, and anionic fluorinated chemicals in aqueous film forming foam formulations and groundwater from U.S. Military bases by nonaqueous large-volume injection HPLC-MS/MS. *Environmental Science and Technology,* 47(10), 5226-5234. https://doi.org/10.1021/es3034999

Barzen-Hanson, K. A., Roberts, S. C., Choyke, S., Oetjen, K., McAlees, A., Riddell, N., McCrindle, R.*, et al.* (2017). Discovery of 40 classes of per- and polyfluoroalkyl substances in historical aqueous film-forming foams (AFFFs) and AFFF-impacted groundwater. *Environmental Science and Technology,* 51(4), 2047-2057. https://doi.org/10.1021/acs.est.6b05843

BBC (2024). Petrol station closed after car crashes into pump. BBC News. Available at: https://www.bbc.co.uk/news/articles/czd5em8484vo

Berhanu, A., Mutanda, I., Taolin, J., Qaria, M. A., Yang, B. & Zhu, D. (2023). A review of microbial degradation of per- and polyfluoroalkyl substances (PFAS): Biotransformation routes and enzymes. *Science of the Total Environment,* 859(Pt 1), 160010. https://doi.org/10.1016/j.scitotenv.2022.160010

Bierbaum, T., Klaas, N., Braun, J., Nürenberg, G., Lange, F. T. & Haslauer, C. (2023). Immobilization of per- and polyfluoroalkyl substances (PFAS): Comparison of leaching behavior by three different leaching tests. *Science of the Total Environment,* 876, 162588. https://doi.org/10.1016/j.scitotenv.2023.162588

BIMCO (2022). IMO agrees to ban PFOS from firefighting systems on board ships. Baltic and International Maritime Council. Available at: https://www.bimco.org/insights-and-information/safety-security-environment/20220309-pfos-prohibition

BIOEX (2024). Bio foam, fluorine-free synthetic multi-expansion foam concentrate effective on hydrocarbon fires. BIOEX. Available at: https://www.bio-ex.com/en/our-products/product/bio-foam/

Björnsdotter, M. K., Yeung, L. W. Y., Kärrman, A. & Jogsten, I. E. (2019). Ultra-short-chain perfluoroalkyl acids including trifluoromethane sulfonic acid in water connected to known and suspected point sources in Sweden. *Environmental Science and Technology,* 53(19), 11093-11101. https://doi.org/10.1021/acs.est.9b02211

Britannia Fire (2025). P50-ECO PFAS free foam extinguisher. Britannia Fire. Available at: https://www.britannia-fire.co.uk/product/p50-eco/#product-intro-text

Brusseau, M. L. (2018). Assessing the potential contributions of additional retention processes to PFAS retardation in the subsurface. *Science of the Total Environment,* 613-614, 176-185. https://doi.org/10.1016/j.scitotenv.2017.09.065

Brusseau, M. L. (2019). Estimating the relative magnitudes of adsorption to solid-water and air/oil-water interfaces for per- and poly-fluoroalkyl substances. *Environmental Pollution,* 254(Pt B), 113102. https://doi.org/10.1016/j.envpol.2019.113102

Brusseau, M. L. (2024a). Field versus laboratory measurements of PFAS sorption by soils and sediments. *Journal of Hazardous Materials Advances,* 16, 100508. https://doi.org/10.1016/j.hazadv.2024.100508

Brusseau, M. L. (2024b). A framework for developing tools to predict PFAS physical–chemical properties and mass-partitioning parameters. *Environments,* 11(8), 164. https://doi.org/10.3390/environments11080164

Brusseau, M. L. & Guo, B. (2022). PFAS concentrations in soil versus soil porewater: Mass distributions and the impact of adsorption at air-water interfaces. *Chemosphere,* 302, 134938. https://doi.org/10.1016/j.chemosphere.2022.134938

Brusseau, M. L. & Van Glubt, S. (2019). The influence of surfactant and solution composition on PFAS adsorption at fluid-fluid interfaces. *Water Research,* 161, 17-26. https://doi.org/10.1016/j.watres.2019.05.095

Buck, R. C., Franklin, J., Berger, U., Conder, J. M., Cousins, I. T., de Voogt, P., Jensen, A. A., *et al.* (2011). Perfluoroalkyl and polyfluoroalkyl substances in the environment: Terminology, classification, and origins. *Integrated Environmental Assessment and Management,* 7(4), 513-541. https://doi.org/10.1002/ieam.258

Butt, C. M., Muir, D. C. & Mabury, S. A. (2014). Biotransformation pathways of fluorotelomer-based polyfluoroalkyl substances: A review. *Environmental Toxicology and Chemistry,* 33(2), 243-267. https://doi.org/10.1002/etc.2407

CAA (2022). Rescue and fire-fighting services (RFFS) requirements. [OTAR Part 140]. Civil Aviation Authority. England: Air Safety Support International Limited. Available at: https://www.airsafety.aero/requirements-and-policy/otars/otar_part_140

CAA (2023). UK airport data January 2023. Civil Aviation Authority. Available at: https://www.caa.co.uk/data-and-analysis/uk-aviation-market/airports/uk-airport-data/uk-airport-data-2023/january-2023/

CAA (2024). CAP 1264: Standards for helicopter landing areas at hospitals. Civil Aviation Authority. England. Available at: https://www.caa.co.uk/our-work/publications/documents/content/cap1264/

Cahill, T. M. (2024). Assessment of potential accumulation of trifluoroacetate in terminal lakes. *Environmental Science and Technology,* 58(6), 2966-2972. https://doi.org/10.1021/acs.est.3c08822

Campo, J., Masia, A., Pico, Y., Farre, M. & Barcelo, D. (2014). Distribution and fate of perfluoroalkyl substances in Mediterranean Spanish sewage treatment plants. *Science of the Total Environment,* 472, 912-922. https://doi.org/10.1016/j.scitotenv.2013.11.056

Campos-Pereira, H., Kleja, D. B., Ahrens, L., Enell, A., Kikuchi, J., Pettersson, M. & Gustafsson, J. P. (2023). Effect of pH, surface charge and soil properties on the solid-solution partitioning of perfluoroalkyl substances (PFASs) in a wide range of temperate soils. *Chemosphere,* 321, 138133. https://doi.org/10.1016/j.chemosphere.2023.138133

Casey, J. & Trazzi, D. (2022). Fluorine-free foam testing. [DOT/FAA/TC-22/23]. U.S. Department of Transportation, Federal Aviation Administration. USA. Available at: https://www.airporttech.tc.faa.gov/DesktopModules/EasyDNNNews/DocumentDownload.ashx?portalid=0&moduleid=3682&articleid=2882&documentid=3054

CCA (2004). Civil contingencies act 2004 (Chapter 36). United Kingdom. Available at: https://www.legislation.gov.uk/ukpga/2004/36/data.pdf

CFRS (2022). FOI 1728- firefighting foam. Cheshire Fire and Rescue Service. Available at: https://www.cheshirefire.gov.uk/your-service/gdpr-data-protection/freedom-of-information/disclosure-log/2022/foi-1728--firefighting-foam/

Chen, H., Choi, Y. J. & Lee, L. S. (2018a). Sorption, aerobic biodegradation, and oxidation potential of PFOS alternatives chlorinated polyfluoroalkyl ether sulfonic acids. *Environmental Science and Technology,* 52(17), 9827-9834. https://doi.org/10.1021/acs.est.8b02913

Chen, S., Zhou, Y., Meng, J. & Wang, T. (2018b). Seasonal and annual variations in removal efficiency of perfluoroalkyl substances by different wastewater treatment processes. *Environmental Pollution,* 242(Pt B), 2059-2067. https://doi.org/10.1016/j.envpol.2018.06.078

Chiesa, L. M., Pavlovic, R., Arioli, F., Nobile, M., Di Cesare, F., Mosconi, G., Falletta, E.*, et al.* (2022). Presence of perfluoroalkyl substances in Mediterranean sea and North Italian lake fish addressed to Italian consumer. *International Journal of Food Science and Technology,* 57(2), 1303-1316. https://doi.org/10.1111/ijfs.15532

CIBSE (2018). Spiritual dome: Lighting design and fire protection at The Macallan distillery*.* CIBSE Journal - Chartered Institution of Building Services Engineers. Available at: https://www.cibsejournal.com/technical/spiritual-dome-lighting-design-and-fire-protection-at-the-macallan-distillery/

Cluett, R., Seshasayee, S. M., Rokoff, L. B., Rifas-Shiman, S. L., Ye, X., Calafat, A. M., Gold, D. R.*, et al.* (2019). Per- and polyfluoroalkyl substance plasma concentrations and bone mineral density in midchildhood: A cross-sectional study (project viva, United States). *Environmental Health Perspectives,* 127(8), 87006. https://doi.org/10.1289/ehp4918

Colomban, C., Kudrik, E. V., Afanasiev, P. & Sorokin, A. B. (2014). Catalytic defluorination of perfluorinated aromatics under oxidative conditions using N-bridged diiron phthalocyanine. *Journal of the American Chemical Society,* 136(32), 11321-11330. https://doi.org/10.1021/ja505437h

COT (2022). Statement on the EFSA opinion on the risks to human health related to the presence of perfluoroalkyl substances in food. Committee on Toxicology. England. Available at: https://cot.food.gov.uk/2022-statementsandpositionpapers

Cotswold Airport (2024). Emergency services training: Cotswold Airport. Cotswold Airport. Available at: https://cotswoldairport.com/emergency-services-training/

Cousins, I. T., DeWitt, J. C., Gluge, J., Goldenman, G., Herzke, D., Lohmann, R., Miller, M.*, et al.* (2020). Strategies for grouping per- and polyfluoroalkyl substances (PFAS) to protect human and environmental health. *Environmental Science: Processes and Impacts,* 22(7), 1444-1460. https://doi.org/10.1039/d0em00147c

Cousins, I. T., Johansson, J. H., Salter, M. E., Sha, B. & Scheringer, M. (2022). Outside the safe operating space of a new planetary boundary for per- and polyfluoroalkyl substances (PFAS). *Environmental Science and Technology,* 56(16), 11172-11179. https://doi.org/10.1021/acs.est.2c02765

Cumbria CC (2022). Environmental Information Regulations 2004, Reference: FOI-12451-2022*.* Cumbria County Council. Available at: https://cumbria.gov.uk/elibrary/Content/Internet/536/6357/4465712421.pdf

D'Agostino, L. A. & Mabury, S. A. (2014). Identification of novel fluorinated surfactants in aqueous film forming foams and commercial surfactant concentrates. *Environmental Science and Technology,* 48(1), 121-129. https://doi.org/10.1021/es403729e

da Silva, B. F., Aristizabal-Henao, J. J., Aufmuth, J., Awkerman, J. & Bowden, J. A. (2022). Survey of per- and polyfluoroalkyl substances (PFAS) in surface water collected in Pensacola, FL. *Heliyon,* 8(8), e10239. https://doi.org/10.1016/j.heliyon.2022.e10239

Dahlbom, S., Mallin, T. & Bobert, M. (2022). Fire test performance of eleven PFAS-free class B firefighting foams varying fuels, admixture, water types and foam generation techniques. *Fire Technology,* 58(3), 1639-1665. https://doi.org/10.1007/s10694-022-01213-6

Darwin, R. L., Bowman, H. L., Hunstad, M., Leach, W. B. & Williams, F. W. (2005). Aircraft carrier flight and hangar deck fire protection: History and current status. *NAWCWD Technical Publication*. [8516]. Naval Air Warfare Center Weapons Division. USA. Available at: https://apps.dtic.mil/sti/pdfs/ADA432176.pdf

Davies, S., Mustard, G. & Turrell, J. (2024). Persistent Organic Pollutants destruction efficiency in UK energy from waste. [UC17375.3]. Defra, Water Research Centre Limited (WRc). England. Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=21649

Dawson, D. E., Lau, C., Pradeep, P., Sayre, R. R., Judson, R. S., Tornero-Velez, R. & Wambaugh, J. F. (2023). A machine learning model to estimate toxicokinetic half-lives of per- and polyfluoro-alkyl substances (PFAS) in multiple species. *Toxics,* 11(2). https://doi.org/10.3390/toxics11020098

Defra (2025). Interim approach to the PMT concept to support UK REACH risk management of PFAS*.* Department for Environment, Food & Rural Affairs. Available at: https://www.gov.uk/government/publications/interim-position-statement-on-the-approach-to-pmt-concept-to-support-uk-reach-risk-management-of-pfas/interim-approach-to-the-pmt-concept-to-support-uk-reach-risk-management-of-pfas

Defra, Environment Agency & Phoenix Engineering (2024). Phase 2 landfill leachate report; investigation of persistent organic pollutants (POPs), per- and poly-fluoroalkyl substances (PFAS) and other Water Framework Directive priority substances in landfill leachates. [CX0110]. Department for Environment Food & Rural Affairs, Environment Agency and Phoenix Engineering. London, England. Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=21648

Denko (2024). Material safety data sheet #858 6% AFFF*.* Denko Inc,. Available at: http://www.denkofoam.com/data6afff.htm

DFR (2024). Defence fire and rescue*.* Available at: https://www.gov.uk/government/groups/defence-fire-risk-management-organisation

DFRMO (2017). Defence infrastructure fire standards: Relating to asset and property protection. Defence Fire Risk Management Organisation, Defence Infrastructure Organisation. Andover, England. Available at: https://assets.publishing.service.gov.uk/media/5a82ccc5ed915d74e6237b30/Defence_InfrastructureFire_Standards-Nov-17.pdf

DfT (2022). Port freight annual statistics: 2022*.* Department for Transport. Available at: https://www.gov.uk/government/statistics/port-freight-annual-statistics-2022#:~:text=the%20route%20taken.-,Overview%20of%20port%20freight%20statistics,before%20the%20COVID%2D19%20pandemic.

Di Nisio, A., Rocca, M. S., De Toni, L., Sabovic, I., Guidolin, D., Dall'Acqua, S., Acquasaliente, L.*, et al.* (2020). Endocrine disruption of vitamin D activity by perfluoro-octanoic acid (PFOA). *Scientific Reports,* 10(1), 16789.

https://doi.org/10.1038/s41598-020-74026-8

Dixon, D. A. (2001). Fluorochemical decomposition process. Pacific Northwest National Laboratory. USA.

DSA (2024). Defence structural fire fighting regulations (SFFR). *DFSR Regulation - DSA02.* [DFSR 0209 (Ed 1)]. Defence Safety Authority. United Kingdom. Available at: https://assets.publishing.service.gov.uk/media/65b0e525160765001118f785/20231215-DSA02_DFSR_Defence_Structural_Fire_Fighting_Regulations-V1.0-O.odt

DWFRS (2022). Freedom of Information request FOI 22 26 polyfluoroalkyl substances (PFAS) & foam systems. Dorset and Wiltshire Fire and Rescue. Available at: https://www.dwfire.org.uk/wp-content/uploads/2022/05/FOI-22-26-Polyfluoroalkyl-Substances-_PFAS_-and-Foam-Systems.pdf

DWI (2022a). Risk assessments under regulation 27 and associated reports under regulation 28 of the water supply (water quality) Regulations 2016 (2018 in Wales) for poly and perfluorinated alkyl substances (PFAS). [DWI Information Letter 03/2022 (now revoked)]. Drinking Water Inspectorate. London, England. Available at: https://dwi.gov.uk/water-companies/information-letters-and-advice-notes/

DWI (2022b). Investigation into the water quality event of PFOS contamination in Duxford, Cambridge rural water quality zone. [2022/8432]. Drinking Water Inspectorate. London, England. Available at: https://dwi-content.s3.eu-west-2.amazonaws.com/wp-content/uploads/2023/04/28102610/2022-8432-PFOS-in-Cambridge-Rural-WQZ-EAL-Final.pdf

EA (2025). A review of the applicability of the screening test for soil adsorption potential, and recommendations for expansion. *Chief Scientist's Group Report.* [ENV6005704R.0]. Environment Agency. Bristol, United Kingdom. Available at: https://www.gov.uk/government/publications/a-review-of-the-applicability-of-the-screening-test-for-soil-adsorption-potential-and-recommendations-for-expansion

Ebert, A., Allendorf, F., Berger, U., Goss, K. U. & Ulrich, N. (2020). Membrane/water partitioning and permeabilities of perfluoroalkyl acids and four of their alternatives and the effects on toxicokinetic behavior. *Environmental Science and Technology,* 54(8), 5051-5061. https://doi.org/10.1021/acs.est.0c00175

ECCC (2023). Supporting document: Ecological state of the science report on short-chain (C4-C7) perfluorocarboxylic acids (SC-PFCAs), short-chain (C4-C7) perfluorosulfonic acids (SC-PFSAs), long-chain (C9-C20) perfluorosulfonic acids (LC-PFSAs). *Information in Support of the Draft State of Per- and Polyfluoroalkyl Substances (PFAS) report.* Environment and Climate Change Canada. Gatineau, Canada. Available at: https://www.canada.ca/en/environment-climate-change/services/evaluating-existing-substances/supporting-document-ecological-state-science-report-sc-pfcas-sc-pfsas-lc-pfsas.html

ECCC & Health Canada (2024). Updated draft state of per- and polyfluoroalkyl substances (PFAS) report. Environment and Climate Change Canada, Health Canada. Canada. Available at: https://www.canada.ca/en/environment-climate-change/services/evaluating-existing-substances/updated-draft-state-per-polyfluoroalkyl-substances-report.html

ECHA (2012a). Member State Committee support document for identification of henicosafluoroundecanoic acid as a Substance of Very High Concern because of its vPvB properties. European Chemicals Agency. Helsinki, Finland. Available at: https://echa.europa.eu/documents/10162/9bcff514-6625-baa9-edd9-80ee9e82c86a

ECHA (2012b). Member State Committee support document for identification of tricosafluorododecanoic acid as a Substance of Very High Concern because of its vPvB properties. European Chemicals Agency. Helsinki, Finland. Available at: https://echa.europa.eu/documents/10162/44fd0731-2211-0216-b984-e3cd0f32d5ca

ECHA (2012c). Member State Committee support document for identification of pentacosafluorotridecanoic acid as a Substance of Very High Concern because of its vPvB properties. European Chemicals Agency. Helsinki, Finland. Available at: https://echa.europa.eu/documents/10162/4894dac8-608d-c1ab-2473-f67e2e314d39

ECHA (2012d). Member State Committee support document for identification of heptacosafluorotetradecanoic acid as a Substance of Very High Concern because of its vPvB properties. European Chemicals Agency. Helsinki, Finland. Available at: https://echa.europa.eu/documents/10162/4bdef30d-3698-a946-4d90-f1e950105f6d

ECHA (2013). Member State Committee support document for identification of pentadecafluorooctanoic acid (PFOA) as a Substance of Very High Concern because of its CMR and PBT properties. European Chemicals Agency. Helsinki, Finland. Available at: https://echa.europa.eu/documents/10162/8059e342-1092-410f-bd85-80118a5526f5

ECHA (2015). Member State Committee support document for identification of perfluorononan-1-oic acid and its sodium and ammonium salts as Substances of Very High Concern because of their toxic for reproduction and PBT properties. European Chemicals Agency. Helsinki, Finland. Available at: https://echa.europa.eu/documents/10162/deb7e1e1-d993-4d60-b3d5-25ba0621a11a

ECHA (2016a). Member State Committee support document for identification of nonadecafluorodecanoic acid (PFDA) and its sodium and ammonium salts as a Substance of Very High Concern because of its toxic for reproduction (article 57c) and persistent, bioaccumulative and toxic (PBT) (Article 57d) properties. European Chemicals Agency. Helsinki, Finland. Available at: https://echa.europa.eu/documents/10162/48c9acdc-7474-b256-e8cb-b0c6c1e5f2d0

ECHA (2016b). Chapter R.16: Environmental exposure assessment. *Guidance on Information Requirements and Chemical Safety Assessment.* European Chemicals Agency. Helsinki, Finland. https://data.europa.eu/doi/10.2823/515110

ECHA (2017a). Member State Committee support document for identification of perfluorohexane-1-sulphonic acid and its salts as Substances of Very High Concern because of their vPvB (article 57e) properties. European Chemicals Agency. Helsinki, Finland. Available at: https://echa.europa.eu/documents/10162/1f48372e-97dd-db9f-4335-8cec7ae55eee

ECHA (2017b). Chapter R.7a: Endpoint specific guidance. *Guidance on Information Requirements and Chemical Safety Assessment.* European Chemicals Agency. Helsinki, Finland. https://data.europa.eu/doi/10.2823/43472

ECHA (2017c). Chapter R.7c: Endpoint specific guidance. *Guidance on Information Requirements and Chemical Safety Assessment.* European Chemicals Agency.

Helsinki, Finland. https://data.europa.eu/doi/10.2823/43472

ECHA (2017d). Chapter R.11: PBT/vPvB assessment. *Guidance on Information Requirements and Chemical Safety Assessment.* European Chemicals Agency. Helsinki, Finland. https://data.europa.eu/doi/10.2823/128621

ECHA (2017e). Chapter R.7b: Endpoint specific guidance. *Guidance on Information Requirements and Chemical Safety Assessment.* European Chemicals Agency. Helsinki, Finland. https://data.europa.eu/doi/10.2823/84188

ECHA (2019a). Undecafluorohexanoic acid (PFHxA), its salts and related substances. *Annex XV Restriction Report.* European Chemicals Agency. Helsinki, Finland. Available at: https://echa.europa.eu/documents/10162/c4e04484-c989-733d-33ed-0f023e2a200e

ECHA (2019b). Member State Committee support document for identification of perfluorobutane sulfonic acid and its salts as Substances of Very High Concern because of their hazardous properties which cause probable serious effects to human health and the environment which give rise to an equivalent level of concern to those of CRM and PBT/vPvB substances (article 57f). European Chemicals Agency. Helsinki, Finland. Available at: https://echa.europa.eu/documents/10162/d6437615-9fc4-7519-cee9-1cc9ad5e8273

ECHA (2019c). Member State Committee support document for identification of 2,3,3,3-tetrafluoro-2-(heptafluoropropoxy)propionic acid, its salts and its acyl halides (covering any of their individual isomers and combinations thereof) as Substances of Very High Concern because of their hazardous properties which cause probable serious effects to human health and the environment which give rise to an equivalent level of concern to those of CMR and PBT/vPvB substances (article 57f). European Chemicals Agency. Helsinki, Finland. Available at: https://www.echa.europa.eu/documents/10162/53fa6a5b-e95f-3128-ea9d-fa27f43b18bc

ECHA (2022a). Member State Committee support document for identification of perfluoroheptanoic acid and its salts as a Substance of Very High Concern because of its toxic for reproduction (article 57c), PBT (article 57d), vPvB (article 57e), equivalent level of concern having probable serious effects to human health (article 57(f) - human health), equivalent level of concern having probable serious effects to the environment (article 57(f) - environment) properties. European Chemicals Agency. Helsinki, Finland. Available at: https://echa.europa.eu/documents/10162/e93617bd-8bd7-627e-ca1c-4543e70e1e6b

ECHA (2022b). Per- and polyfluoroalkyl substances (PFASs) in firefighting foams. *Annexes to the Annex XV Restriction Report.* European Chemicals Agency. Helsinki, Finland. Available at: https://echa.europa.eu/documents/10162/eeb45391-d0b8-9035-f5e4-c334b5dd7fc8

ECHA (2022c). PFAS in firefighting foam comments on Annex XV report. European Chemicals Agency. Helsinki, Finland. Available at: https://echa.europa.eu/pl/registry-of-restriction-intentions/-/dislist/details/0b0236e1856e8ce6

ECHA (2022d). Proposal for a restriction: Per- and polyfluoroalkyl substances (PFASs) in firefighting foams. *Annex XV Restriction Report.* European Chemicals

Agency. Helsinki, Finland. Available at: https://echa.europa.eu/documents/10162/4524f49c-ae14-b01b-71d2-ac3fa916c4e9

ECHA (2023a). Committee for Risk Assessment (RAC) Committee for Socio-economic Analysis (SEAC) Annex to the background document to the opinion on the Annex XV dossier proposing restrictions on per- and polyfluoroalkyl substances (PFAS) in firefighting foams. European Chemicals Agency. Helsinki, Finland. Available at: https://echa.europa.eu/documents/10162/3d8e157a-9312-5fcb-967e-d4ae5b2deb05

ECHA (2023b). Committee for Risk Assessment (RAC) Committee for Socio-economic Analysis (SEAC) opinion on an Annex XV dossier proposing restrictions on per- and polyfluoroalkyl substances (PFAS) in firefighting foams. European Chemicals Agency. Helsinki, Finland. Available at: https://echa.europa.eu/documents/10162/897b2ca5-e15b-e6c5-a2ef-c7af4f1110a1

ECHA (2023c). Committee for Risk Assessment (RAC) Committee for Socio-economic Analysis (SEAC) appendix to the background document to the opinion on the Annex XV dossier proposing restrictions on per- and polyfluoroalkyl substances (PFASs) in firefighting foams. European Chemicals Agency. Helsinki, Finland. Available at: https://echa.europa.eu/documents/10162/6635ea61-5226-4a7f-e2d7-1950fa60f3f9

ECHA (2023d). ECHA Registration Dossier for Trifluoromethanesulphonic acid (CAS No. 1493-13-6). European Chemicals Agency. Available at: https://chem.echa.europa.eu/100.014.625/overview

ECHA (2023e). Committee for Risk Assessment (RAC) Committee for Socio-economic Analysis (SEAC) background document to the opinion on the Annex XV dossier proposing restrictions on per- and polyfluoroalkyl substances (PFAS) in firefighting foams. European Chemicals Agency. Helsinki, Finland. Available at: https://echa.europa.eu/documents/10162/8011247f-14bb-c77e-189e-4df733dd16b2

ECHA (2024). ECHA Registration Dossier for Trifluoroacetic acid (CAS No. 76-005-1). European Chemicals Agency. Available at: https://chem.echa.europa.eu/100.000.846

EEA (2019). EMEP/EEA air pollutant emission inventory guidebook. *Technical guidance to prepare national emission inventories.* [No 13/2019]. European Monitoring and Evaluation Programme, European Environment Agency. Luxembourg. Available at: https://www.eea.europa.eu/publications/emep-eea-guidebook-2019

EFSA, Alvarez, F., Arena, M., Auteri, D., Leite, S. B., Binaglia, M., Castoldi, A. F.*, et al.* (2024). Peer review of the pesticide risk assessment of the active substance flufenacet. *EFSA Journal,* 22(9), e8997. https://doi.org/10.2903/j.efsa.2024.8997

EFSA, Knutsen, H. K., Alexander, J., Barregard, L., Bignami, M., Bruschweiler, B., Ceccatelli, S.*, et al.* (2018). Risk to human health related to the presence of perfluorooctane sulfonic acid and perfluorooctanoic acid in food. *EFSA Journal,* 16(12), e05194. https://doi.org/10.2903/j.efsa.2018.5194

EFSA, Schrenk, D., Bignami, M., Bodin, L., Chipman, J. K., Del Mazo, J., Grasl-Kraupp, B.*, et al.* (2020a). Risk to human health related to the presence of perfluoroalkyl substances in food. *EFSA Journal,* 18(9), e06223. https://doi.org/10.2903/j.efsa.2020.6223

EFSA, Schrenk, D., Bignami, M., Bodin, L., Chipman, J. K., Del Mazo, J., Grasl-Kraupp, B., *et al.* (2020b). Risk assessment of chlorinated paraffins in feed and food. *EFSA Journal,* 18(3), e05991. https://doi.org/10.2903/j.efsa.2020.5991

Eftec (2019, unpublished). Costs of phasing out PFOA containing firefighting foams in the UK, and availability of suitable alternatives. London, England: Economics for the Environment Consultancy (eftec), Defra.

Ehrlich, V., Bil, W., Vandebriel, R., Granum, B., Luijten, M., Lindeman, B., Grandjean, P., *et al.* (2023). Consideration of pathways for immunotoxicity of per- and polyfluoroalkyl substances (PFAS). *Environmental Health,* 22(1), 19. https://doi.org/10.1186/s12940-022-00958-5

Environment Agency (2004). Environmental risk evaluation report: Perfluorooctanesulphonate (PFOS). [SCHO1009BRBL-E-P]. Environment Agency, Building Research Establishment, Risk and Policy Analysts. Wallingford, England. Available at: https://assets.publishing.service.gov.uk/media/5a7b984540f0b645ba3c5549/scho1009brbl-e-e.pdf

Environment Agency (2021). Poly- and perfluoroalkyl substances (PFAS): Sources, pathways and environmental data. Environment Agency. Bristol, England. Available at: https://www.gov.uk/government/publications/poly-and-perfluoroalkyl-substances-pfas-sources-pathways-and-environmental-data

Environment Agency (2024). Storing and treating waste fire extinguishers: RPS 132. Environment Agency. Available at: https://www.gov.uk/government/publications/end-of-life-fire-extinguishers-re-use-and-dismantling/storing-and-treating-waste-fire-extinguishers-for-recovery-rps-132

Environment Agency (2025, unpublished). Rapid evidence assessment of PFAS incineration and alternative remediation methods. England: Environment Agency.

Environment Canada (2006). Ecological screening assessment report on perfluorooctane sulfonate, its salts and its precursors that contain the $C_8F_{17}SO_2$ or $C_8F_{17}SO_3$, or $C_8F_{17}SO_2N$ moiety. Environment Canada. Canada. Available at: https://www.canada.ca/content/dam/eccc/migration/main/lcpe-cepa/documents/substances/spfo-pfos/ecological_sar_pfos_eng.pdf

Environment Canada (2012). Ecological screening assessment report. Long-chain (C_9–C_{20}) perfluorocarboxylic acids, their salts and their precursors. Environment Canada. Canada. Available at: https://www.canada.ca/content/dam/eccc/migration/ese-ees/ca29b043-86e4-4308-bbc0-5ce163feac40/pfcas_en.pdf

Envirotech (2023). EPA exploring new measurement methods for PFAS in air. Envirotech Online. Available at: https://www.envirotech-online.com/news/air-monitoring/6/international-environmental-technology/epa-explores-new-measurement-methods-for-pfas-in-air/60933

Equinor (2024). PFAS in firefighting foams stakeholder engagement meetings. Stakeholder meeting to Park, A., Lloyd, J., Melrose, L., Healy, K., Williamson, L., Appleton, B., Gray, D. & Wilkinson, N., 8 November.

Eriksson, U., Haglund, P. & Karrman, A. (2017). Contribution of precursor compounds to the release of per- and polyfluoroalkyl substances (PFASs) from waste water treatment plants (WWTPs). *Journal of Environmental Sciences,* 61, 80-90. https://doi.org/10.1016/j.jes.2017.05.004

European Commission (2012). Directive 2012/18/EU of the European Parliament and the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC. European Commission. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32012L0018

European Commission (2014). Directive 2014/90/EU of the European Parliament and of the Council of 23 July 2014 on marine equipment and repealing Council Directive 96/98/EC. European Commission. Available at: http://data.europa.eu/eli/dir/2014/90/oj

European Commission (2022). Proposal for a regulation of the European Parliament and of the Council amending regulation (EC) no 1272/2008 of the European Parliament and of the Council on classification, labelling and packaging of substances and mixtures [COM(2022)748 final]. European Commission. Available at: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex:52022PC0748

European Commission (2025). Commission regulation (EU) …/… of xxx amending Annex XVII to regulation (EC) no 1907/2006 of the European Parliament and of the Council as regards per- and polyfluoroalkyl substances in firefighting foams (Draft). European Commission. Available at: https://ec.europa.eu/transparency/comitology-register/screen/documents/102503/2/consult?lang=en

Eurostat (2020). Firefighters and fire-protection in the EU*.* Eurostat, European Union. Available at: https://ec.europa.eu/eurostat/web/products-eurostat-news/-/edn-20200504-1

FAA (2023). Fluorine-free foam (F3) transition awareness webinar. [Recorded seminar] 31 October 2023. Available at: https://www.faa.gov/airports/airport_safety/aircraft_rescue_fire_fighting/f3_transition

FAA (2024). Federal aviation administration national part 139 certalert department of defense's (DoD's) memorandum on rinsing aircraft rescue firefighting (ARFF) vehicles transitioning from aqueous film forming foam (AFFF) to fluorine-free foam (F3). Federal Aviation Administration. Washington, DC, USA. Available at: https://www.faa.gov/sites/faa.gov/files/arp-part-139-cert-alert-24-05-AFFF-Rinse.pdf

FAO (2000). Appendix 2: Parameters of pesticides that influence processes in the soil. *Assessing soil contamination: a reference manual.* Food and Agriculture Organization of the United Nations. Rome, Italy. Available at: https://www.fao.org/4/X2570E/X2570E06.htm

Farley, J. P., Karwoski, S., Back, G. G., Darwin, R., Sievert, E. S. & Lint, J. L. (2023). Fluorine-free foam (F3) application techniques and firefighting tactics. [NRL/6180/MR--2023/1]. Strategic Environmental Research and Development Program and Environmental Security Technology Certification Program. Alexandria, VA, USA. Available at: https://apps.dtic.mil/sti/trecms/pdf/AD1201646.pdf

Faust, J. A. (2022). PFAS on atmospheric aerosol particles: A review. *Environmental Science: Processes and Impacts,* 25, 133-150. https://doi.org/10.1039/D2EM00002D

Fenton, S. E., Ducatman, A., Boobis, A., DeWitt, J. C., Lau, C., Ng, C., Smith, J. S., *et al.* (2021). Per- and polyfluoroalkyl substance toxicity and human health review: Current state of knowledge and strategies for informing future research. *Environmental Toxicology and Chemistry,* 40(3), 606-630. https://doi.org/10.1002/etc.4890

FIA (2022). Guidance document – filling stations forecourts. Fire Industry Association. Hampton, England. Available at: https://www.fia.uk.com/static/170af64b-8550-4dc3-b4a1a1432b37ffa6/Guidance-Document-Filling-Stations-Forecourts-03-22-v2.pdf

FOGTEC (2017). The smarter way of fire fighting. Fogtec Fire Protection. Available at: https://www.tunnel-online.info/download/1691885/fogtec-tunnel-fire-fighting-systems-english.pdf

Fomtec (2025). Trainer e-lite. Fomtec. Available at: https://www.fomtec.com/products/trainer-e-lite/

Frank, H., Christoph, E. H., Holm-Hansen, O. & Bullister, J. L. (2002). Trifluoroacetate in ocean waters. *Environmental Science and Technology,* 36(1), 12-15. https://doi.org/10.1021/es0101532

FSC (2024). Fire service college training. Fire Service College. Available at: https://www.fireservicecollege.ac.uk/sectors/

Government of Canada (2022). Long-chain (C9-C20) perfluorocarboxylic acids (PFCAs), their salts, and their precursors - information sheet. Government of Canada. Available at: https://www.canada.ca/en/health-canada/services/chemical-substances/fact-sheets/chemicals-glance/long-chain-perfluorocarboxylic-acids-pfcas-salts-precursors.html

Guelfo, J. L. & Higgins, C. P. (2013). Subsurface transport potential of perfluoroalkyl acids at aqueous film-forming foam (AFFF)-impacted sites. *Environmental Science and Technology,* 47(9), 4164-4171. https://doi.org/10.1021/es3048043

Guo, P., Furnary, T., Vasiliou, V., Yan, Q., Nyhan, K., Jones, D. P., Johnson, C. H., *et al.* (2022). Non-targeted metabolomics and associations with per- and polyfluoroalkyl substances (PFAS) exposure in humans: A scoping review. *Environment International,* 162, 107159. https://doi.org/10.1016/j.envint.2022.107159

Hakli, O., Ertekin, K., Ozer, M. S. & Aycan, S. (2008). Determination of pka values of clinically important perfluorochemicals in nonaqueous media. *Journal of Analytical Chemistry,* 63(11), 1051-1056. https://doi.org/10.1134/S1061934808110063

Haltermann (2021). Rocket fuel development. American Hydrocarbons, Haltermann Solutions. Available at: https://www.haltermannsolutions.com/tech-talk?id=249256/rocket-fuel-development

Hartson Fire Ltd. (2025). Commander 2ltr AFF foam. Hartson Fire Ltd. Available at: https://hartsonfire.co.uk/collections/foam-fire-extinguishers

Hatton, J., Holton, C. & DiGuiseppi, B. (2018). Occurrence and behavior of per- and polyfluoroalkyl substances from aqueous film-forming foam in groundwater systems. *Remediation Journal,* 28(2), 89-99. https://doi.org/10.1002/rem.21552

Hausman, J. (2012). Contingent valuation: From dubious to hopeless. *Journal of Economic Perspectives,* 26(4), 43-56. http://dx.doi.org/10.1257/jep.26.4.43

Held, T. & Reinhard, M. (2020). Remediation management for local and wide-spread PFAS contaminations. [205-2020]. Environmental Research of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. Dessau-Roßlau, Germany: Umweltbundesamt. Available at: https://www.umweltbundesamt.de/en/publikationen/remediation-management-for-local-wide-spread-pfas

HFRS (2022). Using foam at incidents. Humberside Fire & Rescue Service. Available at: https://humbersidefire.gov.uk/newsroom/news/using-foam-at-incidents

Highways England (2016). Safety advice for drivers using the Dartford tunnels. Highways England. Available at: https://www.connectplusm25.co.uk/wp-content/uploads/2020/02/S160265_Dartford_Tunnel_Safety_Poster_-_Update.pdf

Hill, I. R., Matthiessen, P. & Heimbach, F. (eds.) (1993). *Guidance document on sediment toxicity tests and bioassays for freshwater and marine environments: From the "workshop on sediment toxicity assessment", held at slot moermond congrescentrum, renesse, the Netherlands, 8-10 November 1993.* University of California, USA: Society of Environmental Toxicology and Chemistry (SETAC). Available at: https://books.google.co.uk/books?id=n0wSAQAAIAAJ

Hinnant, K. M., Ananth, R., Farley, J. P., Whitehurst, C. L., S.L., G., Maza, W. A., Snow, A. W.*, et al.* (2020). Extinction performance summary of commercial fluorine-free firefighting foams over a 28 ft2 pool fire detailed by MIL-PRF-24385. [NRL/MR/6185--20-10,031]. Office of Naval Research, Naval Research Laboratory. Arlington, VA, USA. Available at: https://apps.dtic.mil/sti/pdfs/AD1100426.pdf

HM Treasury (2022). The green book: Central government guidance on appraisal and evaluation. [PU3051]. HM Treasury. London, England. Available at: https://assets.publishing.service.gov.uk/media/6645c709bd01f5ed32793cbc/Green_Book_2022__updated_links_.pdf

HM Treasury (2024). GDP deflators at market prices, and money GDP September 2024 (quarterly national accounts). HM Treasury. Available at: https://www.gov.uk/government/statistics/gdp-deflators-at-market-prices-and-money-gdp-september-2024-quarterly-national-accounts

Ho, S. H., Soh, S. X. H., Wang, M. X., Ong, J., Seah, A., Wong, Y., Fang, Z.*, et al.* (2022). Perfluoroalkyl substances and lipid concentrations in the blood: A systematic review of epidemiological studies. *Science of the Total Environment,* 850, 158036. https://doi.org/10.1016/j.scitotenv.2022.158036

Houtz, E. F., Higgins, C. P., Field, J. A. & Sedlak, D. L. (2013). Persistence of perfluoroalkyl acid precursors in AFFF-impacted groundwater and soil. *Environmental Science and Technology,* 47(15), 8187-8195. https://doi.org/10.1021/es4018877

Houtz, E. F., Sutton, R., Park, J. S. & Sedlak, M. (2016). Poly- and perfluoroalkyl substances in wastewater: Significance of unknown precursors, manufacturing shifts, and likely AFFF impacts. *Water Research,* 95, 142-149. http://dx.doi.org/10.1016/j.watres.2016.02.055

HSE (1999). The bulk transfer of dangerous liquids and gases between ship and shore. [HSG 186]. Health and Safety Executive. Richmond, England. Available at: https://www.hse.gov.uk/pubns/priced/hsg186.pdf

HSE (2023). Analysis of the most appropriate regulatory management options (RMOA): Poly- and perfluoroalkyl substances (PFAS). Health and Safety Executive. England. Available at: https://www.hse.gov.uk/REACH/assets/docs/pfas-rmoa.pdf

HSE (2024). COMAH guidance: Active / passive fire protection. Health and Safety Executive. Available at: https://www.hse.gov.uk/comah/sragtech/techmeasfire.htm

Hu, X. C., Tokranov, A. K., Liddie, J., Zhang, X., Grandjean, P., Hart, J. E., Laden, F., *et al.* (2019). Tap water contributions to plasma concentrations of poly- and perfluoroalkyl substances (PFAS) in a nationwide prospective cohort of U.S. Women. *Environmental Health Perspectives,* 127(6), 67006. https://doi.org/10.1289/ehp4093

Humber Freeport (2025). About Saltend Chemicals Park. Humber Freeport. Available at: https://humberfreeport.org/where-are-we/hull-east/saltend-chemicals-park/

IARC (2016). Some chemicals used as solvent and in polymer manufacture. *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans.* [Volume 110]. International Agency for Research on Cancer, World Health Organization. Lyon, France. Available at: https://publications.iarc.fr/547

IARC (2023). Occupational exposure as a firefighter. *IARC Monographs on the Identification of Carcinogenic Hazards to Humans.* [Volume 132]. International Agency for Research on Cancer, World Health Organization. Lyon, France. Available at: https://publications.iarc.fr/615

IFTC (2024). Aviation courses. International Fire Training Centre, Teesside International Airport. Available at: https://iftcentre.com/aviation/

IMO (2022). Sub-committee on ship systems and equipment (SSE), 8th session, 28 February-4 March 2022. International Maritime Organisation. Available at: https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/SSE-8th-session.aspx

IPEN (2018). Fluorine-free firefighting foams (3F) - viable alternatives to fluorinated aqueous film-forming foams (AFFF). [IPEN 2018/POPRC-14]. International Pollutants Elimination Network. Rome, Italy. Available at: https://ipen.org/sites/default/files/documents/IPEN_F3_Position_Paper_POPRC-14_12September2018d.pdf

IPEN (2019). The global PFAS problem: Fluorine-free alternatives as solutions - firefighting foams and other sources - going fluorine-free. International Pollutants Elimination Network. Geneva, Switzerland. Available at: https://ipen.org/sites/default/files/documents/the_global_pfas_problem-v1_5_final_18_april.pdf

Islam, M. & Heintzelman, M. D. (2023). Perceptions of risk: The impacts of pfas contamination on local property values. *[Preprint]*. http://dx.doi.org/10.2139/ssrn.4547307

ITRC (2022). Technical resources for addressing environmental resleases of per- and polyfluoroalkyl substances (PFAS). Interstate Technology Regulatory Council. Available at: https://pfas-1.itrcweb.org/

Jacobs (2023). PFAS – evaluating the economic burden of remediating high-risk sites. *PFAS Risk Screening Project - Phase 4 - Work Package 4 Economic Appraisal.* [B2382404/REP/001]. Jacobs, Environment Agency. Edinburgh, Scotland. Available at: https://assets.publishing.service.gov.uk/media/66ebe9a6c8398625c331e778/Annex_C_PFAS_WP4_Phase_4_-_Report_Rev0_REDACTED.pdf

Jacqz, I., Somuncu, T. & Voorheis, J. (2024). Fighting fire with fire(fighting foam): The long run effects of PFAS use at U.S. Military installations. Iowa State University, University of North Carolina, U.S. Census Bureau. USA. Available at: https://iastate.app.box.com/s/3n0pbwj23rje3clulhbool8jeolm32g6

Jahura, F. T., Mazumder, N. U., Hossain, M. T., Kasebi, A., Girase, A. & Ormond, R. B. (2024). Exploring the prospects and challenges of fluorine-free firefighting foams (F3) as alternatives to aqueous film-forming foams (AFFF): A review. *ACS Omega,* 9(36), 37430-37444. https://doi.org/10.1021/acsomega.4c03673

Jarvis, N. (2016). Extended sorption partitioning models for pesticide leaching risk assessments: Can we improve upon the K_{oc} concept? *Science of the Total Environment,* 539, 294-303. https://doi.org/10.1016/j.scitotenv.2015.09.002

Johnson Controls (2024). Water mist fire protection solutions. Johnson Controls. Available at: https://www.johnsoncontrols.co.uk/oil-and-gas/fire-suppression/water-mist-fire-protection-solutions

Kadlec, S. M., Backe, W. J., Erickson, R. J., Hockett, J. R., Howe, S. E., Mundy, I. D., Piasecki, E.*, et al.* (2024). Sublethal toxicity of 17 per- and polyfluoroalkyl substances with diverse structures to *Ceriodaphnia dubia*, *Hyalella azteca*, and *Chironomus dilutus*. *Environmental Toxicology and Chemistry,* 43(2), 359-373. https://doi.org/10.1002/etc.5784

Kennedy, G. L., Jr., Butenhoff, J. L., Olsen, G. W., O'Connor, J. C., Seacat, A. M., Perkins, R. G., Biegel, L. B.*, et al.* (2004). The toxicology of perfluorooctanoate. *Critical Reviews in Toxicology,* 34(4), 351-384. https://doi.org/10.1080/10408440490464705

Kudo, N. & Kawashima, Y. (2003). Toxicity and toxicokinetics of perfluorooctanoic acid in humans and animals. *The Journal of Toxicological Sciences,* 28(2), 49-57. https://doi.org/10.2131/jts.28.49

LaFond, J. A., Rezes, R., Shojaei, M., Anderson, T., Jackson, W. A., Guelfo, J. L. & Hatzinger, P. B. (2024). Biotransformation of PFAA precursors by oxygenase-expressing bacteria in AFFF-impacted groundwater and in pure-compound studies with 6:2 FTS and EtFOSE. *Environmental Science and Technology,* 58(31), 13820-13832. https://doi.org/10.1021/acs.est.4c01931

Lam, N. H., Cho, C. R., Lee, J. S., Soh, H. Y., Lee, B. C., Lee, J. A., Tatarozako, N.*, et al.* (2014). Perfluorinated alkyl substances in water, sediment, plankton and fish from Korean rivers and lakes: A nationwide survey. *Science of the Total Environment,* 491-492, 154-162. https://doi.org/10.1016/j.scitotenv.2014.01.045

LASTFIRE (2023). Summary of fluorine free foam testing carried out by lastfire. LASTFIRE. Available at: https://www.lastfire.org.uk/default.aspx?ReturnUrl=%2f

LCC (2022). Use of perfluoroalkyl and polyfluoroalkyl substances (PFAS) for firefighting. Lincolnshire County Council. Available at: https://www.lincolnshire.gov.uk/directory-record/69647/use-of-perfluoroalkyl-and-polyfluoroalkyl-substances-pfas-for-firefighting

Lenka, S. P., Kah, M. & Padhye, L. P. (2021). A review of the occurrence, transformation, and removal of poly- and perfluoroalkyl substances (PFAS) in wastewater treatment plants. *Water Research,* 199, 117187. https://doi.org/10.1016/j.watres.2021.117187

Leung, S. C. E., Wanninayake, D., Chen, D., Nguyen, N. T. & Li, Q. (2023). Physicochemical properties and interactions of perfluoroalkyl substances (PFAS) - challenges and opportunities in sensing and remediation. *Science of the Total Environment,* 905, 166764. https://doi.org/10.1016/j.scitotenv.2023.166764

LFB (2022). Freedom of Information request reference number: 6439.1. London Fire Brigade. Available at: https://www.london-fire.gov.uk/media/6542/64391_response.pdf

LGA (2024). Roles and responsibilities of fire & rescue authorities. Local Government Association. Available at: https://www.local.gov.uk/topics/fire-and-rescue/fire-role-models/roles-and-responsibilities-fire-rescue-authorities

Liew, Z., Goudarzi, H. & Oulhote, Y. (2018). Developmental exposures to perfluoroalkyl substances (PFASs): An update of associated health outcomes. *Current environmental health reports,* 5(1), 1-19. https://doi.org/10.1007/s40572-018-0173-4

Lin, L. Y., Wen, L. L., Su, T. C., Chen, P. C. & Lin, C. Y. (2014). Negative association between serum perfluorooctane sulfate concentration and bone mineral density in US premenopausal women: NHANES, 2005-2008. *The Journal of Clinical Endocrinology and Metabolism,* 99(6), 2173-2180. https://doi.org/10.1210/jc.2013-3409

Liu, D., Yan, S., Liu, Y., Chen, Q. & Ren, S. (2024a). Association of prenatal exposure to perfluorinated and polyfluoroalkyl substances with childhood neurodevelopment: A systematic review and meta-analysis. *Ecotoxicology and Environmental Safety,* 271, 115939. https://doi.org/10.1016/j.ecoenv.2024.115939

Liu, M., Glover, C. M., Munoz, G., Duy, S. V., Sauve, S. & Liu, J. (2024b). Hunting the missing fluorine in aqueous film-forming foams containing per- and polyfluoroalkyl substances. *Journal of Hazardous Materials,* 464, 133006. https://doi.org/10.1016/j.jhazmat.2023.133006

Luft, C. M., Schutt, T. C. & Shukla, M. K. (2022). Properties and mechanisms for PFAS adsorption to aqueous clay and humic soil components. *Environmental Science and Technology,* 56(14), 10053-10061. https://doi.org/10.1021/acs.est.2c00499

Lyu, X., Xiao, F., Shen, C., Chen, J., Park, C. M., Sun, Y., Flury, M.*, et al.* (2022). Per- and polyfluoroalkyl substances (PFAS) in subsurface environments: Occurrence, fate, transport, and research prospect. *Reviews of Geophysics,* 60(3). https://doi.org/10.1029/2021RG000765

Lyu, X. J., Li, W. W., Lam, P. K. & Yu, H. Q. (2015). Insights into perfluorooctane sulfonate photodegradation in a catalyst-free aqueous solution. *Scientific Reports,* 5, 9353. https://doi.org/10.1038/srep09353

Maizel, A. C., Thompson, A., Tighe, M., Escobar Veras, S., Rodowa, A. E., Falkenstein-Smith, R., Benner, B.*, et al.* (2023). Per- and polyfluoroalkyl substances in new firefighter turnout gear textiles. *NIST Technical Note*. [NIST TN 2248]. National Institute of Standards and Technology. https://doi.org/10.6028/NIST.TN.2248

Marcus, M. & Mueller, R. (2024). Unregulated contaminants in drinking water: Evidence from PFAS and housing prices. *Journal of Environmental Economics and Management,* 125. https://doi.org/10.1016/j.jeem.2024.102987

Maritime and Coastguard Agency (2023). MGN 667 (M) guidance for the merchant shipping (fire protection) Regulations 2023, merchant shipping notice 1901 (M) and merchant shipping notice 1902 (M). *Marine Guidance Note.* Martitime and Coastguard Agency. England. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1162842/MGN_667_-_Guidance_for_MSNs_1901_and_1902.pdf

Maritime UK (2024). Ports. Maritime UK. Available at: https://www.maritimeuk.org/about/our-sector/ports/#:~:text=There%20are%20about%20120%20commercial,such%20as%20coal%20or%20oil.

McCall, P. J., Laskowski, D. A., Swann, R. L. & Dishburger, H. J. (1981). Measurement of sorption coefficients of organic chemicals and their use, in environmental fate analysis. Testing protocols for environmental fate and movement of toxicants. *Proceedings of AOAC Symposium, 1981.* AOAC International.

McDonough, C. A., Li, W., Bischel, H. N., De Silva, A. O. & DeWitt, J. C. (2022). Widening the lens on PFASs: Direct human exposure to perfluoroalkyl acid precursors (pre-PFAAs). *Environmental Science and Technology,* 56(10), 6004-6013. https://doi.org/10.1021/acs.est.2c00254

Meegoda, J. N., Bezerra de Souza, B., Casarini, M. M. & Kewalramani, J. A. (2022). A review of PFAS destruction technologies. *International Journal of Environmental Research and Public Health,* 19(24), 16397–16397. https://doi.org/10.3390/ijerph192416397

Mejia-Avendano, S., Zhi, Y., Yan, B. & Liu, J. (2020). Sorption of polyfluoroalkyl surfactants on surface soils: Effect of molecular structures, soil properties, and solution chemistry. *Environmental Science and Technology,* 54(3), 1513-1521. https://doi.org/10.1021/acs.est.9b04989

Miller, M. (2024). Fluorine-free foam flows to air force bases as dod removes PFAS from firefighting activities*.* Air Force Installation and Mission Support Center (AFIMSC). Available at: https://www.afimsc.af.mil/News/Article-Display/Article/3724390/fluorine-free-foam-flows-to-air-force-bases-as-dod-removes-pfas-from-firefighti/

MOD (2018). FOI request: PFAS in firefighting foams. [F012018/03195]. Ministry of Defence. Bristol, England. Available at: https://assets.publishing.service.gov.uk/media/5ab2725c40f0b65bb8ef1ee4/2018-03195.pdf

Moneta, B. G., Feo, M. L., Torre, M., Tratzi, P., Aita, S. E., Montone, C. M., Taglioni, E., *et al.* (2023). Occurrence of per- and polyfluorinated alkyl substances in wastewater treatment plants in Northern Italy. *Science of the Total Environment,* 894, 165089. https://doi.org/10.1016/j.scitotenv.2023.165089

Murakami, M., Kuroda, K., Sato, N., Fukushi, T., Takizawa, S. & Takada, H. (2009). Groundwater pollution by perfluorinated surfactants in Tokyo. *Environmental Science and Technology,* 43(10), 3480-3486. https://doi.org/10.1021/es803556w

NASEM (ed.) (2022). *Guidance on PFAS exposure, testing, and clinical follow-up.* National Academies of Sciences, Engineering, and Medicine: The National Academies Press. https://doi.org/10.17226/26156.

Neumann, M. & Schliebner, I. (2019). Protecting the sources of our drinking water: The criteria for identifying persistent, mobile and toxic (PMT) substances and very persistent and very mobile (vPvM) substances under EU regulation REACH (EC) no 1907/2006. [127/2019]. Umweltbundesamt. Dessau-Roßlau, Germany. Available at: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-11-29_texte_127-2019_protecting-sources-drinking-water-pmt.pdf

Neuwald, I. J., Hübner, D., Wiegand, H. L., Valkov, V., Borchers, U., Nödler, K., Scheurer, M., *et al.* (2022). Ultra-short-chain PFASs in the sources of German drinking water: Prevalent, overlooked, difficult to remove, and unregulated. *Environmental Science and Technology,* 56(10), 6380-6390. https://doi.org/10.1021/acs.est.1c07949

NFCC (2015). Environmental protection handbook for the fire and rescue service. National Fire Chiefs Council. England. Available at: https://nfcc.org.uk/wp-content/uploads/2023/10/Environment-Agency-and-DCLG-environmental-handbook.pdf

NFCC (2024, unpublished). Call for evidence response. National Fire Chiefs Council.

NFRS (2022). Request for information (our ref: NFRS2022-31-31). Northamptonshire Fire and Rescue Service. Available at: https://www.northantsfire.gov.uk/wp-content/uploads/2022/04/NFRS2022-31-31PFASFirefighting.pdf

Nguyen, H. T., Thai, P. K., Kaserzon, S. L., O'Brien, J. W. & Mueller, J. F. (2024). Nationwide occurrence and discharge mass load of per- and polyfluoroalkyl substances in effluent and biosolids: A snapshot from 75 wastewater treatment plants across Australia. *Journal of Hazardous Materials,* 470, 134203. https://doi.org/10.1016/j.jhazmat.2024.134203

Nguyen, T. M. H., Braunig, J., Kookana, R. S., Kaserzon, S. L., Knight, E. R., Vo, H. N. P., Kabiri, S., *et al.* (2022). Assessment of mobilization potential of per- and polyfluoroalkyl substances for soil remediation. *Environmental Science and Technology,* 56(14), 10030-10041. https://doi.org/10.1021/acs.est.2c00401

Nguyen, T. M. H., Bräunig, J., Thompson, K., Thompson, J., Kabiri, S., Navarro, D. A., Kookana, R. S., *et al.* (2020). Influences of chemical properties, soil properties, and solution pH on soil–water partitioning coefficients of per- and polyfluoroalkyl substances (PFASs). *Environmental Science and Technology,* 54(24), 15883-15892. https://doi.org/10.1021/acs.est.0c05705

NICNAS (2015a). Direct precursors to perfluoroheptanesulfonate (PFHpS), perfluorohexanesulfonate (PFHxS) and perfluoropentanesulfonate (PFPeS): Environment tier II assessment. National Industrial Chemicals Notification and Assessment Scheme. Australia. Available at: https://www.industrialchemicals.gov.au/sites/default/files/Direct%20precursors%20to%20perfluoroheptanesulfonate%20%28PFHpS%29%2C%20perfluorohexanesulfonate%20%28PFHxS%29%20and%20perfluoropentanesulfonate%20%28PFPeS%29_%20Environment%20tier%20II%20assessment.pdf

NICNAS (2015b). Direct precursors to perfluorooctanesulfonate (PFOS): Environment tier II assessment. National Industrial Chemicals Notification and Assessment Scheme. Australia. Available at: https://www.industrialchemicals.gov.au/sites/default/files/Direct%20precursors%20to%20perfluorooctanesulfonate%20%28PFOS%29_%20Environment%20tier%20II%20assessment.pdf

NICNAS (2015c). Short-chain perfluorocarboxylic acids and their direct precursors: Environment tier II assessment. National Industrial Chemicals Notification and Assessment Scheme. Australia. Available at: https://www.industrialchemicals.gov.au/sites/default/files/Short-chain%20perfluorocarboxylic%20acids%20and%20their%20direct%20precursors_%20Environment%20tier%20II%20assessment.pdf

NICNAS (2015d). Perfluoroheptanoic acid (PFHpA) and its direct precursors: Environment tier II assessment. National Industrial Chemical Notification and Assessment Scheme. Australia. Available at: https://www.industrialchemicals.gov.au/sites/default/files/Perfluoroheptanoic%20acid%20%28PFHpA%29%20and%20its%20direct%20precursors_%20Environment%20tier%20II%20assessment.pdf

NICNAS (2015e). Perfluorooctanoic acid (PFOA) and its direct precursors: Environment tier II assessment. National Industrial Chemicals Notification and Assessment Scheme. Australia. Available at: https://www.industrialchemicals.gov.au/sites/default/files/Perfluorooctanoic%20acid%20%28PFOA%29%20and%20its%20direct%20precursors_%20Environment%20tier%20II%20assessment.pdf

NICNAS (2015f). Direct precursors to perfluorononanesulfonate (PFNS) and perfluorodecanesulfonate (PFDS): Environment tier II assessment. National Industrial Chemicals Notification and Assessment Scheme. Australia. Available at: https://www.industrialchemicals.gov.au/sites/default/files/Direct%20precursors%20to%20perfluorononanesulfonate%20%28PFNS%29%20and%20perfluorodecanesulfonate%20%28PFDS%29_%20Environment%20tier%20II%20assessment.pdf

NICNAS (2015g). Indirect precursors to perfluoroalkyl sulfonates: Environment tier II assessment. National Industrial Chemicals Notification and Assessment Scheme. Australia. Available at: https://www.industrialchemicals.gov.au/sites/default/files/Indirect%20precursors%20to%20perfluoroalkyl%20sulfonates_%20Environment%20tier%20II%20assessment.pdf

NICNAS (2015h). Perfluorobutanesulfonic acid and its direct precursors: Environment tier II assessment. National Industrial Chemical Notification and Assessment Scheme. Australia. Available at: https://www.industrialchemicals.gov.au/sites/default/files/Perfluorobutanesulfonic%20a cid%20and%20its%20direct%20precursors_%20Environment%20tier%20II%20assessment.pdf

NICNAS (2018). Perfluoroalkyl phosphonic and phosphinic acids: Environmental tier II assessment. National Industrial Chemicals Notification and Assessment Scheme. Australia. Available at: https://www.industrialchemicals.gov.au/sites/default/files/Perfluoroalkyl%20phosphonic%20and%20phosphinic%20acids_%20Environment%20tier%20II%20assessment.pdf

NITA (2024). Aviation training. Newcastle International Training Academy, Newcastle International Airport. Available at: https://www.newcastleairport.com/training-academy/aviation-training/

Nordic Council of Ministers (2019). The cost of inaction a socioeconomic analysis of environmental and health impacts linked to exposure to PFAS. [2019:516]. Nordic Council of Ministers. Copenhagen, Denmark. https://doi.org/10.6027/TN2019-516

NYFRS (2022). Freedom of Information request (EIR request) – 2669. North Yorkshire Fire and Rescue Service. Available at: https://www.northyorksfire.gov.uk/wp-content/uploads/2022/04/2669.pdf

OECD (2018). Summary report on updating the OECD 2007 list of per- and polyfluoroalkyl substances (PFASs). *OECD Series on Risk Management of Chemicals.* [No. 39]. OECD Publishing. Paris, France. Available at: https://doi.org/10.1787/1a14ad6c-en

OECD (2019). Guiding principles and key elements for establishing a weight of evidence for chemical assessment. *OECD Series on Testing and Assessment.* [No. 311]. OECD Publishing. Paris, France. https://doi.org/10.1787/f11597f6-en

OECD (2021a). Emission scenario document on the use of aqueous film-forming foams in firefighting. *Emission Scenario Documents.* [40]. OECD Publishing. Paris, France. https://doi.org/10.1787/7a84d2b6-en

OECD (2021b). Reconciling terminology of the universe of per- and polyfluoroalkyl substances: Recommendations and practical guidance. *OECD Series on Risk Management.* [No. 61]. OECD Publishing. Paris, France. https://doi.org/10.1787/e458e796-en

OECD (2022). Fact cards of major groups of per- and polyfluoroalkyl substances (PFASs). *OECD Series on Risk Management.* [No. 68]. OECD Publishing. Paris, France. Available at: https://www.oecd.org/en/publications/fact-cards-of-major-groups-of-per-and-polyfluoroalkyl-substances-pfass_59e7ffc6-en.html

Oil Technics (2024). Welcome to oil technics. Oil Technics (Fire Fighting Products) Ltd. Available at: https://www.firefightingfoam.com/about/

Oosterhuis, F. & Brouwer, R. (2015). Benchmark development for the proportionality assessment of PBT and vPvB substances. [Report R-15/11]. IVM Institute for Environmental Studies. Amsterdam, The Netherlands. Available at: https://echa.europa.eu/documents/10162/17241/R15_11_pbt_benchmark_report_en.pdf

Pan, C. G., Liu, Y. S. & Ying, G. G. (2016). Perfluoroalkyl substances (PFASs) in wastewater treatment plants and drinking water treatment plants: Removal efficiency and exposure risk. *Water Research,* 106, 562-570. https://doi.org/10.1016/j.watres.2016.10.045

Parsons, J. R., Saez, M., Dolfing, J. & de Voogt, P. (2008). Biodegradation of perfluorinated compounds. In: Whiteacre, D. (ed.) *Reviews of environmental contamination and toxicology vol 196.* New York, NY, USA: Springer. https://doi.org/10.1007/978-0-387-78444-1_2

Pawlowski, S., Aicher, L., Berends, A., Curtis-Jackson, P., Haner, A., Hollender, J., Jene, B.*, et al.* (2023). Mobility in the context of exposure-based assessment of chemicals for drinking water resource protection. *Integrated Environmental Assessment and Management,* 19(3), 775-791. https://doi.org/10.1002/ieam.4705

Pelch, K. E., McKnight, T. & Reade, A. (2023). 70 analyte PFAS test method highlights need for expanded testing of PFAS in drinking water. *Science of the Total Environment,* 876, 162978. https://doi.org/10.1016/j.scitotenv.2023.162978

Pelch, K. E., Reade, A., Kwiatkowski, C. F., Merced-Nieves, F. M., Cavalier, H., Schultz, K., Wolffe, T.*, et al.* (2022). The PFAS-tox database: A systematic evidence map of health studies on 29 per- and polyfluoroalkyl substances. *Environment International,* 167, 107408. https://doi.org/10.1016/j.envint.2022.107408

PELG (2024). PELG petrol filling stations - guidance on managing the risks of fire and explosion (the red guide). Energy Institute. London, England. Available at: https://www.energyinst.org/technical/publications

Pfotenhauer, D., Sellers, E., Olson, M., Praedel, K. & Shafer, M. (2022). PFAS concentrations and deposition in precipitation: An intensive 5-month study at national atmospheric deposition program – national trends sites (NADP-NTN) across Wisconsin, USA. *Atmospheric Environment,* 291, 119368. https://doi.org/10.1016/j.atmosenv.2022.119368

Pickard, H. M., Criscitiello, A. S., Persaud, D., Spencer, C., Muir, D. C. G., Lehnherr, I., Sharp, M. J.*, et al.* (2020). Ice core record of persistent short-chain fluorinated alkyl acids: Evidence of the impact from global environmental regulations. *Geophysical Research Letters,* 47(10). https://doi.org/10.1029/2020GL087535

Pizzurro, D. M., Seeley, M., Kerper, L. E. & Beck, B. D. (2019). Interspecies differences in perfluoroalkyl substances (PFAS) toxicokinetics and application to health-based criteria. *Regulatory Toxicology and Pharmacology,* 106, 239-250. https://doi.org/10.1016/j.yrtph.2019.05.008

Place, B. J. & Field, J. A. (2012). Identification of novel fluorochemicals in aqueous film-forming foams used by the US military. *Environmental Science and Technology,* 46(13), 7120-7127. https://doi.org/10.1021/es301465n

Port of Milford Haven (2024, unpublished). Port of milford haven Entry & departure guidelines for vessels. Port of Milford Haven, England. Available at: https://www.mhpa.co.uk/media/af3khlx4/mar-ops-gui-003-port-entry-and-departure-guidlines-j.pdf

Prevedouros, K., Cousins, I. T., Buck, R. C. & Korzeniowski, S. H. (2006). Sources, fate and transport of perfluorocarboxylates. *Environmental Science and Technology,* 40(1), 32-44. https://doi.org/10.1021/es0512475

Price, T. C. (2022). *Economic valuation of PFAS remediation in New Hampshire municipal drinking water systems: A contingent valuation approach.* MSc thesis., University of New Hampshire, USA. Available at: https://scholars.unh.edu/thesis/1619

Puma Energy (2020). Milford haven terminal: Marine terminal Information and Regulations. [72/JETTY/DOC/01 Rev. 7.00]. Puma Energy UK. England. Available at: https://captainslog.gr/wp-content/uploads/2020/12/Milford-Haven-terminals-rules-and-regulations.pdf

Radke, E. G., Wright, J. M., Christensen, K., Lin, C. J., Goldstone, A. E., Lemeris, C. & Thayer, K. A. (2022). Epidemiology evidence for health effects of 150 per- and polyfluoroalkyl substances: A systematic evidence map. *Environmental Health Perspectives,* 130(9), 96003. https://doi.org/10.1289/ehp11185

Ragnarsdottir, O., Abou-Elwafa Abdallah, M. & Harrad, S. (2024). Dermal bioavailability of perfluoroalkyl substances using *in vitro* 3D human skin equivalent models. *Environment International,* 188, 108772. https://doi.org/10.1016/j.envint.2024.108772

RBFRS (2022). Request number 2021-0090 (firefighting – use of PFAS). Royal Berkshire Fire and Rerscue Service. Available at: https://www.rbfrs.co.uk/app/uploads/2024/08/RBFRS-Information-Requests-Disclosure-Log-2022-Jan-Dec.pdf

Rice, P. A., Aungst, J., Cooper, J., Bandele, O. & Kabadi, S. V. (2020). Comparative analysis of the toxicological databases for 6:2 fluorotelomer alcohol (6:2 FTOH) and perfluorohexanoic acid (PFHxA). *Food and Chemical Toxicology,* 138, 111210. https://doi.org/10.1016/j.fct.2020.111210

Ross, I. (2020). Disposal of AFFF, FFFP and FP: Challenges and emerging solutions. *The Catalyst (JOIFF),* Q4 2020, 30-31. Available at: https://www.joiff.com/wp-content/uploads/Catalyst-Q4-FINAL.pdf

Ross, I. & Storch, P. (2020). Foam transition: Is it as simple as "foam out / foam in"? *The Catalyst (JOIFF),* 2020 Q2 (Supplement), 1-19. Available at: https://joiff.com/wp-content/uploads/2020/05/JOIFF-Catalyst-Q2-Foam-Supplement-13May20.pdf

RPS Group (2024). PFAS at airports: Managing your responsibilities and liabilities. Civil Aviation Authority, RPS Group. United Kingdom. Available at: https://www.caa.co.uk/media/xgfm3aoe/pfas-at-airports-managing-your-responsibilities-and-liabilities.pdf

Ruyle, B. J., Thackray, C. P., Butt, C. M., LeBlanc, D. R., Tokranov, A. K., Vecitis, C. D. & Sunderland, E. M. (2023). Centurial persistence of forever chemicals at military fire training sites. *Environmental Science and Technology,* 57(21), 8096-8106. https://doi.org/10.1021/acs.est.3c00675

Sabljić, A., Güsten, H., Verhaar, H. & Hermens, J. (1995). QSAR modelling of soil sorption. Improvements and systematics of log K_{OC} vs log K_{OW} correlations. *Chemosphere,* 31(11-12), 4489-4514. https://doi.org/10.1016/0045-6535(95)00327-5

Sadia, M., Nollen, I., Helmus, R., Ter Laak, T. L., Been, F., Praetorius, A. & van Wezel, A. P. (2023). Occurrence, fate, and related health risks of PFAS in raw and produced drinking water. *Environmental Science and Technology,* 57(8), 3062-3074. https://doi.org/10.1021/acs.est.2c06015

Saez, M., de Voogt, P. & Parsons, J. R. (2008). Persistence of perfluoroalkylated substances in closed bottle tests with municipal sewage sludge. *Environmental Science and Pollution Research,* 15(6), 472-477. https://doi.org/10.1007/s11356-008-0020-5

Safelincs (2025). P50 service-free 6ltr foam fire extinguisher*.* Safelincs. Available at: https://www.safelincs.co.uk/britannia-6ltr-foam/

Scheurer, M., Nodler, K., Freeling, F., Janda, J., Happel, O., Riegel, M., Muller, U.*, et al.* (2017). Small, mobile, persistent: Trifluoroacetate in the water cycle - overlooked sources, pathways, and consequences for drinking water supply. *Water Research,* 126, 460-471. https://doi.org/10.1016/j.watres.2017.09.045

Seow, J. (2013). Fire fighting foams with perfluorochemicals - environmental review. Department of Environment and Conservation, Western Australia. Australia. Available at: https://cswab.org/wp-content/uploads/2018/03/Fire-Fighting-Foams-with-PFAS-Env-Review-June-2013-Australia-.pdf

SEPA, Environment Agency & HSE (2008). Containment of bulk hazardous liquids at COMAH establishments containment policy. *Supporting guidance for secondary and tertiary containment.* Scottish Environment Protection Agency, Environment Agency, Health & Safety Executive. United Kingdom. Available at: https://www.sepa.org.uk/media/426907/comah_containment_policy_supporting_guidelines.pdf

Sha, B., Johansson, J. H., Tunved, P., Bohlin-Nizzetto, P., Cousins, I. T. & Salter, M. E. (2022). Sea spray aerosol (SSA) as a source of perfluoroalkyl acids (PFAAs) to the atmosphere: Field evidence from long-term air monitoring. *Environmental Science and Technology,* 56(1), 228-238. https://doi.org/10.1021/acs.est.1c04277

Shirke, A. V., Radke, E. G., Lin, C., Blain, R., Vetter, N., Lemeris, C., Hartman, P.*, et al.* (2024). Expanded systematic evidence map for hundreds of per- and polyfluoroalkyl substances (PFAS) and comprehensive PFAS human health dashboard. *Environmental Health Perspectives,* 132(2), 26001. https://doi.org/10.1289/ehp13423

Shropshire FRS (2022). Perfluoroalkyl and polyfluoroalkyl substances (PFAS) FOI reference 1190*.* Shropshire Fire and Rescue Service. Available at: https://www.shropshirefire.gov.uk/perfluoroalkyl-and-polyfluoroalkyl-substances-pfas

Shu, X., Pulicharla, R., Kumar, P. & Brar, S. K. (2023). Comparison between chemical and biological degradation processes for perfluorooctanoic acid. *Soil Systems,* 7(4). https://doi.org/10.3390/soilsystems7040091

Sigmund, G., Arp, H. P. H., Aumeier, B. M., Bucheli, T. D., Chefetz, B., Chen, W., Droge, S. T. J.*, et al.* (2022). Sorption and mobility of charged organic compounds: How to confront and overcome limitations in their assessment. *Environmental Science and Technology,* 56(8), 4702-4710. https://doi.org/10.1021/acs.est.2c00570

Smart, B. E. (1994). Characteristics of C-F systems. In: Banks, R. E., Smart, B. E. & Tatlow, J. C. (eds.) *Organofluorine chemistry: Principles and commmercial applications.* New York, USA: Plenum.

Song, P., Li, D., Wang, X. & Zhong, X. (2018). Effects of perfluorooctanoic acid exposure during pregnancy on the reproduction and development of male offspring mice. *Andrologia,* 50(8), e13059. https://doi.org/10.1111/and.13059

Staffordshire FRS (2022). FOI reference 041/22*.* Staffordshire Fire and Rescue Service. Available at: https://www.staffordshirefire.gov.uk/media/kvvlnon5/foi_041_23032022.pdf

Stoiber, T., Evans, S. & Naidenko, O. V. (2020). Disposal of products and materials containing per- and polyfluoroalkyl substances (PFAS): A cyclical problem. *Chemosphere,* 260, 127659. https://doi.org/10.1016/j.chemosphere.2020.127659

Strawn, D. G. (2021). Sorption mechanisms of chemicals in soils. *Soil Systems,* 5(1), 13. https://doi.org/10.3390/soilsystems5010013

SWFRS (2019). Request for Information held by SWFRS. [110_1920]. South Wales Fire and Rescue Services. Pontyclun, Wales. Available at: https://www.southwales-fire.gov.uk/app/uploads/2020/02/110_1920.pdf

Torres, F. G. & De-la-Torre, G. E. (2022). Per- and polyfluoroalkyl substances (PFASs) in consumable species and food products. *Journal of Food Science and Technology*. https://doi.org/10.1007/s13197-022-05545-7

Trazzi, D. & Casey, J. (2023). Evaluation of effects from mixing fluorine-free foam concentrates. [DOT/FAA/TC-TN23/73]. Federal Aviation Administration. Washington, DC, USA. Available at: https://www.airporttech.tc.faa.gov/DesktopModules/EasyDNNNews/DocumentDownload.ashx?portalid=0&moduleid=3682&articleid=2937&documentid=3116

Trozzolo, L. & Howard, J. (2024). Challenges associated with atmospheric transport of PFAS*.* TRC Companies, Inc. Available at: https://www.trccompanies.com/insights/challenges-associated-with-atmospheric-transport-of-pfas/

Tyne Tunnels (2018). Safe driving in the Tyne Tunnels*.* Tyne Tunnels. Available at: https://www.tt2.co.uk/content/uploads/2021/04/Tyne-Tunnel-Safety-Information.pdf

UBA (2021). The final PMT/vPvM criteria after public consultation*.* Umweltbundesamt. Available at: https://www.umweltbundesamt.de/en/the-final-pmtvpvm-criteria-after-public

UK Government (2002). The dangerous substances and explosive atmospheres regulations 2002 [2002 No. 2776]. Available at: https://www.legislation.gov.uk/uksi/2002/2776/contents

UK Government (2005). The regulatory reform (fire safety) order 2005 [2005 No. 1541]. Available at: https://www.legislation.gov.uk/uksi/2005/1541/contents

UK Government (2016a). The dangerous goods in harbour areas regulations 2016 [2016 No. 721]. Available at:

https://www.legislation.gov.uk/uksi/2016/721/contents/made

UK Government (2016b). The merchant shipping (marine equipment) regulations 2016 [2016 No. 1025]. Available at: https://www.legislation.gov.uk/uksi/2016/1025/contents

UK Government (2018). Space industry act 2018 [2018 c.5]. Available at: https://www.legislation.gov.uk/ukpga/2018/5/pdfs/ukpga_20180005_en.pdf

UK Government (2019). Research and analysis extractive industries in the UK: Background information on oil and gas. Department for Business, Energy & Industrial Strategy. Available at: https://www.gov.uk/government/publications/extractive-industries-transparency-initiative-payments-report-2017/extractive-industries-in-the-uk-background-information-on-oil-and-gas

UK Government (2020). Agreement in the form of an exchange of notes between the government of the United Kingdom of Great Britain and Northern Ireland and the government of the United States of America on technology safeguards associated with United States participation in space launches from the United Kingdom [USA No. 1 (2020)]. Available at: https://assets.publishing.service.gov.uk/media/5f886c5b8fa8f504267c453b/CS_UK_USA_1.2020_USA_Techno_Safeguards_Space_Launches.pdf

UK Government (2021). The REACH etc. (amendment) regulations 2021 [2021 No. 904]. Available at: https://www.legislation.gov.uk/uksi/2021/904/made

UK Space Agency, DfT & CAA (2023). Launch UK: A guide to UK spaceports. UK Space Agency, Department for Transport, Civil Aviation Authority. United Kingdom. Available at: https://assets.publishing.service.gov.uk/media/643e6a4222ef3b000c66f3d1/Spaceport_brochure_17.4.23.pdf

UN POPS (2006). Risk profile on perfluorooctane sulfonate. *Report of the Persistent Organic Pollutants Review Committee on the work of its Second Meeting.* [UNEP/POPS/POPRC.2/17/Add.5]. Persistent Organic Pollutants Review Committee, United Nations Stockholm Convention on Persistent Organic Pollutants. Geneva, Switzerland. Available at: http://chm.pops.int/Portals/0/Repository/poprc2/UNEP-POPS-POPRC.2-17-Add.5.English.PDF

UN POPS (2016). Risk profile on pentadecafluorooctanoic acid (CAS no: 335-67-1, PFOA, perfluorooctanoic acid), its salts and PFOA-related compounds. *Report of the Persistent Organic Pollutants Review Committee on the work of its twelfth meeting.* [UNEP/POPS/POPRC.12/11/Add.2]. Persistent Organic Pollutants Review Committee, United Nations Stockholm Convention on Persistent Organic Pollutants. Geneva, Switzerland. Available at: https://chm.pops.int/TheConvention/POPsReviewCommittee/Reports

UN POPS (2018). Risk profile on perfluorohexane sulfonic acid (PFHxS), its salts and PFHxS-related compounds. *Report of the Persistent Organic Pollutants Review Committee on the work of its fourteenth meeting.* [UNEP/POPS/POPRC.14/6/Add.1]. Persistent Organic Pollutants Review Committee, United Nations Stockholm Convention on Persistent Organic Pollutants. Geneva, Switzerland. Available at: https://chm.pops.int/TheConvention/POPsReviewCommittee/Reports

UN POPS (2021). Proposal to list long-chain perfluorocarboxylic acids, their salts and related compounds in Annexes A, B and/or C to the Stockholm Convention on Persistent Organic Pollutants. *Persistent Organic Pollutants Review Committee Seventeenth meeting.* [UNEP/POPS/POPRC.17/7]. Persistent Organic Pollutants Review Committee, United Nations Stockholm Convention on Persistent Organic Pollutants. Geneva, Switzerland. Available at: https://chm.pops.int/TheConvention/POPsReviewCommittee/Reports

UN POPS (2023). Risk profile for long-chain perfluorocarboxylic acids, their salts and related compounds. *Report of the Persistent Organic Pollutants Review Committee on the work of its eighteenth meeting.* [UNEP/POPS/POPRC.18/11/Add.4]. Persistent Organic Pollutants Review Committee, United Nations Stockholm Convention on Persistent Organic Pollutants. Geneva, Switzerland. Available at: https://chm.pops.int/TheConvention/POPsReviewCommittee/Reports

US DoD (2022). Temporary prohibition on incineration of materials containing per- and polyfluoroalkyl substances (PFAS). US Department of Defense, USA. Available at: https://subscriber.politicopro.com/eenews/f/eenews/?id=00000180-8fe1-d3ee-a392-9ffbecd00000

US DoD (2024a). Qualified product database: MIL-PRF-32725 - fire extinguishing agent, fluorine-free foam (F3) liquid concentrate, for land-based, fresh water applications. Department of Defense, USA. Available at: https://qpldocs.dla.mil/search/parts.aspx?qpl=4513&param=QPL-32725&type=256[Accessed: 09 October 2024]

US DoD (2024b). Department of defense incineration moratorium report to congress February 2024. Defense, U. D. O., United States: Office of the Assistant Secretary of Defense for Energy, Installations, and Environment. Available at: https://www.acq.osd.mil/eie/eer/ecc/pfas/docs/reports/Incineration-Mortatorium.pdf

US EPA (2012). Estimation programs interface suite™ for Microsoft® Windows, v 4.11. US Environmental Protection Agency. Washington, DC, USA. Available at: https://www.epa.gov/tsca-screening-tools/epi-suitetm-estimation-program-interface

US EPA (2020). Per- and polyfluoroalkyl substances (PFAS): Incineration to manage PFAS waste streams. *Technical BRIEF.* US Environmental Protection Agency. USA. Available at: https://www.epa.gov/sites/default/files/2019-09/documents/technical_brief_pfas_incineration_ioaa_approved_final_july_2019.pdf

US EPA (2021). Other test method 45 (OTM-45): Measurement of selected per- and polyfluorinated alkyl substances from stationary sources. US Environmental Protection Agency. USA. Available at: https://www.epa.gov/sites/default/files/2021-01/documents/otm_45_semivolatile_pfas_1-13-21.pdf

US EPA (2022a). Health assessment workspace collaborative (HAWC): Public assessments/ORD SEM PFAS 150 (2022)/visualizations. United States Environmental Protection Agency. Available at: https://hawc.epa.gov/summary/assessment/100500085/visuals/

US EPA (2022b). Guidance for reporting on the environmental fate and transport of the stressors of concern in problem formulations. US Environmental Protection Agency. Available at: https://www.epa.gov/pesticide-science-and-assessing-pesticide-risks/guidance-reporting-environmental-fate-and-transport#footnotes

US EPA (2024a). Interim guidance on the destruction and disposal of perfluoroalkyl and polyfluoroalkyl substances and materials containing perfluoroalkyl and polyfluoroalkyl substances. *Interim guidance for public comment.* [Version 2 (2024)]. US Environmental Protection Agency. USA. Available at: https://www.epa.gov/system/files/documents/2024-04/2024-interim-guidance-on-pfas-destruction-and-disposal.pdf

US EPA (2024b). Characterization and quantification of per- and polyfluoroalkyl substances in landfill gas and estimate of emissions from U.S. Landfills. US Environmental Protection Agency. USA. Available at: https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract_id/10990/report/0

US EPA (2024c). Health assessment workspace collaborative (HAWC): Public assessments/ORD SEM expanded PFAS (2024)/visualizations*.* United States Environmental Protection Agency. Available at: https://hawc.epa.gov/summary/assessment/100500256/visuals/

US EPA (2024d). Other test method 50 (otm-50): Sampling and analysis of volatile fluorinated compounds from stationary sources using passivated stainless-steel canisters. USA: US Environmental Protection Agency. Available at: https://www.epa.gov/system/files/documents/2025-01/otm-50-release-1-r1.pdf

US EPA (2024e). Economic analysis for the final per- and polyfluoroalkyl substances national primary drinking water regulation. [EPA-815-R-24-001]. US Environmental Protection Agency. Washington, DC, USA. Available at: https://www.epa.gov/system/files/documents/2024-04/pfas-npdwr_final-rule_ea.pdf

US EPA (2024f). Fact sheet: 2010/2015 PFOA stewardship program*.* US Environmental Protection Agency. Available at: https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/fact-sheet-20102015-pfoa-stewardship-program

Wackett, L. P. (2022). Nothing lasts forever: Understanding microbial biodegradation of polyfluorinated compounds and perfluorinated alkyl substances. *Microbial biotechnology,* 15(3), 773-792. https://doi.org/10.1111/1751-7915.13928

Wang, L., Yang, T., Liu, X., Liu, J. & Liu, W. (2024). Critical evaluation and meta-analysis of ecotoxicological data on per- and polyfluoroalkyl substances (PFAS) in freshwater species. *Environmental Science and Technology,* 58(40), 17555-17566. https://doi.org/10.1021/acs.est.4c04818

Wang, W., Rhodes, G., Ge, J., Yu, X. & Li, H. (2020). Uptake and accumulation of per- and polyfluoroalkyl substances in plants. *Chemosphere,* 261, 127584. https://doi.org/10.1016/j.chemosphere.2020.127584

Wang, Z., Cousins, I. T., Berger, U., Hungerbuhler, K. & Scheringer, M. (2016). Comparative assessment of the environmental hazards of and exposure to perfluoroalkyl phosphonic and phosphinic acids (PFPAs and PFPiAs): Current knowledge, gaps, challenges and research needs. *Environment International,* 89-90, 235-247. https://doi.org/10.1016/j.envint.2016.01.023

Wanzek, T. A., Field, J. A. & Kostarelos, K. (2024). Repeated aqueous film-forming foams applications: Impacts on polyfluoroalkyl substances retention in saturated soil. *Environmental Science and Technology,* 58(3), 1659-1668.

https://doi.org/10.1021/acs.est.3c04595

Water UK (2018). Protocol for the disposal of contaminated water and associated wastes at incidents. [Version 16]. United Kingdom. Available at: https://www.water.org.uk/sites/default/files/wp/2018/11/Contaminated-Water-Disposal-Protocol.pdf

What Do They Know (2024). COMAH sites list 2024*.* What Do They Know. Available at: https://www.whatdotheyknow.com/request/comah_sites_list_2024

Wilson, M. (2024). What firefighting lessons could we learn from japan's A350 crash on 2 Jan. 2024? *The Catalyst (JOIFF),* Q1 2024, 44-47. Available at: https://issuu.com/joiff/docs/catalyst-q1-2

WMFS (2022). Firefighting foams and substances: FOI request number 22037*.* West Midlands Fire Service. Available at: https://www.wmfs.net/foi/22037-firefighting-foams-and-substances/

Wood (2020). The use of PFAS and fluorine-free alternatives in fire-fighting foams. *Report produced for European Commission DG Environment / European Chemicals Agency.* [Specific contracts No 07.0203/2018/791749/ENV.B.2 and ECHA/2018/561]. Wood Environment & Infrastructure Solutions UK Ltd. London, United Kingdom. Available at: https://echa.europa.eu/documents/10162/6755610/pfas_flourine-free_alternatives_fire_fighting_en.pdf/d5b24e2a-d027-0168-cdd8-f723c675fa98

WSP (2023). Socio-economic analysis of applying a UK REACH restriction on PFAS in firefighting foams. [853262-WOOD-RP-OP-00001_3]. WSP Environment & Infrastructure Solutions UK Limited. London, United Kingdom.

WSP (formerly Wood Group Ltd) (2022, unpublished). Persistent Organic Pollutants (POPs) - cost benefit analysis POPs Annex IV for PFOA and PFHxS. Wood Group on behalf of the Environment Agency (UK).

Wu, S., Tong, C. & Liu, J. (2025). Obesogenic effects of six classes of emerging contaminants. *Journal of Environmental Sciences,* 151, 252-272. https://doi.org/10.1016/j.jes.2024.03.032

Xie, M. Y., Lin, Z. Y., Sun, X. F., Feng, J. J., Mai, L., Wu, C. C., Huang, G. L.*, et al.* (2024). Per- and polyfluoroalkyl substances (PFAS) exposure in plasma and their blood-brain barrier transmission efficiency-a pilot study. *Environment International,* 187, 108719. https://doi.org/10.1016/j.envint.2024.108719

Yuan, Y., Ding, X., Cheng, Y., Kang, H., Luo, T., Zhang, X., Kuang, H.*, et al.* (2020). PFOA evokes extracellular Ca(2+) influx and compromises progesterone-induced response in human sperm. *Chemosphere,* 241, 125074. https://doi.org/10.1016/j.chemosphere.2019.125074

Zahm, S., Bonde, J. P., Chiu, W. A., Hoppin, J., Kanno, J., Abdallah, M., Blystone, C. R.*, et al.* (2024). Carcinogenicity of perfluorooctanoic acid and perfluorooctanesulfonic acid. *The Lancet Oncology,* 25(1), 16-17. https://doi.org/10.1016/s1470-2045(23)00622-8

Zhang, Z., Sangion, A., Wang, S., Gouin, T., Brown, T., Arnot, J. A. & Li, L. (2023). Hazard vs. Exposure: Does it make a difference in identifying chemicals with

persistence and mobility concerns? *Water Research*.
https://doi.org/10.1016/j.watres.2023.120610

Zhou, J., Saeidi, N., Wick, L. Y., Kopinke, F.-D. & Georgi, A. (2021). Adsorption of polar and ionic organic compounds on activated carbon: Surface chemistry matters. *Science of the Total Environment,* 794, 148508.
https://doi.org/10.1016/j.scitotenv.2021.148508

Zhou, Z., Liang, Y., Shi, Y., Xu, L. & Cai, Y. (2013). Occurrence and transport of perfluoroalkyl acids (PFAAs), including short-chain PFAAs in Tangxun lake, China. *Environmental Science and Technology,* 47(16), 9249-9257.
https://doi.org/10.1021/es402120y

[Inside rear cover – leave blank – remove this text before publishing]

Further information

For information about health and safety, or to report inconsistencies or inaccuracies in this guidance, visit the HSE website.

You can order HSE priced publications at the HSE books website.

HSE priced publications are also available from bookshops.

Published by the Health and Safety Executive 08/25.