Background Document to the Agency Opinion on the Proposal for a Restriction

Per- and polyfluoroalkyl substances (PFAS) in firefighting foams

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BACKGROUND DOCUMENT TO THE AGENCY OPINION ON THE PROPOSAL FOR A RESTRICTION: PER AND POLYFLUOROALKYL SUBSTANCES (PFAS) IN FIREFIGHTING FOAMS

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Contents

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
HTI	High temperature 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	Non-organic carbon normalised soil-water partition 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
MACC	Marginal abatement cost curve
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

Summary

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.

This document 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, including options for a restriction under UK REACH.

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 vessels, 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 50 tonnes of PFAS are emitted to the GB environment from use in such firefighting foams per year.

Once PFAS enter the environment from the use of FFF, 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 are suspected carcinogens. Various terminal degradation products and other PFAS have resulted in a range of adverse effects in experimental studies in laboratory animals, and some have been reported to cause harm to the developing child and adverse effects in organs such as the liver or in the immune system in humans.

Although it may be possible to derive thresholds for some PFAS for which there are sufficient data, 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.

Environmental emissions occur from all uses of PFAS-containing FFF in GB, with surface and ground water identified as compartments of particular concern.

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 adequately control emissions of PFAS into the environment following the use of firefighting foams or ensure appropriate management of PFAS FFF at the end of use. 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 in the population.

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.

A restriction on the placing on the market and use of PFAS in firefighting foams is considered an effective measure to reduce the identified risks.

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 any restriction on the placing on the market and use of PFAS-containing firefighting foams should include sector-/use-specific transition periods (as defined in Table 1 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 course of this work.

The Agency therefore proposes that a restriction under UK REACH, with sector/use specific transition periods, is appropriate to address the identified risks.

However, as the proposed transition periods are 5 years or longer, the Agency concludes that measures should be in place to minimise the impact of emissions of PFAS into the environment resulting from use of FFF during this time.

The Agency also acknowledges that emissions can result from the handling of waste stemming from the use of PFAS-containing foams (including wastewater) during this time, and also from remaining stocks of PFAS-containing foam that have not been used to fight a fire. As acknowledged in Section 2 of the Government's PFAS plan, specific environmental/waste legislation and permitting to control PFAS is in place outside of UK REACH and could be further clarified or strengthened to address this issue. However, the Agency notes that the decision makers may choose to address emissions from these sources within this restriction and has therefore assessed multiple restriction options (RO1, RO2a and RO2b) against the criteria of effectiveness, practicality and monitorability (as required under Annex 15 of UK REACH), including whether the restrictions are proportionate and cost-effective.

Each of the 3 REACH restriction options (RO1, RO2a and RO2b) will:

- Result in a restriction on the placing on the market and use of PFAS in firefighting foam in a concentration equal to or greater than 1mg/L of total organic fluorine from PFAS.
- Define PFAS 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).

- Establish sector/use specific transition periods (refer to Table 1 below).
- Require the labelling of foams which are placed on the market during the transition period where they contain equal to or greater than 1mg/L of total organic fluorine from PFAS.

Further, for uses with transition periods of 5 years and above (with the exception of portable fire extinguishers) each option will require users to:

- Ensure PFAS-containing foams are only used for fires involving flammable liquids (Class B fires)
- Ensure emissions to the environment and direct and indirect human exposure to PFAS-containing foams are reduced to as low a level as is reasonably practicable.
- Establish and maintain a PFAS-containing firefighting foams management plan specific to the place of use.

RO2a includes the additional requirement for users to ensure the collection and labelling of stock of unused foam, and to ensure its handling in such a way that the PFAS content is destroyed or irreversibly transformed.

RO2b includes an additional requirement for users to ensure stocks of unused foam **and** PFAS containing waste, including wastewater, originating from the use of PFAS-containing foams are collected separately and labelled – where this is technically and practically possible – also to ensure their handling in such a way that PFAS content is destroyed or irreversibly transformed.

The conclusions of the Agency are summarised in the Opinion (HSE, 2026)

Table 1: Proposed transition periods

	Sector/use	UK		EU	
		Placing on the market	Use	Placing on the market	Use
1	Portable fire extinguishers (defined by BS EN3-7, BS EN-1866 and BS EN-16856)	6 months	5 years	1 year (or 18 months for alcohol resistant foams)	5 years
2	COMAH[a] sites; except for those already covered by the arrangements for aviation (see point 6)	10 years	10 years	10 years	10 years
3	Training and testing[b]; except testing of firefighting systems for their function	18 months	18 months	18 months	18 months
4	Fire and rescue services (FRS); except 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	18 months	18 months	18 months
5	On board civilian vessels[c] where FFF has been placed on board before entry into force	10 years	10 years	10 years (for ships with FFF placed on board before 23 October 2025)	10 years (for ships with FFF placed on board before 23 October 2025)
6	Civilian aviation sites	5 years	5 years	5 years	5 years

7	Defence[d]; except for military vessels where a 10 year transition period will be applicable	5 years	5 years	5 years (and 10 years for military vessels)	5 years (and10 years military vessels)
8	Offshore oil and gas installations	10 years	10 years	10 years	10 years
9	All other uses[e]	5 years	5 years	5 years	5 years

[a]Where COMAH refers to the Control of Major Accident Hazards (COMAH) Regulations 2015.

[b]A separate transition period is considered appropriate for training with FFF compared to their use during live incidents. Given 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.

[c] Civilian vessel means all non-military waterborne craft, including sea-going vessels and inland-waterway craft.

[d]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.

[e]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.

PFAS grouping and chain length

Table 2: 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

PFAS group	PFAS sub-group	Perfluorinated Cn (total Cn)	PFAS abbr.	Substance name	CAS RN
		17 (18)	PFODA	Perfluorooctadecanoic acid	16517-11-6
	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

PFAS group	PFAS sub-group	Perfluorinated Cn (total Cn)	PFAS abbr.	Substance name	CAS RN
		8 (8)	9Cl-PF3ONS	Perfluoro(2-((6-chlorohexyl)oxy)ethanesulfonic acid	756426-58-1
PFAA Precursor	PASF-based substances	6 (6)	FHxSA	Perfluorohexane sulfonamide	41997-13-1
		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.

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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, 2021a). 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.

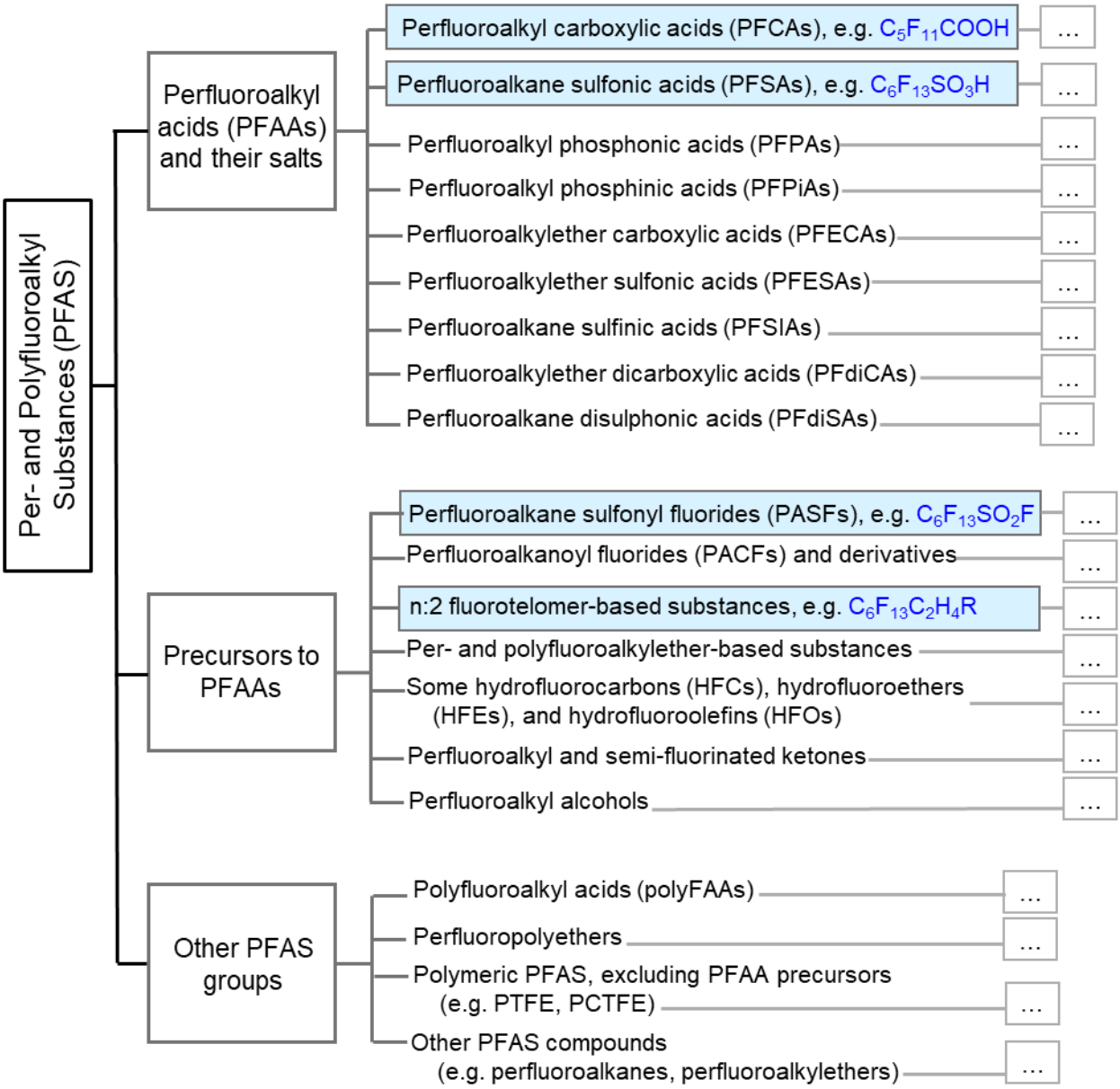
In 2021, the OECD provided a definition of PFAS based on chemical structure, refining the earlier work of Buck *et al*. (2011), with the intention of providing a consistent and coherent terminology. OECD (2021a) defines PFAS as “fluorinated substances that contain at least one fully fluorinated methyl 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 (2021a) 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.

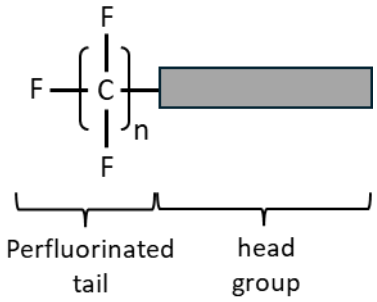
1.2.3 Function of PFAS in FFFs

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, aligning the definition of PFAS for the proposed restriction with the OECD definition of PFAS to encompass the widest range of PFAS in the scope of the restriction reduces the potential for regrettable substitution.

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 that support implementability, enforceability and 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, 2023b). 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

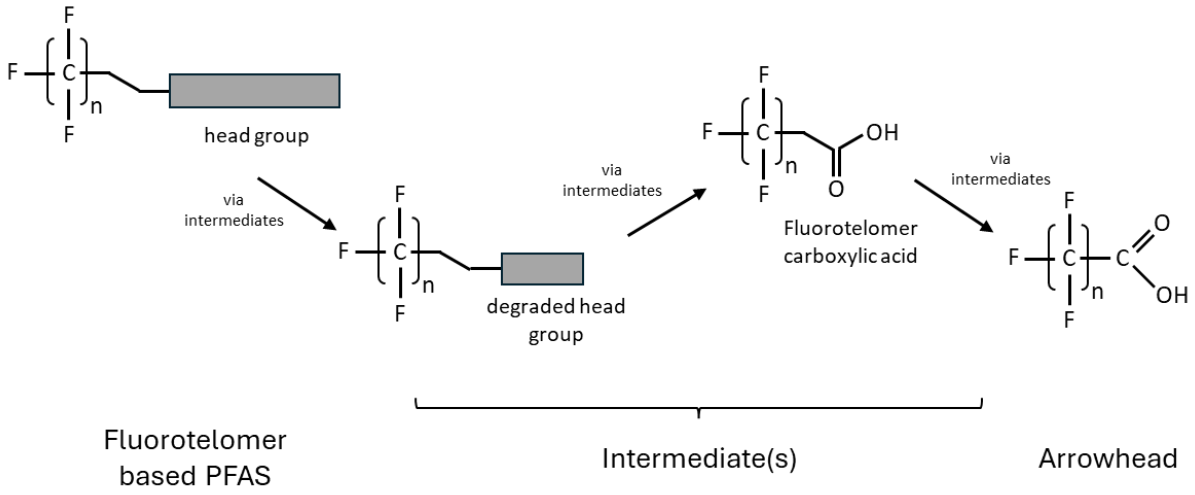
PFAS that meet the OECD (2021a) definition are in scope of this report (Section 1.2.5). However, given the thousands of PFAS that meet this definition, together with a lack of information on the hazards of most of them, it is not feasible to undertake a comprehensive hazard assessment of all substances 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 Table 2 on 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 is fragmented at best, with most available data concentrated on 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, 2022b). 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 Persistent, Mobile and Toxic (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, 2023e; 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

Studies in animals and data from humans indicate that PFAS are readily absorbed via the oral, inhalation and dermal routes (ATSDR, 2021; ECHA, 2023e; EFSA *et al.*, 2020a). Data are mostly 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 (2023e) 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, 2023e).

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 of occupational exposures to PFOS, PFHxS, PFOA and a range of other PFCAs (ECHA, 2023e).

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, 2023e; 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, 2023e).

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, 2023e; 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, 2023e; 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 (Xie *et al.*, 2024) 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, 2023e). Brain-to-serum ratios increase with carbon chain-length, as demonstrated for PFHxS, PFOS, PFNA, PFDA, PFUnDA and N-MeFOSAA in post-mortem human samples (Suzuki *et al.*, 2025).

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, 2023e). ECHA (2023e) 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, 2023e).

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, 2023e; EFSA *et al.*, 2020b). They can thus contribute to the overall load of these substances (ECHA, 2023e).

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, 2023e). 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, 2023e). ECHA (2023e) 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, 2023e; 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, have been reported to 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 have 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, 2022a). 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, 2023e; EFSA *et al.*, 2020a).

The liver findings with individual members of PFAS sub-groups are summarised in Annex B.5 of ECHA (2023e). 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 ≥ 8 and PFSAs with C ≥ 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 ≥ 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, 2023e). 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, 2023e; 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, 2023e).

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, 2022a). 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 (2023e).

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, 2023e); these were listed by ECHA (2023e) 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, 2023e). The thyroid findings from animal studies with individual members of PFAS sub-groups are summarised in Annex B.5 by ECHA (2023e).

(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. 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 (2023e) noted that PFAS can interfere with the thyroid on several levels, including thyroid hormone biogenesis, distribution and receptor binding (ECHA, 2023e; 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, 2023e; 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 (2023e) 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) 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,

2022a). 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, 2022a).

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. Reviews by ECCC and Health Canada (2024) and others (ECHA, 2023e; 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 ≥ 8 and PFSAs of C ≥ 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	

PFAS sub-group	Perfluorinated Cn (total Cn)	PFAS abbr.	Target organs, tissues, systems	Classification*
Long-chain PFSAs (≥C6)	7 (7)	PFHpS		
	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	

PFAS sub-group	Perfluorinated Cn (total Cn)	PFAS abbr.	Target organs, tissues, systems	Classification*
	6	EEA-NH4	Liver, kidney	STOT RE 2 proposed under GB CLP
	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 or consulted on a GB CLP opinion and/or technical report in which the stated mandatory classification and labelling are proposed.

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, 2022a). 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) 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, 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 (2022a) 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 (2022a), 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 (IARC, 2025). 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).

IARC also 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, 2019b).

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 (IARC, 2025; NASEM, 2022). 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, 2023e), 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 is 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		

PFAS sub-group	Perfluorinated Cn (total Cn)	PFAS abbr.	Target tissues	Classification*
Long-chain PFSAs (≥C6)	7 (7)	PFHpS		
	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	Liver, testes	Carc 2 proposed under GB CLP

PFAS sub-group	Perfluorinated Cn (total Cn)	PFAS abbr.	Target tissues	Classification*
	6 (3)	F-DIOX		
	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.

Carc 2 proposed = HSE has published or consulted on a GB CLP opinion and/or technical report in which the stated mandatory classification and labelling are proposed.

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, 2023e).

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, 2023e; 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, 2022a; ECHA, 2023e; 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, 2022a). 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 (2022a) 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”, although 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, 2023e; 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.

HSE has proposed that EEA-NH4 (a PFECA) receive a mandatory classification for developmental toxicity under GB CLP. The EU's Risk Assessment Committee has recently (June 2026) adopted opinions on the harmonised classification of TFA, sodium trifluoroacetate and other inorganic salts of trifluoroacetate, recommending classifications for developmental toxicity (Repr. 1B, H360Df). These will be considered by HSE in accordance with the GB CLP Article 37 procedure. 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 (2023e) 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 (2019b) 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, 2015c), 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, 2019c). 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 (2023e) 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, fertility	Repro. 1B in EU CLP
	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	Repro 1B proposed under GB CLP
	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 or consulted on a GB CLP opinion and/or technical report in which the stated mandatory classification and labelling are proposed.

Under assessment (EU CLP) = Currently under assessment for harmonised classification in the EU. HSE has yet to assess the substance for a mandatory classification and labelling proposal under GB CLP.

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 repeated-dose studies of PFAS in laboratory animals 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										
Total 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										
Total 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 have not been demonstrated to 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 would meet the toxicity criterion.

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. As noted in, for example, section 3.1.1, PFAS are often encountered in the environment as poorly characterised complex mixtures of PFAAs. 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, 2023e), 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 have 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.

For P, M and T, the number of other regulatory agencies reaching a conclusion for each carbon chain length is reported by the Agency in the relevant sections. These assessments are not necessarily completely independent and may use the same data sources. The number of assessments is not an indicator of reliability/confidence in a conclusion for a particular chain length – each assessment will have considered the reliability of the data when reaching their conclusion. 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 as

that is the remit of the Environment Agency. PFAS monitoring data were not available from either the Scottish Environmental Protection Agency (SEPA) or Natural Resources Wales (NRW).

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). As these studies have not been used to provide key endpoint data to compare with regulatory thresholds to determine whether a PFAA is P, M or T they have not been formally assessed for reliability (e.g., using a Klimisch score). Instead, their relevance to the assessment has been considered, and any uncertainties noted by the Agency.

2.4.2 Physicochemical properties

The physicochemical properties that can be used in environmental hazard screening to provide an indication of likely environmental fate, including bioaccumulation and mobility, 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 log K_{OW} > 2
n-octanol water partition co-efficient	log K_{OW}	unitless	> 2	High potential for bioaccumulation in air breathing organisms when log 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 fearing) 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 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 (2023e) 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 to whether they can be used as lines of evidence in the hazard assessment.

For this assessment, the Agency has considered K_{OC}, K_d, vapour pressure and water solubility data within the weight-of-evidence to assess potential mobility. While experimental and predicted physicochemical data have been gathered from OECD and other regulatory reports, these are used with caution in light of the uncertainty of these data.

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 too low to measure 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 (Table 2.7). 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, 2015h); 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, 2015f, 2015g). ECHA has concluded that PFHxA and PFHpA are vP (ECHA, 2019a, 2022d).

- 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, 2015b, 2015d, 2015e); 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, 2015c, 2015e);

and ECHA (whilst the UK was a member) has concluded that PFBS (C4) is vP (ECHA, 2019c).

- 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, 2023c) 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 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, 2026). 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?

Substances may have the potential to move through and between environmental compartments and breach natural barriers; in the case of the PMT concept, mobility aims to describe the particular concern associated with the movement of chemicals through the terrestrial environment to water bodies (Defra, 2025). Intrinsic properties of a substance that can lead to environmental mobility 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 and an adsorption control within an inherent biodegradability test, or predictions can be made. 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 and to focus on those chemicals most likely to sorb to sediment, a log K_{OC} or log K_{OW} of ≥ 3 is used as a trigger value for sediment effects assessment (ECHA, 2017b). ECHA (2017c) 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 (2022a).

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 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/sediment 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 simple way to determine if the use of K_{OC} is appropriate to determine the potential for mobility is if K_d is proportional to the organic carbon content.

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, 2022d). 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 (2015f).
- Ultra-short chain: No regulatory assessments have considered mobility for ultra-short chain PFCAs.

In addition, HFPO-DA (GenX®) a PFCA precursor was identified as vM by ECHA (2019b) whilst the UK was still a member.

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 Long Range Transport Potential (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, 2019c). NICNAS identified PFBS as likely mobile (NICNAS, 2015c). 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 ≤ 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, 2023c). 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 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 English 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. In addition, 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, indicating that following use, these compounds are able to move through soils to reach the groundwater.

- Short chain PFCAs: All four of the short chain PFCAs monitored for have been detected in English 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. In addition, the case studies in Section 3.1.10 and Annex E.9 show that short chain PFCAs were found in groundwater samples from 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 routinely 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). The Environment Agency detected TFA in 43 of 49 groundwater samples from sites across England representing a range of geologies when testing a newly validated analytical method in 2024 (EA, 2026b).

- Long chain PFSAs: Seven of the eight long chain PFSAs monitored for have been detected in English 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. In addition, the case studies in Section 3.1.10 and Annex E.9 show that long chain PFSAs were found in groundwater samples from Angus Fire (C6-8), Duxford airfield (C6 and C8) and RAF St Athan (PFOS), sites connected to PFAS-containing FFF contamination, indicating that following use, these compounds are able to move through soils to reach the groundwater.

- Short chain PFSAs: Both PFBS and PFPeS have been found in English 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. In addition, the case studies in Section 3.1.10 and Annex E.9 show that short chain PFSAs were found in groundwater samples from

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 from England between July 2021 and November 2024.

PFAA Group	Substance	Minimum concentration (µg/L)	Maximum concentration (µg/L)	Total number of samples	Percentage of samples greater than LOD (%)
Long chain PFCAs	PFODA (C18)	<LOD	0.013	3752	0.32
	PFHxDA (C16)	<LOD	0.005	1827	0.16
	PFTeDA (C14)	<LOD	0.0098	3063	0.29
	PFTrDA (C13)	<LOD	0.00328	3327	0.03
	PFDoDA (C12)	<LOD	0.022	4540	0.09
	PFUnDA (C11)	<LOD	0.072	4552	0.22
	PFDA (C10)	<LOD	0.0052	4545	0.31
	PFNA (C9)	<LOD	0.02	4573	0.83
	PFOA (C8)	<LOD	0.48	4664	19.58
Short chain PFCAs	PFHpA (C7)	<LOD	0.15	4569	7.99
	PFHxA (C6)	<LOD	0.21	4565	15.55
	PFPeA (C5)	<LOD	0.24	4518	10.85
	PFBA (C4)	<LOD	0.96	4486	13.42
Long chain PFSAs	PFTrDS (C13)	<LOD	0.0047	536	2.05
	PFDoDS (C12)	<LOD	0.0069	4258	0.02
	PFUnDS (C11)	<LOD	<LOD	4317	0.00

PFAA Group	Substance	Minimum concentration (µg/L)	Maximum concentration (µg/L)	Total number of samples	Percentage of samples greater than LOD (%)
	PFDS (C10)	<LOD	0.0016	4366	0.09
	PFNS (C9)	<LOD	0.00101	4332	0.05
	PFOS (C8)	<LOD	0.86	3243	22.20
	PFHpS (C7)	<LOD	0.02	4513	2.19
	PFHxS (C6)	<LOD	0.15	3963	21.65
Short chain PFSAs	PFPeS (C5)	<LOD	0.038	4389	6.08
	PFBS (C4)	<LOD	0.038	4500	14.98

<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.

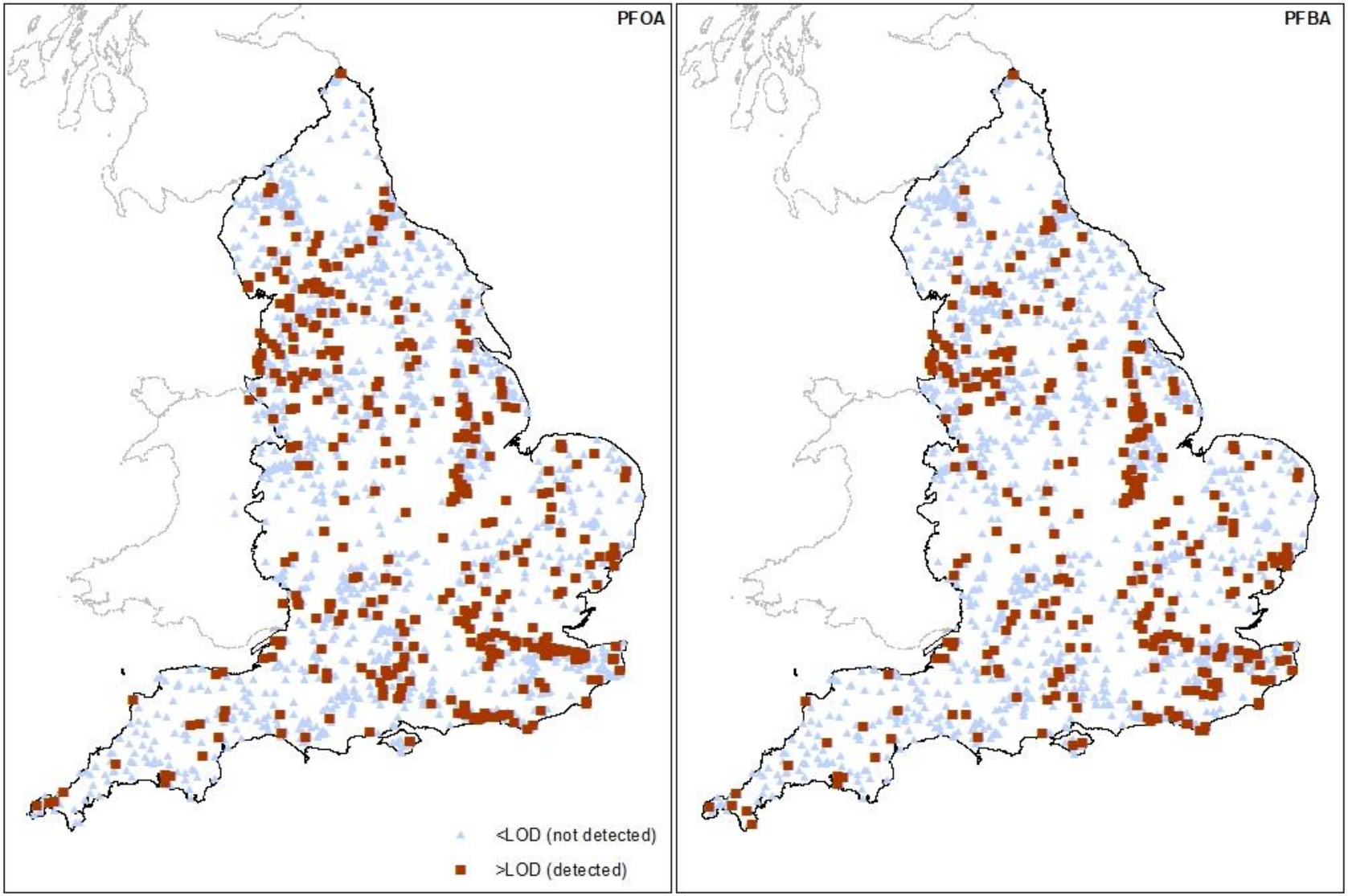
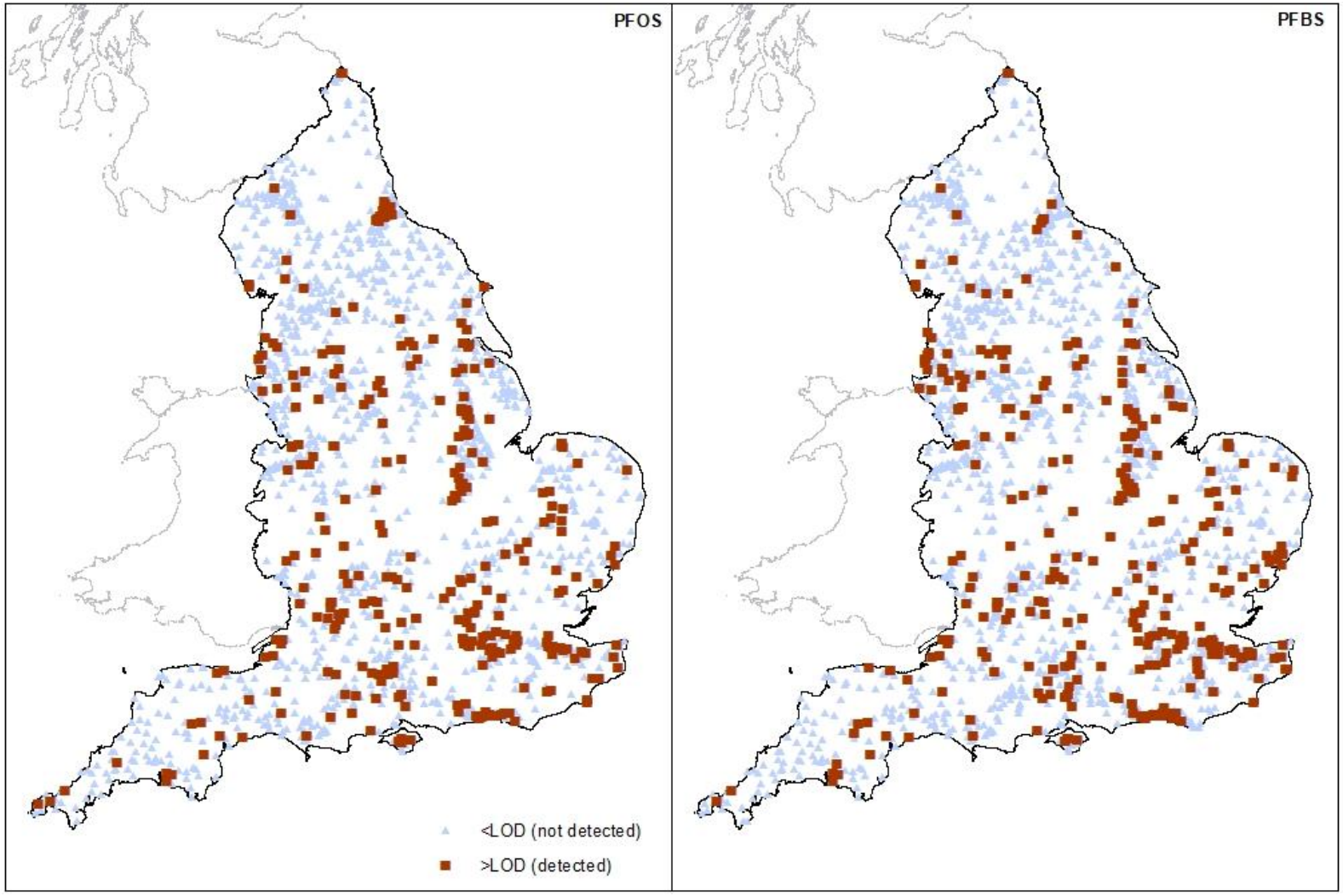


Figure 2.3: Maximum concentrations of PFOS and PFBS measured in Environment Agency groundwater samples between July 2021 and November 2024. Data were available for England only.



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 and intermediates, 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). Bold values highlight the highest concentration between the influent and effluent.

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**

PFAA Group	PFAA	LOD	Henriksdal		Gässlösa		Umeå	
			Influent	Effluent	Influent	Effluent	Influent	Effluent
Long chain PFSAs	PFOS (C8)	0.7	1.1	1	0.9	**1.5**	**1.7**	1.5
	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 (including, but not limited to PFAAs) 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 show variability as to whether concentrations of the PFAAs were higher in the influent or the effluent. Similar pictures were seen in October 2021, February 2022 and May 2022. The authors noted that where higher concentrations were present in the effluents than the influents, it indicated that biotransformation of PFAA precursors to the terminal arrowheads occurred during biological treatment. Overall, the study found that influent wastewater was generally dominated by PFPeA (23%), followed by PFHxS (14%), while effluent wastewater was dominated by PFBS (26%) and PFOS (21%). Finally, Moneta *et al.* (2023) also identified 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). Bold values highlight the highest concentration between the influent and effluent.

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 routinely monitor ultra-short chain PFCAs and PFSAs, but TFA has been detected in English groundwater samples and the presence of both ultra-short chain PFCAs and PFSAs in groundwaters has been demonstrated elsewhere (Frank *et al.*, 2002; Pickard *et al.*, 2020). These data demonstrate that PFAAs can move between environmental compartments 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 effects in laboratory animals, human health effects and/or ecotoxicological effects. For context, Table E.1 in Annex E sets out the criteria by which each regulatory authority or jurisdiction determines if a substance is considered to be toxic or not. In some cases, these criteria are not equivalent to the criteria for assigning toxicity under Annex 13 of UK REACH.

More national / international regulatory assessments (some of which include both human health and ecotoxicological effects) 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, 2015h). 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, 2015g) and concluded that C4 to C6 PFCAs are not toxic (NICNAS, 2015f). 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, 2022d), 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, the EU's Risk Assessment Committee has recently (June 2026) adopted an opinion recommending that TFA (C2), sodium trifluoroacetate and other

inorganic salts of trifluoroacetic acid receive a harmonised classification that would meet the toxicity criterion; HSE will consider their mandatory classification in due course under the GB CLP Article 37 process.

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, 2015d), but found uncertain toxicity for PFHxS (C6) and PFHpS (C7) (NICNAS, 2015e). 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 (2015c, 2015e) 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, 2019c).

- 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, 2015a, 2015d).

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. 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).

2.4.5.4 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, 2023e; 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 (2023e) 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

In Section 1.2.4 the Agency 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.

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 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.
Mobility	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.
Toxicity	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. 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 complicates 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 to understand these properties, 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 hindered 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 where 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. In the current version of the analysis, the Agency first estimate the quantities in GB using a top-down approach. These quantities are then triangulated and refined using a bottom-up approach (detailed in the SEA section and SEA Annex G). The top-approach estimates are 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: Estimates 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 6.4.2.10), the Agency estimates **50 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.

Although these sales figures are extrapolated from EU estimates, during the consultation period, the Agency has received information on domestic market sales that are broadly consistent with these sales figures. For the purpose of the socioeconomic analysis in Section 6, each sector is sub-divided into subpopulations reflecting facility type. This segmentation is essential to the bottom-up cost and emission reduction analysis because within-sector variability could be large. As a result of segmentation, the total sales figures may be different from the estimates here. To further consult on these sales figures, a breakdown of sales by sector and subpopulation (including use tonnage per site) is included in Annex G.

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.

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

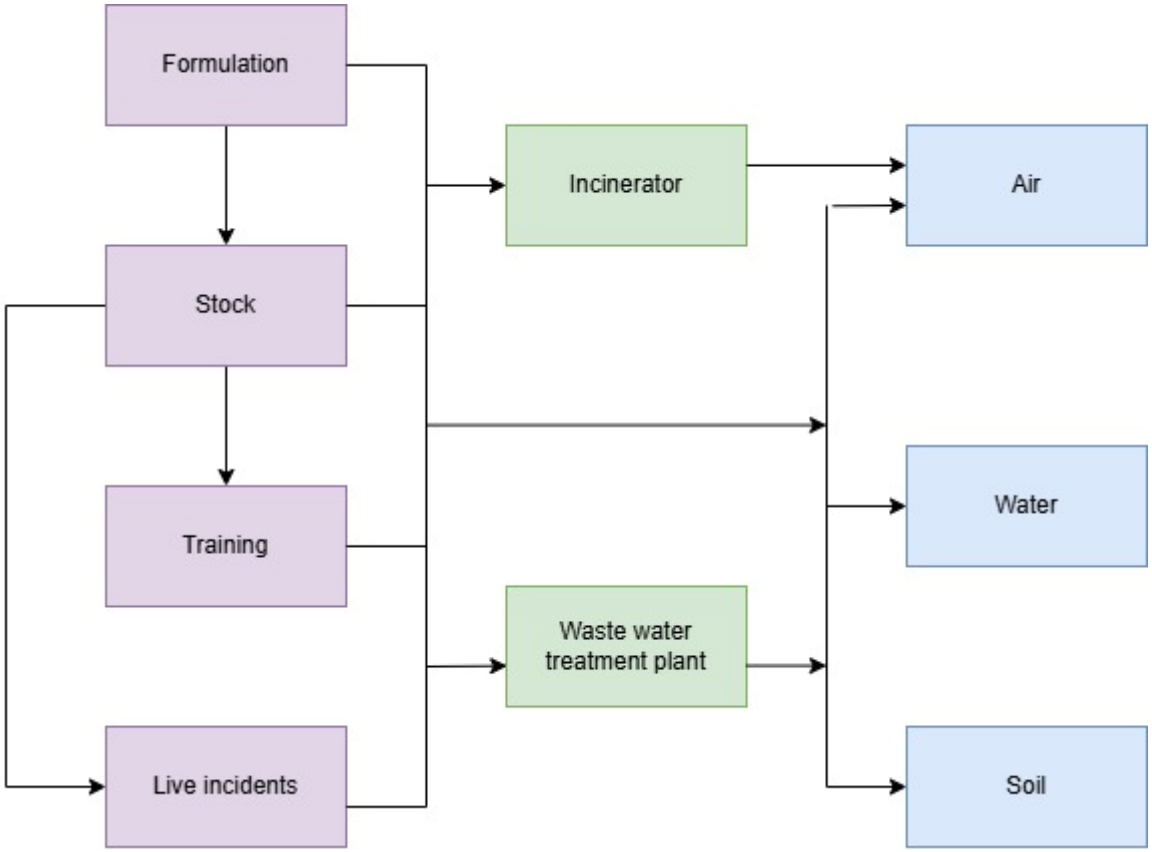
3.1.3 Life cycle stages and releases

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 (stock)
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. Direct and indirect emissions of PFAS to air, water and soil will result in environmental exposure of these compartments, and the potential for humans to be exposed via air or drinking water or in food after uptake and accumulation by plants or animals.

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 (2023a) 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, 2021b).

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, 2023e). 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 (2023a) 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 (2023a) 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. Whether 97% of containment is possible in practice is dependent on the design of the training area, so containment could be lower and releases directly to the environment higher. This is also dependent on factors such as the weather, as spread of foam could be higher in more windy conditions.

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, although these will not impact the PFAS levels in the water. 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). The amount of containment possible differs by site and the location of the fire within the site. Some sites, such as those regulated under the COMAH framework, are required to have engineered containment in place for firewater. However, without pre-installed systems, containment is more

challenging and relies on temporary methods such as drain covers and improvised barriers. Therefore, the worst case is that there is no containment on any site. For live incidents, ECHA (2023a) 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 (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, on each specific site. ECHA (2023a) 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. 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 water miscible polar solvent or alcohol fires, which would otherwise absorb into the foam and destroy the bubble structure. 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 (Section 3.1.10.5), 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. However, even at COMAH sites or airports containment may only be partial, depending on the size of the incident and the amount of firewater produced. 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.

According to the NFCC during an incident, once fire water run-off has been contained, responsibility transfers to the owner / operator of the site where the incident occurred (Public Consultation, 2026).

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. While the foam / water is generally contained

there is no evidence that any PFAS foams used for training was subsequently collected and the PFAS destroyed.

A number of foam manufacturers supply fluorine-free training foams, for example Trainer E-lite™ from Fomtec (Fomtec, 2025) or Trainol™ 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 run-off 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 many 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). There has been no other information available regarding the use of PFAS in routine testing of equipment.

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. 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. The fire at Buncefield did lead to environmental release of a large amount of PFAS, and more information on this can be found in the Buncefield case study (Section 3.1.10.5).

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, 2023d). 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 majority of gas platforms in the southern end of the North Sea are unmanned. 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 run-off and clean-up

after incidents is particularly low. Counter to this, stakeholders responding to the consultation highlight the risks associated with a premature transition in this sector (Section 5.3.4.4).

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), refer to Section 3.1.10.2. 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 run-off (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, 2023e) (ECHA, 2023a). 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, 2023a; 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) and Liverpool (Public Consultation, 2026). 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 permit reviews and monitoring required 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, 2023a).

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 (HTI) (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 F3s 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 some 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 50 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 are 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 currently 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, 2023e).

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, 2024d) 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, 2023a; 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, 2023a; 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, 2023b). 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 high temperature incinerators (HTI) 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. Veolia, the operator of a hazardous waste incinerator in GB, have developed a patented technology (Veolia, 2025) which breaks down up to 99.9999% of several targeted PFAS using a catalyst which is added during the thermal treatment to accelerate the degradation. The company is planning to install this system in the Ellesmere Port plant (WMW, 2025). 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, 2024a). 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 HTI with currently only two in operation capable of running at the requisite temperatures to destroy PFAS (Environment Agency, 2025) with a third due to become operational in 2027(OEP, 2026). The operational sites are permitted installations regulated by the Environment Agency and located in Southampton and Ellesmere Port, the new site is based in Avonmouth. All the 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 operational HTIs to ensure that a minimum secondary combustion chamber of 1,100 °C is maintained when burning waste firefighting foams. The Environment Agency issued a permit for the Avonmouth site (EPR/LP3505Q/V002), it will maintain temperatures exceeding 1,100 °C with a residence time of at least 2 seconds. In the call for evidence response Fuels Industry UK expressed concerns regarding the UK's limited HTI 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). The permitted capacities of the three HTI are shown in Table 3.3 and show that in 2024 there was a theoretical capacity of approximately 47,000 tonnes.

Table 3.3 : Hazardous waste incinerator capacity and receipts

Facility	Permitted capacity tonnes per year	Waste receipts in 2024 tonnes per year (EA, 2026a)
Veolia: Ellesmere Port	100,000	67,637
Tradebe: Southampton	48,000	33,241
Grundons: Avonmouth	20,000	Not operational until 2027

A report commissioned by the Office of Environmental Protection (OEP) aimed to assess whether there is sufficient current and future capacity to safely manage hazardous and POPs wastes (OEP, 2026). The report concluded that if all the current waste containing POPs above the relevant waste limit (and not just those POPs which are PFAS and require this type of disposal) require high temperature incineration there will be insufficient capacity in the UK. However, the Agency understands that much of the newer POPs wastes, particularly those in waste plastic can be incinerated in municipal waste incinerators [personal communication June 2026] so HTI is not necessary. Therefore, on the evidence available, the Agency considers that sufficient HTI capacity should be available should a restriction be implemented. However, it is appreciated that there could be demand peaks which could necessitate storage and delay in incineration, as well as planned maintenance, and the possible need for prioritisation of this capacity to deal with any PFOA or PFOS legacy waste that may be found.

Some questions remain regarding the efficacy of HTI 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, 2024a).

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, 2024e). 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 is 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). This leaves some gaps in the legislative landscape where the release of PFAS into the environment should be prevented, but it is not possible in the absence of additional controls at their end of life and use.

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 concentrate 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). The potential for environmental exposure is primarily focussed on the proven contamination at localised hotspots, for example in groundwater, surface water or drinking water close to contamination sources. However, the persistence and mobility of PFAS means that high local exposures will lead to more widespread contamination over longer time periods as the PFAS disperse. Conclusions from each case study 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, 2022b). 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 in local soils.

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 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 (non-GB) 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 (studies listed in 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 are consistent in the identity of PFAS that 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.

Under the UN Stockholm Convention on Persistent Organic Pollutants (POPs), several long chain PFAAs have already been concluded to meet the criteria to be considered as POPs, i.e. PFCA: PFOA, C9 - C21 PFCAs; PFSA: PFOS, PFHxS. The POPs criteria include 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 SVHCs 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 with continued emission 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 either that no threshold exists or that it is not possible to establish an acceptable concentration, and so exposure needs to be minimised to be as low as possible.

PFCAs and PFSAs tend to remain in the human body for a long-time following exposure, with continued exposure expected to lead to increased body burdens. The reported toxicological and health effects resulting from PFAS exposure include carcinogenicity (assumed to be non-genotoxic), developmental toxicity (harm to the developing child) and adverse effects in organs such as the liver or to the immune system. As demonstrated by the availability of health-based guidance values for a small number of PFAS (summarised in (COT, 2022b)), it could be possible to derive meaningful thresholds of effect for those PFAS in firefighting foams or for their transformation products where the data are sufficient to do so. However, these data are not available for most PFAS.

In addition, PFAS-containing FFF are complex mixtures whose composition is not publicly available, and they may degrade to a combination of PFCAs and PFSAs via a range of intermediates with different degrees of persistence. It is therefore impossible to establish effects-based thresholds accounting for all relevant PFAS and their potential mixture

effects. In any case, 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 and any emissions indicate a risk that is not adequately controlled. The scale of the risk can be estimated based on the total emissions to the environment, and the restriction aims to manage these risks by minimising emissions.

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 evidence of 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 in GB to be ~50 tonnes. Environmental exposure modelling has not been conducted by the Agency due to the use patterns and 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. In particular, the potential for contamination of groundwaters, surface waters and drinking waters following use of PFAS containing FFF has been demonstrated in a series of GB case studies. 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 from use and end of life stages where, as established above, these substances persist and are able to contaminate ground and surface water.
- 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, their disposal may not be fully controlled under Hazardous Waste Regulations (The Hazardous Waste (England and Wales) Regulations 2005), and PFAS-containing foam wastes could potentially result in releases to sewer or landfill.
- 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 and aid practical considerations around monitorability and enforceability.

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 concentrate is unknown due to producers maintaining a high level of confidentiality for their proprietary foam formulations. Whilst current F3s 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 (2021b) 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 stabilisers, bactericides, corrosion inhibitors, and solvents and result in a highly stable homogenous foam blanket. They may be used with fresh or seawater, however, they must be properly aspirated (Jahura *et al.*, 2024; National Foam; Wood, 2020).

5.1.2 Properties and Performance of F3s

Unlike the fluorosurfactant foams, F3 do not form an aqueous film to extinguish fires. This is the most important functional difference between the F3 and PFAS-containing foams. 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 interface of the water miscible/polar liquid fuel and the foam to prevent destruction of the foam bubble structure by fuel absorption. (F3 with alcohol resistant properties tend to be referred to as alcohol-resistant synthetic fluorine-free foams (AR SFFF)).
- 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/ft2) or litres per minute per square foot (L/min/ft2).

*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 (National Foam, undated):

- Low Expansion Foam: Expansion ratio ≥ 2:1 ≤ 20:1. Designed for controlling flammable liquid (Class B) fires.
- Medium Expansion Foam: Expansion ratio ≥ 20:1 ≤ 200:1. Used to suppress the vapourisation of hazardous chemicals, e.g. highly water reactive chemicals and low boiling organics.
- High Expansion Foam: Expansion ratio ≥ 200:1. Designed for confined space firefighting e.g. aircraft hangers, basements, and on-board ships.

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 safety data sheets (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, 2023e).

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 identified by stakeholders on the GB market (this is not an exhaustive list), 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 (2023e), 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

[$] Classifications currently differ between EU and GB MCLs, but the opinion of the GB CLP Agency proposes to update the entry to include Acute Tox. 3 for inhalation (H331) within the GB MCL to align with the EU.

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, 2023e).

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 biochemical oxygen demand (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 chemical oxygen demand (COD).

IPEN (2018) highlights that all PFAS-containing and F3s 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). The components of F3 foams (many of which are also present in PFAS-containing foams) would therefore not be expected to meet the P or vP criteria and so would not be considered to have PMT or vPvM-type properties.

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 the 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). F3 foams would therefore not fulfil the P or vP criteria and so would not be considered to have PMT or vPvM-type properties. An exception to this 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 human health hazard classifications that are broadly similar to, or less severe than, those of the FFF.

The ecotoxicological information for components of F3 products listed on the SDS indicates concerns for aquatic environmental release with several labelled as harmful and others lacking information. However, these components may also be present in PFAS-containing foams. None of the F3 formulations in Table 5.3 meet the criteria for PBT or vPvB, although ReHealing RF1 1% is listed as having insufficient data for assessment. None of the components, and therefore none of the formulations, are expected to have PMT or vPvM-type properties and so do not have the same concerns around the potential for long-term exposure that PFAS do.

It is emphasised that the conclusions on risks are based on the information provided in the SDS and not all human health or environmental hazard endpoints (e.g. endocrine disrupting effects) have been assessed in detail for each component by the foam manufacturers. This follows the same approach as ECHA (ECHA, 2023e).

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, 2023e).

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.

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.

Both Wilson Consulting (Public Consultation, 2026) and the FIA (Public Consultation, 2026) have highlighted a perceived “better than reality” performance issue for F3s because current international approval standards (e.g., EN1568-3, ISO7203-1, UL162, Lastfire, FM 5130, IMO) utilise heptane as the test fuel rather than gasoline. Heptane “is rarely if ever stored or used in bulk, particularly offshore, by defence, aviation, shipping, other transportation etc.” Gasoline and to a lesser extent kerosene (Jet A1 aviation fuel) contain volatile aromatic components that attack and break down the fluorine free foam blanket and can then be subject to reignition, whereas these are absent in heptane. Therefore, in real world scenarios with gasoline or aviation fuel that may be more challenging than the standard test conditions, these respondents raise the concern that F3s may not be suppress the fires effectively.

Conversely, fire and rescue services have suggested that aviation and kerosene fires do not pose any particular problem for F3 (Stakeholder Engagement, FRS, 2025). Therefore, it may be that – as with many of the concerns relating to F3 – these issues can be overcome with training and appropriate deployment techniques.

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 viscosity of non-Newtonian F3s is exacerbated at lower temperatures making under proportioning a potential problem where F3 agents may be too stiff to proportion accurately, potentially delivering incomplete mixing, where globules of foam sink to the bottom of the pipe (globularisation). Minimum F3 use temperatures are often around +2°C (Wilson, M., Public consultation, Feb 2026, Oil Technics, Public consultation, Feb 2026). Stakeholder engagement with FRS reported this can be counteracted with storage of foam

in Intermediate Bulk Containers (IBCs) of 1000 L capacity which can be insulated and stored in a heated garage if needed, prior to use (Stakeholder Engagement with FRS, Dec 2025). The use of IBCs also provides the advantage that if used previously with PFAS foams, rather than integrated tanks, decontamination is far less of a challenge (Stakeholder Engagement, FRS, Nov 2025). It is expected the GB climate would make foam concentrates more susceptible to extremes of cold than heat. Consideration and mitigation steps have been taken by FRS to overcome this. No information has been received by the Agency to confirm if this strategy is also used or practicable in challenging conditions such as offshore and marine settings.

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 (2022a) 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, 2023a). 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 or public consultation, 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, 2023a).

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.

For the public consultation for this restriction process, designers of the High Speed Two (HS2) railway system under construction in GB provided information on fire safety they are considering during the works. They state that any fixed installations are water or gaseous suppression systems (HS2, Public consultation, Feb 2026). Portable fire extinguishers will be F3 for any Class B fires. They go on to state that if needed, F3 foam in a fixed system is a viable alternative as long as it performs to the required standard and overall, there were no concerns.

Information provided during the public consultation by one respondent considered a number of differing fire supression methods for transition away from AFFFs. It was concluded the primary replacement for AFFF would be F3s but water mist and gas suppression may be suitable for some vehicle types. As with all transitions, compatibility with systems, testing viscosity and nozzle compatibility would be required in areas with increased fire risk such as engines, power packs or cooling systems where previously AFFF was used (Public consultation, Feb 2026). Specific formulation of the F3s may be required where fuel is present, but this is predominantly based on preliminary testing data and not live fire incidents (Public consultation, Feb 2026).

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, 2022b). Whilst this concern is not limited to rail transportation, the comment was made in relation to numerous settings, including rail transportation. Section 5.3.2 of this background document further discusses foam storage.

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, 2022b).

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, 2023d).

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 when transporting hazardous materials albeit at lesser volumes and generally require response from 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, however information provided by stakeholders in the Public consultation does not raise specific concerns for efficacy in this sector as a whole (RSSB, HS2, Public consultation, Feb 2026).

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, 2022b).

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 (EVs) are powered using lithium-ion batteries, which, if a fire arises, may require the use of foam-based firefighting to extinguish. The difficulties of tackling a lithium-ion battery fire are that the energy they store is released as heat, known as thermal runaway. Cooling the battery is challenging as they are contained in casing for protection

and getting water to penetrate is difficult. The batteries also release organic chemicals when damaged, including flammable toxic gases such as carbon monoxide and hydrogen cyanide (Essex FRS, 2023).

During the stakeholder engagement meeting with the ORR (ORR, June 2024) firefighting EV fires 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. Tactics for firefighting EV fires were discussed in an article in the National Fire Protection Association journal (NFPA, 2025). The article describes an incidence in the US of a hybrid Sport Utility Vehicle (SUV) fire at a charging station that spread to other charging EVs. The fire was “quickly and effectively contained using a hose line and foam”. Other cases of EV fires and firefighting approaches were discussed. EV fires require considerably greater volumes of water than standard vehicle fires, (up to 30,000 L compared to 1-2000 L for a typical internal combustion engine car fire) therefore alternative methods of extinguishment are being considered (Essex FRS, July 2023). The approach using water also requires capture of the contaminated fire water owing to the release of toxic substances from the battery and EV fires in remote areas may require more water than the capacity of attending appliances. The Agency assumes that the F3 foam would be used for any training or live fire events for FRS that have transitioned, indeed no specific requirements for PFAS foam for EV fires has been reported, and therefore EV fires would not likely cause a barrier to transition.

The FPA recommend open air charging where practicable and a sprinkler system for enclosed car parks with EV charging facilities {FPA, 2023 #5625. This is not expected to extinguish the fire, but control the spread of the fire. 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, 2023d). 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, 2023d). 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, linking 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) however this is data from a considerable time ago and transition to F3s is likely to have had a much greater uptake as confidence in products grows and technical developments and regulatory pressures influence the market. 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. Comments received during the call for evidence and public consultation come from individual sites or companies with multiple COMAH sites based in GB and does not make up the whole of the use sector. It is unclear what percentage of the sites have transitioned, or what percentage of the F3 market supplies the chemical and petrochemical sector from the information received. 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). It is unclear if technical advances in foams that have already made it to market would now be suitable for the remaining 20% but the Agency is aware that F3 foam development is rapidly addressing specialised uses and requirements (Stakeholder engagement, FRS, 2025, Stakeholder engagement, Equinor, 2025).

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. Some sites house storage tanks 90 m in

diameter. 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.

The concept and logistics of how mutual aid works in practice were discussed in talks with FRS (Nov and Dec 2025). COMAH sites have regular meetings with FRS in the area. In

some areas a single foam concentrate is held across the whole response area of the individual FRS, at multiple sites, strategically placed to allow a quick response if needed. There are also communications and plans between neighbouring fire brigades who work together to exchange knowledge and support. Where COMAH sites sign up to a mutual aid agreement, this is in coordination with the FRS but not legally enforced by them. The mutual aid agreements between COMAH sites are funded collaboratively. One FRS stated that all of the sites they oversee work off a standard application rate for all foam of 10.4 L/min which exceeds application rates of a number of performance standards and is calculated to include a safety factor. The FRSs spoken to during stakeholder engagement covered multiple COMAH sites in the response area and had transitioned to F3 foam.

If sites hold PFAS foam, the FRS responding may choose to not use this, instead using their own supply to avoid contamination of equipment. The FRS has a record of the foam stocks held in their response area and can bring emergency stock to site. In areas with a large number of COMAH sites, there is the option to use foam stock from other facilities, neighbouring FRS as well as UK distributors of foam such as Angus Fire, Hawkes and Terburg who also hold 40 000 L of foam stock each. There is also national resilience coordination where support of additional foam, equipment and personnel can be requested if required in case of major emergencies. In cases of a national emergency, any foam that could be offered would be used (Stakeholder engagement with FRS, Nov and Dec 2025).

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.

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, 2023a).

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, 2023d).

5.3.4.2.7 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.

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.

5.3.4.2.8 Suppression 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. Fire and Rescue Services that cover multiple sites have also transitioned to F3 alternatives and have well considered stocks of foam and response plans in place should a fire break out, plus further contingency plans at a National level.

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, 2023d). 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 challenges 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 (Call for evidence, CNOOC). CNOOC stated that there is currently no 1% F3 Concentrate on the market and, 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. This extra storage space is not always available on oil platforms. For example, the CNOOC Scott platform utilises a central foam storage skid of 4000 litre capacity. Changing the induction rate to 3% would require an increase in capacity by 8000 litres with the corresponding increase in weight of approximately 8.25 tonnes, not including the additional weight of the larger storage tank. This also does not include additional storage capacity for the extra discharge duration required to assure control and extinguishment (CNOOC, Public consultation, Feb 2026).

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). The foam enhanced deluge systems currently installed in the UK sector use one of three methods of introducing and metering foam concentrate into the water stream. These are fixed rate proportioners, Balanced Pressure proportioners or Turbine pump units. These units are also not readily adjustable to deliver an increased rate of foam concentrate and this would, in the majority of cases, require the

replacement of the proportioning equipment. Depending on the concentrate delivery flow rate required due to the higher proportioning rate there may also be a requirement to increase pipework and control valve size. The time required to replace proportioning equipment and foam concentrate delivery pipework would leave the platform without effective fire protection for the duration of the modification work which would be unacceptable, resulting in a requirement to shut down the platform for the change out leading to massive financial losses (CNOOC, Public consultation, Feb 2026).

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). OEUK stated that standard UL162 is used for the UK Continental Shelf and to its knowledge *"no alternative AFFF LF C6 foam* [presumed Low Freeze Aqueous Film-Forming Foam] *has yet been accredited to the existing UL162 standard. Similarly, fluorine-free foams, referred to as F3 LF to our knowledge, have not yet passed low temperature, sea water UL162 accreditation"* (OEUK, Public Consultation, 2026).

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).

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). They 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, 2023e).

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, 2022a). 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, 2022a), 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, 2023e).

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, 2023d) 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, 2023d) 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.

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 (incurring significant financial costs) 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 are still in use in maritime vessels. 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).

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.

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.

The Maritime & Coastguard Agency (MCA) (Public Consultation, 2026) highlighted enforcement of any restriction as a serious consideration: "*Neither the Environment Agency (EA) or devolved equivalents, have the powers (or desire) to board and inspect ships. Furthermore, Port State Control inspections undertaken by the MCA on foreign ships in UK ports, can only apply the Merchant Shipping Regulations which apply the IMO regulations (including the Safety of Life at Sea (SOLAS) convention, which prescribes fire safety for ships (Chapter II-2). As such, there will need to be alterations to either the role of the EA and the devolved equivalents or the powers of MCA inspectors to allow for effective enforcement of any ban on PFAS containing firefighting foams on non-UK ships in UK waters, outside of a maritime ban through IMO."* However, if the ban on PFAS in firefighting foams was adopted by the IMO, the MCA would have enforcement powers for this. Any ban on PFAS in firefighting foams agreed by the IMO and included in SOLAS Chapter II-2 would automatically be adopted into UK law by the ambulatory reference provision contained within the Merchant Shipping (Fire Protection) Regulations 2023. The IMO develops regulations for ships which travel internationally, which are then enforced by individual states. As many ships will travel to the UK from overseas there is a significant risk that these ships will be carrying firefighting foams containing PFAS, unless the IMO also introduces a ban. It is anticipated that the EU will submit a paper to the IMO Ship Safety and Equipment (SSE) sub-committee session 12 scheduled for March 2026 to

propose a ban on PFAS in ships' firefighting foams. This is likely to propose a ban on PFAS foams in new ships from 2030 and existing ships from 2035.

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, 2023a). 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, 2023a).

The MCA provided additional information in its response to the Public Consultation (2026). Foam firefighting systems are an internationally approved firefighting system on ships' cargo spaces (including spaces for the carriage of vehicles on cargo ships) and in machinery spaces. Further to that a deck foam firefighting system is mandated for chemical tankers (including oil and LNG tankers) and as such are found on all chemical tankers. Portable foam fire extinguishers are also required in machinery spaces and when certain categories of dangerous goods are carried. Concerns previously shared during stakeholder engagement and the call for evidence with regard to transition to F3 in the marine sector were also echoed:

- Whether there is evidence that F3 can match the effectiveness of PFAS foams on large Class B fires, including tanker-deck scenarios?
- The need for validated test methods to verify PFAS-free foams prior to any ban.
- The readiness of global supply chains to support a transition to F3, and whether a phased maritime implementation would ease pressures?
- The feasibility of replacing PFAS foams without full system cleaning, given the high cost of decontamination, and whether such an approach could still deliver acceptable environmental benefits?
- The capacity of disposal facilities to handle PFAS foam waste, and whether a delayed phase-out would help distribute disposal demand over time?

The FIA, Oil Technics and Wilson Consulting (Public Consultation, 2026) all provided a comprehensive list of concerns regarding F3 suitability for the marine sector, including issues such as: seawater compatibility, temperature extremes, ability to be deployed in high wind situations, higher application rates and concentrate storage issues, higher viscosity and sheer-thinning issues causing proportioning and application issues, compatibility with varying different flammable liquid cargoes, and mutual aid flexibility.

Eurofeu (Public Consultation, 2026) states that most deck-foam systems on civilian vessels currently use Newtonian (low-viscosity) foam concentrates. Higher-viscosity, non-Newtonian (or shear-thinning) concentrates are generally limited to chemical tankers. To be used onboard, all foam concentrates must be listed under IMO / Marine Equipment Directive (MED) requirements. At present, F3 foams that meet IMO/MED standards are

exclusively non-Newtonian. Transitioning away from a Newtonian to a non-Newtonian product requires significant technical changes to the on-board fire protection system.

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 low potential for retention of run-off, 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).

Eurofeu (Public Consultation, 2026) states that converting existing onboard foam systems to more viscous foams with the proper Class societies product approvals [assumed to mean more viscous foams needing to meet IMO product approval] will not be possible within a short 3-years-transition period. Onboard fire extinguishing systems are deeply integrated with the vessel's construction and it is typically very difficult to modify the system to fit to the requirements of F3s. The complexity of such a task leads to extended dock times which has the potential to exceed the foreseen transition time. Eurofeu recommends extending the transition period to >5 years.

The UK Chamber of Shipping (Public Consultation, 2026) submitted a public consultation response in conjunction with the British Rig Owners Association (BROA). BROA operates as a specialist association within the Chamber, representing offshore energy vessels and rig operators active across the UK Continental Shelf (Public Consultation, 2026). The UK Chamber of Shipping claimed that F3 suitability across the full range of maritime environments is not yet fully demonstrated. As well as needing to be reliably effective in sub-zero temperatures, saltwater conditions and confined spaces, many F3 products require significant modification of proportioning equipment, delivery systems and certification processes to achieve equivalent Class B performance. Transition typically involves engineering redesign, material-compatibility assessment and crew retraining. The UK Chamber of Shipping recommends aligning the maritime transition period with the 10-year window proposed for offshore, recognising the engineering, dry-dock scheduling and system-modification constraints faced by vessels.

ECHA originally 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."* Subsequently, ECHA recommended a 5-year transitional period for the marine sector, following further stakeholder engagement (ECHA, 2023d). However, in October 2025, the EU adopted a ten-year transition period for civilian ships with firefighting foams placed on board before 23 October 2025 within Commission Regulation (EU) 2025/1988 (European Commission, 2025). This was in consideration of the requirement for modifications to the foam systems of civil ships already fitted with PFAS-containing foams, which can only be carried out during drydock.

The FIA, Oil Technics and Wilson Consulting (Public Consultation, 2026) all supported extending the proposed transition period for the marine sector to 10-years, in line with the proposal for the off-shore sector and EU Commission Regulation (EU) 2025/1988 (European Commission, 2025).

5.3.4.4.4 Uncertainties and remaining concerns relevant to the technical assessment

The scale of use of PFAS-containing foams in marine vessels and the requirement for and reliance on specifically foam extinguishment is uncertain. It is expected that bulk tankers

transporting petrochemicals and chemicals globally will rely on foam fire suppression, however the use of foam in, for example, engine rooms of other vessels such as ferries and other cargo carrying vessels is not clear but there is an expectation there is some reliance on foam-based fire suppression. Therefore, the scale of the number of vessels that will require retrofitting of foam systems with F3 alternatives or indeed another method of firefighting such as gas- or water-based suppression is uncertain, but could be considerable.

There is a lack of data regarding the use, quantities and performance of F3 in live incident situations in the marine sector, in common with other use sectors. 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). These estimates are based on a snapshot of the market around a decade ago and there have been technical advances in foams and successful transitions in the intervening years and the proportion of F3 used in this sector may have altered in this time.

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 combined spaces, use in high wind conditions and potential to cause corrosion, compatibility between different F3 and for different cargos, as well as modification of proportioning equipment, delivery systems and certification processes are acknowledged. Dry dock capacity will ultimately dictate the pace of transition within the marine sector for those vessels that are required to retrofit systems to comply with any PFAS restriction.

The European Union adopted a ten-year transition period for civilian ships with firefighting foams placed on board before 23 October 2025 within Commission Regulation (EU) 2025/1988 (European Commission, 2025). On the basis of its justification and on additional information provided by stakeholders in the Public Consultation (2026), the Agency agrees that a ten-year transition period for civilian ships with PFAS-containing

firefighting foams already placed on board at the time of the restriction becoming law is appropriate.

The marine sector is in a unique position with regards to enforcement in that compliance is a global issue for vessels entering British waters. The role of enforcement will need careful consideration and joint cooperation between EA and devolved agencies as well as the IMO and the MCA.

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 Federal Aviation Administration (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 reviewing the removal and replacement with fluorine-free alternatives. Fluorinated foams have not been used on assets controlled by Heathrow Airport Ltd since 2016, and Churches is supporting the transition of the British Airways hangars 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. 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." Similar comments

were echoed in stakeholder engagement meetings with the Fire and Rescue Services. Most airports have transitioned and kerosine is an easier oil to extinguish when compared with, for example a large atmospheric storage tank fire (Fire and Rescue Services, November 2025).

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); and in its response to the public consultation (Public Consultation, 2026). 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 F3s as will be used in any live incident, without the required cleanup, storage and incineration costs associated with PFAS-foam use. 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,Stuttgart, all Finavia airports in Finland, all Avinor airports in Norway and all Swedavia airports in Sweden) 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).

Liverpool Airport Fire Station confirmed that it had identified the risks and hazards using PFAS-containing foams in 2024/15, and the airport fire service now operate using Ecopol A foam (Public Consultation, 2026).

Essex Fire Rescue Service confirmed that they considered kerosine-based fires as 'knock-down' fires that F3 could deal with very effectively, hence the reason many airports had already transitioned (stakeholder meeting, Essex FRS, November 2025).

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, 2024b). 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, 2024b), 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, 2024b).

5.3.4.5.4 Transition periods for the aviation sector

When discussing potential transition periods Wood, 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"*. (Wood, 2020)

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, 2022c). 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, 2023a).

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.

In contrast to information it shared in the June 2024 Stakeholder meeting, the FIA (Public Consultation, 2026) while acknowledging that most "*Civil aviation sites have already transitioned to F3*," argues for a 5-year transition period with a review to determine if effective F3 alternatives exist on the basis that the following have not been considered:

- Passenger aircraft represent confined spaces.
- High volumes of passengers are quickly exposed to danger from smoke and fire.
- Passengers can die from excessive toxic smoke inhalation, so speed and reliability are critical to avoiding catastrophic fires, which F3s have demonstrated may not be achievable under challenging conditions.
- Unavoidable delays from damage/obstructions to exits.
- High viscosity concentrates and shear-thinning solutions causing higher system pressure losses.
- Sometimes safety dictates it may be safer for passengers to remain confined inside
- Aviation fires can spread rapidly.
- Escalation can occur rapidly.
- Re-ignition is also increasingly likely with F3s from smouldering composite materials.
- Composite materials have also been shown to be difficult to extinguish.
- Many aircraft firefighters for their own safety require forceful application of non-aspirated foam spray (at typically 3-4:1 expansion) to reach the target areas while

maintaining a safe distance for their own protection. F3s have demonstrated an inability to provide such critical protection.

Wilson Consulting (Public Consultation, 2026) argues for a ten-year transition period for the aviation sector. It echoes concerns expressed by the FIA (Public Consultation, 2026) with regard to transition to F3s. The comprehensive response highlights uncertainty that F3s will perform effectively in real-world incidents compared with small-scale testing. In particular citing less effective fire suppression performance of F3s, exemplified with comparison of 2016 incidents of "two aircraft fires in Dubai where F3 was believed to be used, and Singapore where ICAO approved AFFF and FFFP were believed to be used. The B777 in Dubai burned for 16 hours, while the B777 in Singapore was extinguished in 5 minutes." Similarly, FIA (Public Consultation, 2026) state "two claimed 'F3 successes' at London's Heathrow in 2013 had little impact and arguably were unnecessary according to the official air accident investigation reports," although it should be emphasised that this sentiment is not explicitly stated in either of these reports (AAIB, 2015a, 2015b).

The CAA (Public Consultation, 2026) confirmed that UK transition to fluorine free fire fighting foam concentrates has happened steadily since 2012 and currently 71% of RFFS units at aerodromes overseen by the CAA have transitioned. CAA states that the biggest challenges faced have been related to the logistics of changing concentrates whilst keeping the RFFS available and therefore the airport open. The CAA confirmed that it agreed with the Agency's proposed transition periods (Public Consultation, 2026).

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. Responses to the public consultation referenced a few air crash incidents with deployment of F3s. Relevant air crash investigation reports do not provide detail regarding effectiveness of F3s, and stakeholders have used the limited evidence to both support and cast doubt on their effectiveness (refs).

The CAA confirmed that there have only been a few incidents where F3 has been deployed at incidents, but that it has performed well (Public Consultation, 2026).

5.3.4.5.6 Aviation summary and conclusion

Fluorine-free firefighting foam alternatives already exist. They are used by major GB airports (approximately 71 % of CAA governed airports) and internationally. Stakeholders consider that whilst non-fluorinated foams require different firefighting techniques, training and application, 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. It is noted that from October 25, the European Union has adopted a five-year transition period for civilian aviation (including civilian airports) within Commission Regulation (EU) 2025/1988 (European Commission, 2025).

5.3.4.6 Military/Defence

5.3.4.6.1 General Concerns

As noted in Section 3.1.6.6, 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 and dedicated municipal fire services for military bases have similar concerns to the civilian municipal sector, 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) Despite this being considered in the ECHA restriction, the MoD have informed the Agency that they use alternative methods of fire suppression (e.g. water) when munitions are involved, owing to the risk of explosion being the primary concern instead of the fire.

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.

During the public consultation the MoD advised the Agency internally that, all concerns had been captured and reflected accurately in the Annex 15 dossier and transition periods were adequate at this time. (Personal communication, February 2025).

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, 2023a). 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 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.

As a single nation state the readiness to transition will be more aligned than in the EU, and these issues have not been considered further. The Agency suggests that the following transition periods are applicable for Defence.

MoD locations with bulk fuel storage are subject to Major Accident Control Regulations (MACR), which aim to deliver, as far as reasonably practical, standards at least as good as those required by the COMAH (1999) regulation. Akin to the COMAH regulations, MACR sites operate under a tier system to differentiate sites based on the type and/or volume of dangerous substances stored. These volumes are the same as mentioned in the COMAH regulations, including for petroleum products and other liquids that require adequate class B fire countermeasures. The MoD have substantiated, via internal communication, that

any of their sites that fall under the MACR would not require the same 10-year transition period as those that fall under the COMAH sector.

Considering this, it is the Agency's opinion that all uses within the military will receive a 5 year transition period, including bulk fuel storage areas. The exception to this will be naval vessels, which will be aligned with civilian shipping and offshore, receiving a 10 year transition period. This is due to the time needed to retrofit vessels to accommodate F3s, to allow time for the technical ability of F3s to meet the extreme conditions encountered at sea (e.g. sub-zero temperatures, windy conditions and compatibility of F3s with seawater).

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% among others have met this 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 the 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 fires in proximity to explosives or munitions. 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 where an 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.

After due consideration and consultation with MoD the Agency suggests a 5-year transition period, with the exception 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, 2023a). 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, onboard 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 mobile 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 mobile 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.

5.3.4.7.2 Call for evidence and public consultation

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 portable fire extinguishers, 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 (Britannia Fire, 2025), have fully transitioned their entire range to be PFAS free within 2 years. The most prominent barrier to transition was gaining appropriate certification from companies, as they have limited time and resources. There are multiple examples of fluorine free 3, 6 and 9L portable extinguishers such as those produced by Britannia in GB. These retail at a similar or slightly higher price than AFFFs and some are designed to tackle a wider range of fires, including Class-F (cooking oils and fats) fires and electrical fires.

Further information from the public consultation has highlighted various companies that utilise portable fire extinguishers, that now either use or plan to use F3s exclusively. These include, TATA Steel that has multiple sites across GB and where handheld extinguishers are required throughout the infrastructure of HS2.

Uncertainty around the availability of larger mobile units, predominantly 45-150L units, is still a consideration for this sector. Information from the public consultation demonstrates the widespread replacement of PFAS containing AFFF in the aforementioned handheld extinguishers but does not address larger units. Alternatively, the absence of concerns raised during the public consultation and ECHAs inclusion of all ready-for-use extinguishers in their 18 month transition period for cessation of manufacture and placing on the market suggests that obtaining F3 units is not an issue.

As of the publication of this background document, there is evidence of a single 50L fluorine free mobile fire extinguisher available in GB.

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. Refilling an extinguisher with F3 will not require the entire unit to be replaced, as extinguishers of all sizes house the active fire supressing agent in an internal chamber or cartridge, which is mixed with water from the main cylinder upon discharge. During this process the cartridge is rinsed with water or can be replaced entirely, reducing overall costs and likelihood of rebound.

ECHA originally 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 of all size, 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.

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 EU 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 other 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 enter into force after the EU restriction, which would allow some further 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 and mobile 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 mobile units, from 45 to 150L, containing fluorine-free foam that are sold in the UK. An information search reveals that retailers in the UK only stock the smaller handheld units. Larger mobile 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 mobile (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. Some suppliers and retailers do not currently have a fluorine-free version of the larger mobile units currently listed.

The Commission have allowed a 12 month transition period for the placing on the market of most PFAS-containing extinguishers. Predominantly, this is to allow for different certification requirements across Member States which would not be required in GB. The Commission have also opted for an 18 month transition period for alcohol-resistant foams in fire extinguishers. They have 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

The hazards of alternatives to PFAS in FFF were assessed in Section 5.2 of the background document. Of the fluorine-free foams (F3) assessed, none of the components, and therefore none of the formulations, would fulfil the P or vP criteria. Therefore, they do

not have PMT or vPvM-type properties and so do not have the same concerns around the potential for long-term exposure that PFAS-containing FFF do.

However, issues around the functionality and perceived efficacy of F3 have been identified, noting that a key difference of these foams is that 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 received from stakeholders regarding the use of F3 stem from this one issue. These include:

- It potentially taking longer to extinguish fires, with more foam required to maintain sufficient foam coverage.
- The need for F3 to be applied differently and more discriminately than PFAS-containing foams.
- The potential need to aspirate foams (i.e., to draw air into the foam) to maintain a more substantial foam and perform better. However, this compromises the range from which they can be applied (i.e., foam from a non-aspirated device will travel further).
- It being easier to break the foam blanket, resulting in re-ignition, so greater care or a modified approach to firefighting must be taken.
- F3 not performing as well in testing, or tests requiring modification to account for a different application method.

However, these concerns do not necessarily apply to all uses of every alternative foam, and industry has found ways to address them:

Concern	Management
It potentially taking longer to extinguish fires, with more foam required to maintain sufficient foam coverage.	Whilst, in many cases, it can take longer to extinguish fires without the resulting film from the PFAS-containing foam, this can be overly simplistic. “Extinguishing time” is often conflated with volume of foam required or application rate. It is also dependent on the user, application method, and matching of appropriate equipment and foam to the fire scenario. There are F3 products available on the market which have passed fire-performance tests such as those in BS EN 1568, meaning they can extinguish within the required test windows under those controlled conditions.

More foam is required than existing tanks currently hold.	Working with process safety specialists to determine *if* more foam is actually required, or if existing tank space is sufficient (within relevant safety constraints). Testing and finding a different foam which does not need as high a proportioning rate and thereby reducing the amount of foam required to be held. Retrofitting existing foam and tank infrastructure to accommodate increased foam quantity. (Such infrastructure change can be costly and contributes heavily to the need for longer transition periods.)
The need for F3 to be applied differently and more discriminately than PFAS-containing foams.	This is likely to apply more to application on large fires, e.g., by already trained professionals. Increased training to ensure that the foams are applied efficaciously.
The need to aspirate foams (i.e. to draw air into the foam) in more situations to maintain a more substantial foam and for it to perform better. However, this compromises the range from which they can be applied (i.e. foam from a non-aspirated device will travel further).	For FRS, this would predominantly be managed through training and adapted firefighting procedures. For fixed systems where this is a concern, for example on the decks of larger vessels, this could be mitigated through the addition of more foam monitors, reducing the distance over which each one is required deliver foam. (Such infrastructure change can be costly and contributes heavily to the need for longer transition periods.)
It being easier to break the foam blanket, resulting in re-ignition, so greater care or a modified approach to firefighting must be taken.	This is effectively the same concern as above for more discriminate foam application. This is likely to apply more to application on large fires, e.g. by already trained professionals. Increased training to ensure that the foams are applied efficaciously.

F3 not performing as well in testing, or tests requiring modification to account for a different application method	There are examples of F3 not performing as well as PFAS-containing foams in tests, however they can still succeed in those tests. That is, F3 are able to meet the standards set. F3 generally requires application to be more discriminate than PFAS foams to achieve comparable performance. As noted throughout, this is manageable through operator training.

If left unaddressed and F3 are used inappropriately, there could be potential concerns for the safety of users of firefighting foams. However, the industry is already aware that changes to application technique and adequate training are required. Demonstration of such risk mitigation can be seen in the voluntary transitions of higher risk operators, such as FRS, and their responses that they are satisfied with the performance of their chosen F3.

To note, most of these concerns do not apply to the use of portable fire extinguishers, especially those which are likely to be operated by inexperienced users, due to the locations in which they are typically installed and the fires that they are likely to be used on (often Class A).

Concerns were also raised about the inability to mix F3 from different manufacturers or with PFAS-containing foams. However, this is not exclusive to F3 and has also been a consideration for PFAS-containing foams. Furthermore, stakeholders have informed the Agency that testing should be undertaken to minimise incompatibilities from foam mixing, regardless of the type of foam being used – as advised by foam suppliers and producers.

Several other concerns have been raised by stakeholders, but the Agency notes that whilst they are concerns, they could also be viewed as potential solutions to some issues, as discussed above. These include:

- A need for training with F3
- More vigilant visualisation of the fire and progress of suppression.
- Requirement for different application rates, methods and tools.

The Agency notes that the main issue is that these solutions come at a cost and require time to implement.

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 F3s.

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

The Agency acknowledges that 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 eductors, 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.

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

That is not to say that each stakeholder in every sector could transition immediately i.e., with F3 as a drop-in alternative. However, the fact that stakeholders across each sector have transitioned indicates that questions relating to foam efficacy are not necessarily insurmountable obstacles. Rather, the Agency considers that sufficient time is needed for users to work with suppliers to find appropriate foams for their use, and to train with those new foams to ensure they can perform efficaciously.

The Agency therefore considers that alternatives are broadly available and viable and that the primary barriers to transition are cost and time. That is, alternatives to PFAS foams are **technically feasibl**e and the challenges are predominantly related to **economic feasibility**.

The Agency is aware that there will be instances where GB stakeholders have not yet been able to invest in researching a safe transition away from PFAS-containing foams. This may be due to perceived ineffectiveness of F3, not having legislative certainty that PFAS-containing foams will be prohibited in GB, or a concern that there is not currently an appropriate F3 for their use. To account for this, the Agency has considered longer transition periods where appropriate.

Based on the initial findings in this report and responses to the first public consultation, the Agency considers the following substitution timeframes to be reasonable for switching to

alternatives to AFFF. The Agency has also taken into account also the findings of ECHA and the European Commission 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 vessels[£], where FFF have been placed on board before entry into force.	10 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.

[£]Civilian vessel means all non-military waterborne craft, including sea-going vessels and inland-waterway craft.

*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. Eventually, over the *very* long term, these arrowheads will likely all degrade to trifluoroacetic acid (TFA), an ultra-short chain PFAA. 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.

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 PFAAs, the terminal degradation products of the PFAS in FFF, 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 and mobile 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 a 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 (2026) 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,) 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 2025 values, 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 6.12 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 SEA is mainly based on what it considers to be the 'best estimate' of these parameters with the data that is currently available. A number of data gaps exist and the SEA relies largely on parameter estimates extrapolated from the EU restriction. In this version of the SEA, additional sensitivity analysis has been undertaken to provide upper and lower bound of estimates, and the Agency will seek to narrow down the ranges if relevant information is received in this consultation. In line with the uncertainty, **the Agency recommends that current quantitative estimates are treated as an order of magnitude exercise** as a significant degree of uncertainty remains.

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 options analysis concludes that a restriction is the most appropriate measure in line with the criteria outlined in Annex 15 of UK REACH. Following this analysis, the Agency proposes restriction on **the placing on market and use of PFAS in FFFs, putting forward three different restriction options for consideration by the decision maker.** Discussion around the proportionality of this restriction can be found in Section 6.4.4.

6.3 Options analysis

Section 4 concluded that the use of PFAS in firefighting foam results in risks that are not adequately controlled. In response to the identification of this risk, the Agency has conducted screening 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.

6.3.1 Baseline

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. 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 is now PFAS-free although this is unevenly split between sectors of use.

For modelling purpose, the Agency assumes that further transition to PFAS-free foams will not occur without regulations that mandate this. This is mainly because differences in the costs of transition are expected across sectors and certain users demonstrating hesitance to switch to alternatives out of concerns around their efficacy. The Agency believes that existing incentives are insufficient for these users to transition to PFAS-free foams in the absence of government intervention, and it is assumed that no further changes in use will occur under the baseline ("do nothing") scenario'. That being said, market changes at the international level may induce some further transition, although the Agency currently has limited information on this and will seek to gain further understanding in the public consultation on the draft opinion. Another aspect of the baseline is how users handle PFAS wastes including unused stock of PFAS-containing foams and wastewater under the current legislations, such as waste legislation. The Agency currently has limited information on this and assumes all PFAS wastes go into wastewater treatment plant or eventually go into the environment, unless they are already regulated under POPs or other regulations. This assumption is discussed in more detail in Section 6.4.1 Baseline and Section 6.4.2.3 Disposal cost of unused stock.

6.3.2 Other risk management options than restriction (RMOs)

6.3.2.1 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 not accounted for.

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, allowing the possibility of these PFAS-containing products being used and PFAS being released to the environment long after the instruments are implemented.

Moreover, unlike regulatory charges, which may be imposed to recover the costs of regulation, environmental taxes are fiscal measures requiring government and parliamentary approval. This makes them less straightforward for a government department outside of the UK Treasury to introduce independently. 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 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 RMO 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 to F3 foams 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.

6.3.2.3 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.

6.3.2.4 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 Background Document. 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.

Such legislation would be primarily environmentally focused and would be wider than UK REACH in scope, covering all areas of sale, use, disposal and waste of PFAS. As such, this is not something that the Agency is able to take forward to scope and/or plan. It would require the powers to make additional legislation 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.

6.3.2.5 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, 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 work.

NOTE: the updating and amendment of the relevant waste/permitting legislation which is already in place to deal with waste from the use of PFAS containing foams was not assessed as a standalone regulatory option. This is because even with amendments this legislation would not manage all the identified risks. Although there may be a financial/regulatory incentive to move away from PFAS-containing foams with regard to costs for permitting and control measures – these costs may not result in transition to F3 foams as some industries would prefer to go down the permitting route than transition. This would also still allow use even where waste could not be controlled, as it is not always possible to control all emissions. It is also very unlikely that this legislation would be reopened for this specific/narrow purpose i.e. to control PFAS emissions from FFF, although it is possible this legislation will be updated more widely to deal with the broad issue of PFAS waste and to response to relevant actions in the PFAS plan [UK Gov 2026] but this will also take time to look across all relevant PFAS sources. The Agency therefore concluded that this measure was not an option without combination with, or existence of, a restriction on manufacture, use and placing on the market (as in RO1).

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 its variations (i.e. RO1, RO2a and RO2b) have been taken forward for economic appraisal.

6.3.3 Analysis of Restriction 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).

Each 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.

6.3.3.1 REACH restriction options (RO1, RO2a and RO2b)

For **regulatory options using REACH** three restriction options have been identified, all options will:

- Result in restricting PFAS - containing foams from being placed on the market in GB and used where they contain equal to or greater than 1mg/L of total organic fluorine from PFAS
- Establish sector/use specific transition periods
- Require the labelling of foams which are placed on the market during the transition period where they contain equal to or greater than 1mg/L of total organic fluorine from PFAS

Further, for uses with transition periods of 5 years and above (with the exception of portable fire extinguishers) each option will:

- Require emissions to the environment from and direct and indirect human exposure to PFAS-containing foams to be as low as reasonably practicable
- Require users of such foams to establish and maintain a PFAS-containing firefighting foams' management plan specific to the place of use.

RO1: provides a 'standard management plan' requiring users to set out details of the volumes of PFAS foams on site, details of the use conditions and how emissions are controlled, details on the type and methods of cleaning and maintenance of equipment, plans (and follow-up) in the event of accidental leakage/spillage of PFAS foam and a strategy for substituting PFAS foams with fluorine-free alternatives. This option requires that once considered as waste, any foams or associated waste products from use should be handled in accordance with measures prescribed by the relevant enforcing authority, thereby using appropriate legislation outside of REACH to manage waste, which reflects what normally happens in other REACH restrictions.

RO2a: includes the additional requirement for users to ensure the labelling and separate collection of stock of unused foam, and to ensure its handling in such a way that PFAS content is destroyed or irreversibly transformed.
In addition to the baseline requirements outlined in RO1, information on the collection of unused foam and measures to ensure adequate treatment of this should also be included in the management plan. This option also requires that (additional to the specific requirement for unused foams for specific uses) once considered as waste, any foams or associated waste products from use should be handled in accordance with measures prescribed by the relevant enforcing authority (as above, these measures would outside the scope of the REACH restriction).

RO2b: includes an additional requirement for users to ensure the labelling and separate collection of stock of unused foam **and** PFAS-containing waste, including wastewater, originating from the use of PFAS foams – where this is technically and practically possible – also to ensure their handling in such a way that PFAS content is destroyed or irreversibly transformed.

In addition to the standard requirements outlined in RO1, information on the collection of unused foam **and** PFAS waste and measures to ensure adequate treatment of this should also be included in the management plan.

Additional information to support the restriction options

Concentration limits

All options include a restriction on the placing on the market and use where the concentration of total organic fluorine from PFAS is **equal to or greater than 1 mg/L** in the firefighting foam.

The Agency notes that PFAS analysis is complicated by the large number of PFAS known to be produced and the limited number of analytical standards. Targeted methods cannot determine all PFAS present in any foam concentrate. Therefore, the concentration limit proposed by the Agency is based on non-targeted analysis of the fluorine content of the

sample. Basing the threshold on a measure of fluorine from PFAS, instead of the concentration of PFAS, has several benefits. It allows a 'total' analytical technique to be used that is broadly available and does not require any prior knowledge of the PFAS present nor reference standards for each individual PFAS.
To demonstrate compliance with this threshold different analytical methods could be used either in sequence or by selecting an appropriate method based on prior knowledge of the foam concentrate formulation or operator preference:

- Total Fluorine (TF). TF detects and quantifies the fluorine present in a sample, whether from PFAS or any other inorganic or organic fluorine sources. If the TF is below 1 mg/L then this is sufficient to demonstrate that the threshold is met. If the TF is equal to or above 1 mg/L a more specific analysis method should be used.

- Total Organic Fluorine (TOF). TOF detects and quantifies the fluorine present in PFAS and any other organic fluorine present in a sample. If the TOF is below 1 mg/L then this is sufficient to demonstrate that the threshold is met. If the TOF is equal to or above 1 mg/L a more specific analysis method should be used.

- If other sources of organic fluorine are known to be present in the FFF, these could be quantified and used with the data on TOF to demonstrate that the total fluorine from PFAS is below the threshold.

The Total Oxidisable PFAS (TOP) Assay converts PFAA precursors to PFAA for quantification, which could then be converted to a concentration of fluorine. Although this is described as a total PFAS measure it does not necessarily detect all PFAS as oxidation may not be 100% efficient and the result is dependent on the range of PFAA analysed for. As such, if this method is used the operator must be able to justify that it is suitable for demonstrating compliance with the threshold and includes all relevant PFAA, especially ultra short PFCA. Reported LoD are able to quantify PFCA at the required levels, though LoD were not reported for all relevant PFCA (Annex B).

The Agency understands that the available analytical methods (Annex B) are able to quantify total and organic fluorine at this level. As PFAS are typically composed of 50-80% fluorine, a FFF with a total organic fluorine concentration of <1 mg/L would have a total PFAS concentration of up to <2 mg/L. The EU restriction on PFAS in FFF sets a threshold of 1 mg/L total PFAS. The Agency considers that a threshold based on total organic fluorine is more explicitly defined, easier to enforce against and would have no practical effect on the restriction, as to provide functionality the PFAS would need to be present at >1000 mg/L in the FFF, so the threshold would still be able to distinguish PFAS-containing concentrates from PFAS-free alternatives.

A threshold is also proposed to assist with demonstrating compliance with the requirement to transition to PFAS-free alternatives. When documentation is not available to demonstrate that transition has occurred, a threshold for foams originating from equipment

that has previously been contaminated with PFAS is required to aid enforcement. This threshold must be below the concentration of PFAS that would be present if using a PFAS FFF (and accounting for dilution) but allow for some rebound of PFAS from the equipment. A threshold of 50 mg/L total organic fluorine from PFAS is proposed. The same analytical approach can be used as for the placing on the market threshold of 1 mg/L total organic fluorine. As PFAS are typically composed of 50-80% fluorine, a foam with a total organic fluorine concentration of <50 mg/L would have a total PFAS concentration of up to <100 mg/L. The EU restriction on PFAS in FFF sets a threshold of 50 mg/L total PFAS in foams originating from equipment previously contaminated with PFAS. The Agency considers that a threshold based on total organic fluorine is more explicitly defined, easier to enforce against and would have no practical effect on the restriction as the threshold would still be able to distinguish PFAS-containing foams from PFAS-free foams which have been contaminated by rebound PFAS.

The restriction options have been assessed against the Annex 15 criteria to determine their appropriateness.

Effectiveness in reducing identified risk

Placing on the market/use

The three options presented target the placing on the GB market and all uses of PFAS in FFF. This would result in the eventual complete elimination of additional PFAS-containing FFF being placed on the market or used within a decade of the legislation entering into force, and therefore avoid associated future PFAS emissions in GB from the use of FFF . As all restriction options cover the use of PFAS in FFF, formulation of PFAS-containing foams (including for export only) would also be prohibited in GB.

The Agency considers that suitable alternatives to PFAS-containing FFF exist and are available, an assessment of the risks of these alternatives has been conducted (see Section 5 of the Background Document) and these alternatives do not have the persistence and mobility concerns associated with PFAS foams. There are also examples of transition in all the sectors examined by the Agency, however we acknowledge that sectors have had to adapt application techniques and equipment for F3 foams, and that there has not been testing on extreme events which could lead to caution on transition to F3.

All options set the same differential transition periods across the various sectors/users. Therefore, aiming to set periods which are proportional to the challenges faced by each sector. Longer transition periods have been recommended where the evidence suggests that sectors require longer to transition due to technical, economic or logistical challenges. However, longer transition periods have been offset by the need for further risk management in the form of PFAS management plans and/or the need to manage unused foams and waste to an acceptable level (see below).

Ultimately, all restriction options would prevent on-going releases of PFAS from FFF by preventing placing on the market and use. Therefore, all are effective measures to reduce the identified risks to the environment and human health via the environment.

Additional risk management measures

The Agency has also considered the effectiveness of the additional risk management measures provided in RO1, RO2a and RO2b, which are proposed to minimise the impact of emissions into the environment resulting from the ongoing use of PFAS-containing foams during the longer transition periods of 5 years or above (excluding portable fire extinguishers). This includes the requirements to reduce emissions and the establishment of a PFAS management plan for the place of use: requiring documentation of use conditions and volumes of PFAS-containing foam, details on cleaning and maintenance of equipment, accidental spillage arrangements and a strategy for substitution to F3. These are assessed to be effective measures to reduce emissions of PFAS resulting from the continued use of these foams during the extended period of transition.

Measures to manage unused foams/waste

The identified restriction options also include provisions to ensure adequate handling of waste generated from the use of PFAS-containing foams, or unused stocks generated as a consequence of the restriction. Bearing in mind the regulatory responsibilities to manage waste should usually reside within the most appropriate framework, the options address this in different ways:

- RO1 states that once considered as waste, any unused foams or associated waste products from use should be handled in accordance with measures prescribed by the relevant enforcing authority under the relevant legislation, which is in line with what happens normally for REACH restriction. This option is considered partly effective, as the current framework is not joined up on the management of these PFAS when they become waste, creating difficulties and inconsistencies in their management.

- RO2a states that for those uses where the transition period is 5 years or above (with the exception of portable fire extinguishers) unused foams containing equal to or greater than 1mg/L total organic fluorine from PFAS should be collected and handled for treatment in such a way that the destruction or irreversible transformation of the PFAS content is ensured. The information on collection and adequate treatment must be included in the PFAS-containing firefighting foam management plan. In addition, RO2a also mirrors the clause in RO1 that once considered as waste, unused foams (that do not fall under the 5-year transition period) and associated waste products should be disposed of in line with measures from the relevant enforcing authority. This option is considered to be effective in reducing the majority of emissions to the environment from the use of PFAS-containing FFF (i.e. including the concentrated stocks of unused foams) as their disposal would be actively managed through the REACH restriction . However, as

the approach to other PFAS-containing waste is the same as RO1, it is also only partly effective (as above)..

- RO2b states for those uses where the transition period is 5 years or above (with the exception of portable fire extinguishers), unused foams and PFAS-containing waste, including wastewater, originating from the use of firefighting foams (where technically and practically possible) should be collected and handled for treatment in such a way that the destruction or irreversible transformation of the PFAS content is ensured. This applies to unused foams and waste from the use of foams containing equal to or greater than 1mg/L total organic fluorine from PFAS. The information on collection and adequate treatment shall be included in the PFAS-containing firefighting foam management plan. This option covers the management of unused foams and PFAS-containing waste over the longest transition periods, so would be effective at minimising identified emissions of PFAS resulting from the use of FFF but lacks clarity on the parameters of what is technically and practically possible.

Practicality

All options set the same transition periods across the various specific sectors/users. For all options, as outlined above and in Section 5, the Agency considers that suitable alternatives to PFAS-containing FFF exist and are available, albeit with necessary caveats 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.

It is suggested that the restriction could be implemented in the most practical way possible through appropriate transition periods to account for issues raised around timescales needed for full transition in certain sectors (see Section 5.4) Therefore, longer transition periods have been recommended where the evidence suggests that industries and sectors require them, i.e., due to technical, or logistical challenges, or to minimise the impact of significant capital expenditure. Implementation could also be enhanced by other elements, such as communication campaigns including case studies from transition in sectors etc. These could assist with managing any challenges which may occur during the transition period.

Therefore, in the Agency's view all options are implementable with regard to the availability of alternatives and economic feasibility to transition within the time period derogated for by use.

An aspect which could impact the implementability of the options is the capacity and capability to meet the requirements for destruction or irreversible transformation of the PFAS content. As discussed above in the socioeconomic assessment, demand for high temperature incineration at its peak (i.e. 10 years after coming into force) would exceed

the expected available capacity. This would increase the cost but also the need to store PFAS-containing waste or unused foams on site until capability becomes available. RO2b could make the highest demands on HTI requiring the need for this type of destruction for unused foams and PFAS containing waste, however we do not have an estimate as to how much PFAS-containing waste will be created as a result of this restriction (with the exception of wastewater). Additionally, for RO2b the expectation for some sectors (offshore/marine) to contain wastewater is technically infeasible, this is covered in the suggested restriction intent by the inclusion of aspects of technical and practical feasibility.

Therefore, if the capacity or capability for HTI remains the same – or if no other novel methods which could irreversibly transform or destroy PFAS are developed and scaled up, there could be limitations on the implementability of RO2a and even more so RO2b owing to peaks in demand from this restriction, or the need to incinerate any discovered legacy POPs (PFOA/PFOS) waste.

With regard to enforceability – for all options, regulatory bodies will be able to verify compliance in a number of ways. Sellers of foams could also be audited to check compliance of the foams and labelling aspects of any restriction. For users, this would be principally achieved through audits of purchase documentation for F3 and demonstration that PFAS foam has been replaced. 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 and cleaning and maintenance of equipment.

For each option, the Agency considers that the restriction for placing on the market and use should apply where the concentration of total organic fluorine from PFAS is **equal to or greater than 1 mg/L** in the firefighting foam. 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. It is also sufficiently high to be above background levels.

The Agency considers that the inclusion of “total organic fluorine from PFAS” to the scope of the restriction, instead of “sum of all PFAS” to be more reflective of the ability of dutyholder to comply with the restriction. Any analysis of PFAS is complicated by the large numbers of PFAS vs the limited amount of analytical standards. Therefore, the concentration limit is based on non-targeted analysis of the fluorine content of the sample. This has the benefit of allowing a ‘total’ analytical technique to be used that is broadly available and that does not require reference standards for each individual PFAS. This is more practical and allows dutyholders to better comply

The Agency is of the view that analytical testing of ‘end-of-pipe emissions’ would be a last resort when the dutyholder was unable to provide any other evidence of transition (as above). In those instances, a threshold would be required to support enforcement. It has been suggested that the conservative 50 mg/L limit could be used here. Noting it is

possible for a dutyholder to have replaced their PFAS-containing foams with F3, cleaned their equipment/infrastructure and still potentially be in breach of the 50mg/L threshold (this in known as “rebound” and discussed in Section 3.1.7 and Annex E.11).

The enforceability of RO1 could also be hampered in respect of the provisions to manage and handle unused foams and PFAS containing waste, given that the current regulatory framework is not joined up on the management of PFAS waste. It is likely to be more enforceable to have the explicit provision to destroy or irreversibly transform PFAS wastes written into the text of the restriction as is presented in RO2a and RO2b. Guidance would be required to comply with this provision, particularly on aspects of PFAS-containing waste for RO2b and what “technically and practically possible” could mean in context. RO1 relies on prescriptive measures from the relevant enforcing authorities which would be linked to legal provisions in existence on permitting and waste which are outside of UK REACH. The somewhat fragmented nature of waste legislation and enforcement could limit the scope of enforcement of RO1 compared to RO2a and RO2b, unless changes were made to this legislation within the transition periods.

The Agency also acknowledges that enforceability of the restriction in marine uses is complicated by boats/ships being registered in different countries where there may be different or no restrictions on the uses of PFAS. As is acknowledged in ECHA’s background document, further action involving the IMO – who regulate international shipping, will be required to ensure that REACH restrictions on PFAS on vessels operating internationally are fully functional and enforceable.

With respect to the manageability, the Agency acknowledges that although the levels of PFAS foam from PFEs are low, they are used in far wider and diverse settings such as offices, cafes, etc where the SMEs could be higher. There are also existing requirements on the disposal and waste of PFEs which have been taken into account when exempting PFEs from risk management requirements on uses with transitional periods of 5 years or above.

Additional guidance will be drafted to facilitate any restriction put in place by the decision makers and will need to cover PFAS management plans and however Defra, Scotland and Wales choose to address the handling of unused stocks of foams and PFAS-containing waste.

Overall, the Agency considers all options to be practical and implementable with regard to availability of alternatives and economic feasibility to comply with the transition periods suggested. However, due to the availability and capacity of the only acknowledged method to destroy or irreversibly transform PFAS content – high temperature incineration (HTI) – it may be more difficult for dutyholders to comply promptly with RO2a and even more so RO2b (which required the additional use if HTI for PFAS-containing waste) especially if there are peak in demand at certain times. This could necessitate the storage of not-

utilised foam and/or PFAS containing waste for a period of years until facilities are available.

On enforceability, RO2a and RO2b may be more enforceable with regard to not-utilised foams and/or PFAS containing waste due to inclusion in the UK REACH restriction.

It is acknowledged that to aid manageability all options will require guidance to some extent to help affected dutyholders understand their responsibilities. This will be made available before the relevant responsibilities enter into force, therefore the Agency concludes that the restriction options are all manageable.

Monitorability

For all options, 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 local 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. This could be used to monitor compliance with the requirement in all options to reduce emissions to as low a level as reasonably practicable, and also to ensure that unused foams and PFAS-containing waste is being handled as required by the restriction. For RO2a and RO2b given that the correct treatment of unused foam would lead to 90% abatement (see Section 6.4.4 for further information), and that RO2b would require (where technical and practically possible) the further control of PFAS-waste monitoring we would not expect to see any increases around sites with transition periods of 5 years or above. However, as RO1 and RO2a also require dutyholders to comply with any requirements set out by the relevant enforcing authority it would be expected that monitoring could show compliance with this provision. It is acknowledged that due to other sources of PFAS from uses which are not covered by the restriction, compliance for all uses of PFAS including FFF may be difficult to monitor and demonstrate compliance as a whole and linking any environmental contamination to a specific source is not easy to do and therefore will not be used to monitor compliance.

As all restriction options place the same limits on use and placing on the market, the Agency considers all options to be monitorable.

Authorities will be able to verify when a user is not in compliance with the restriction requirements. The management plan will require record-keeping requirement on the continued use of PFAS FFF for uses with transition periods of 5 years and over, dutyholders are required to provide this upon inspection. Compliance visits could take

place at both user and formulator/producer sites, in addition to tracking online sales of foam concentrate and are expected the primary mechanism to ensure compliance.

The Agency therefore concludes that all options are monitorable.

6.4 Economic Impact analysis of Proposed Restriction

In the previous version of the SEA, a top-down approach was applied, where the total tonnages were used as a starting point, and split into sector tonnages by applying the sector shares. The emissions and costs under the restriction option were applied at the sector level as a single unit cost or emission per site multiplied by a site count. In the same sector, sites' behaviour on stock top-up, use and disposal were assumed to be the same.

During the public consultation in 2025 and opinion development, some limitations with the approach became apparent:

- The use of a single sector-average unit cost masked large within-sector variability in capital requirements and timing of capital events. A Large Atmospheric Storage Tank (LAST) refinery transition (capital cost £25 million at central estimate) and a lower-tier Control of Major Accident Hazards (COMAH) site transition (capital cost £5,000) were both counted as 'COMAH sites' in the previous version, yet their capital costs differ by four orders of magnitude per site.

- The different behaviour of stock top-up, use and disposal of sites across and within sectors was not captured in the model. For example, a 12% (central) use rate was assumed across all sectors, from LAST sites to ready-to-use extinguishers. This had implications on the restriction cost estimates such as stock disposal at the end of transition period, masking some of the cost and emission differences that could become important when accessing cost-effectiveness at a more granular level.

- Differences in firewater collectability across and within sectors, which are important in RO2b, were not captured.

- Differences in F3 alternative availability and foam volume uplift across and within sectors, which affect replacement/substitution costs, were not captured.

For these reasons, in this version of the SEA, the Agency adopts a bottom-up approach, which disaggregates each use sector into subpopulations (see Annex G.1), and applies separate parameter values for:

- Number of affected sites

- PFAS-containing foam stock per site

- Annual use rate per site

- Transition path (substitution progress during the transition period)
- Capital cost of transition per site (engineering works, new systems)
- Firewater management cost per site (testing, training, incident response)
- Firewater collection efficiency

This current version of the model tracks stocks, flows (purchase, use, disposal), and emissions for each sector subpopulation under baseline and restriction scenarios. Costs and reduction in emissions are aggregated from the sector subpopulation level upward. This structure permits a marginal abatement cost curve to be drawn by sector and subpopulation, and thus allows evaluation of cost-effectiveness at a more granular level (Section 6.4.4). This also allows discussion of transition period options by subpopulation (Annex G.4.2).

6.4.1 Baseline

6.4.1.1 Baseline Sales

Prior to appraising the impacts of the proposed restriction options, it is necessary to outline the assumed baseline scenario in terms of the actual current sales of PFAS-containing firefighting foams. This relates to how the sales of PFAS-containing FFFs is expected to behave in the absence of any intervention (restriction in this case) - i.e., the ‘do-nothing’ scenario.

In the previous version of the SEA published in August 2025, a top-down approach was adopted in deriving the sales figure. First, the annual tonnages of FFF concentrate were extrapolated from EU figures (detailed in Section 3.1.2). Then, the sector shares taken from Wood (2020) and ECHA (2022a) were applied to the annual tonnages to obtain the sector annual tonnages. While the Agency has received some information on sales that is broadly consistent with the extrapolated sales figures in the public consultation, the Agency has not received UK-specific information that would verify these figures directly, or updates that reflect the recent trend of PFAS-containing FFF sales. Therefore, the Agency keeps the central estimate of sales derived from the top-down approach, but deviates from the low and high estimates to maintain consistency between the assumptions in the current bottom-up approach. See Annex G for these assumptions and how the low and high estimates are derived. Figure 6.1 illustrates the top-down and bottom-up models.

Figure 6.1: Top-down and bottom-up models

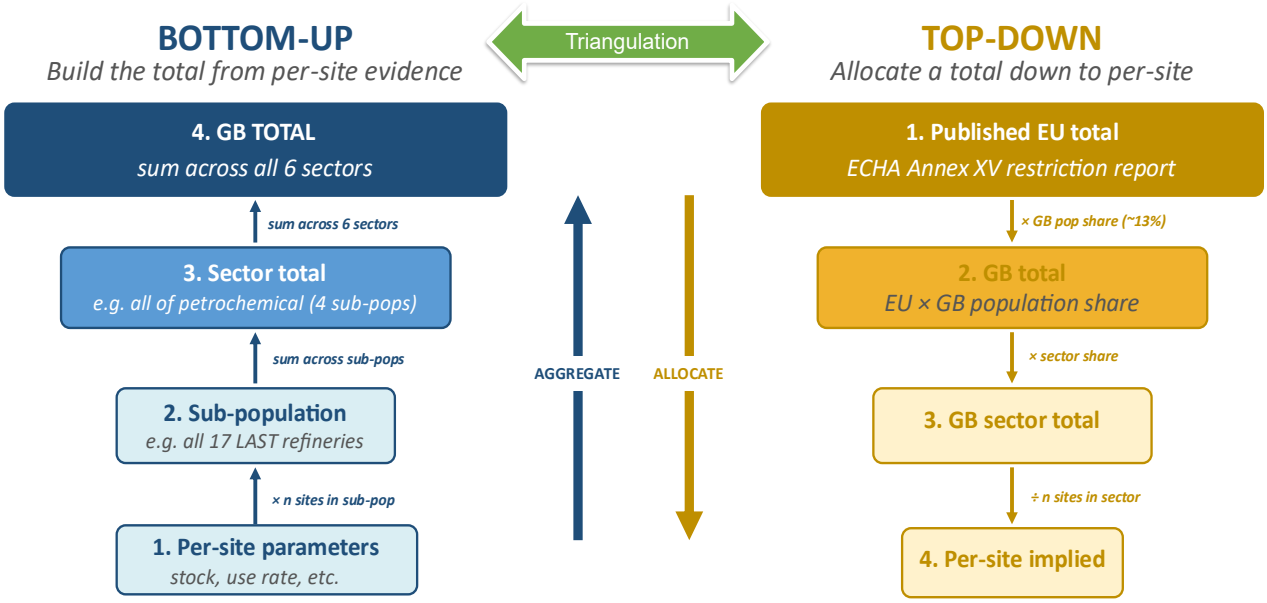


Table 6.1 presents the annual tonnages of FFF concentrate that the Agency assumes to be sold in the UK per year, reproduced from Section 3.1.2 and Annex G where greater detail is outlined on the methodology behind the estimates. The main economic impact analysis will include a 'central'/best estimate, and a lower bound and upper bound by adopting both ends of every parameter will be provided in Section 6.4.5 Sensitivity analysis. Note that these bounds are not to be interpreted as market estimates or confidence interval on their own; instead, these stack the extremes of every parameter simultaneously to provide artificial boundaries resulting from model assumptions.

Table 6.1: Estimates of PFAS-containing foam concentrate sales

PFAS-containing foam concentrate sales (t/year)		
	Estimates (top-down)	**Estimates (bottom-up)**
Low or lower bound* (all parameter low)	1,300	636*
Central	2,000	2,060
High or upper bound* (all parameter high)	2,500	5,348*

For current purposes, these tonnages are held constant across the 30-year appraisal period, assuming that these tonnages have captured the transition induced by other regulations such as EU REACH and POPs regulations. This is plausible as per the

considerations outlined in Section 6.2. 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 regulations, such as Defence Fire & Rescue Structural Fire-fighting Regulations (DSA, 2024) in the military sector presumably take place and induce further transition from PFAS-containing FFF to F3 foams, the Agency acknowledges that this might overestimate the impacts (both benefits and costs) attributable to the UK REACH restriction but concludes that impacts on key conclusions will be limited (as benefits and costs are affected by the same manner).

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 sales associated with each of these sectors. As a result, ECHA's apportionment across sectors (estimates from Wood (2020) and ECHA (2022a)) will be assumed to also represent the distribution within the GB market as a starting point of sales estimates in each sector. These sales figures by sector are then triangulated and revised using the bottom-up approach, by dividing each sector into sector subpopulations and making assumptions on the size of subpopulation, stock, use and disposal behaviours of each subpopulation. The market breakdown and sales are as follows:

Table 6.2: Sector-specific market share and sales (Wood (2020) and ECHA (2022a); Agency's revision)

Sector	PFAS-based foam concentrate (share)	PFAS-based foam concentrate (tonnes/year)
(Petro)chemical	61%	1,255

Military	7%	149
Marine	13%	267
Aviation	12%	252
Fire and rescue services	6%	118
Ready-to-use	1%	20
Total	100%	2,061

It should be noted the Agency's sector definition is slightly different from ECHA's definition. 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. In addition, the baseline sales figure of the fire and rescue services is revised downward due to the fact that many FRS in the UK should have transitioned between the Wood or ECHA analysis and now, as supported by the responses from the public consultation. Some subpopulations in the military sector are expected to have transitioned by the end of 2027 complying to Defence Regulations according to DSA (2024). This does not change the baseline sales at the beginning of the appraisal period but the evolution of sales in the sector in the baseline. For the complete description of baseline assumptions, please see Annex G.

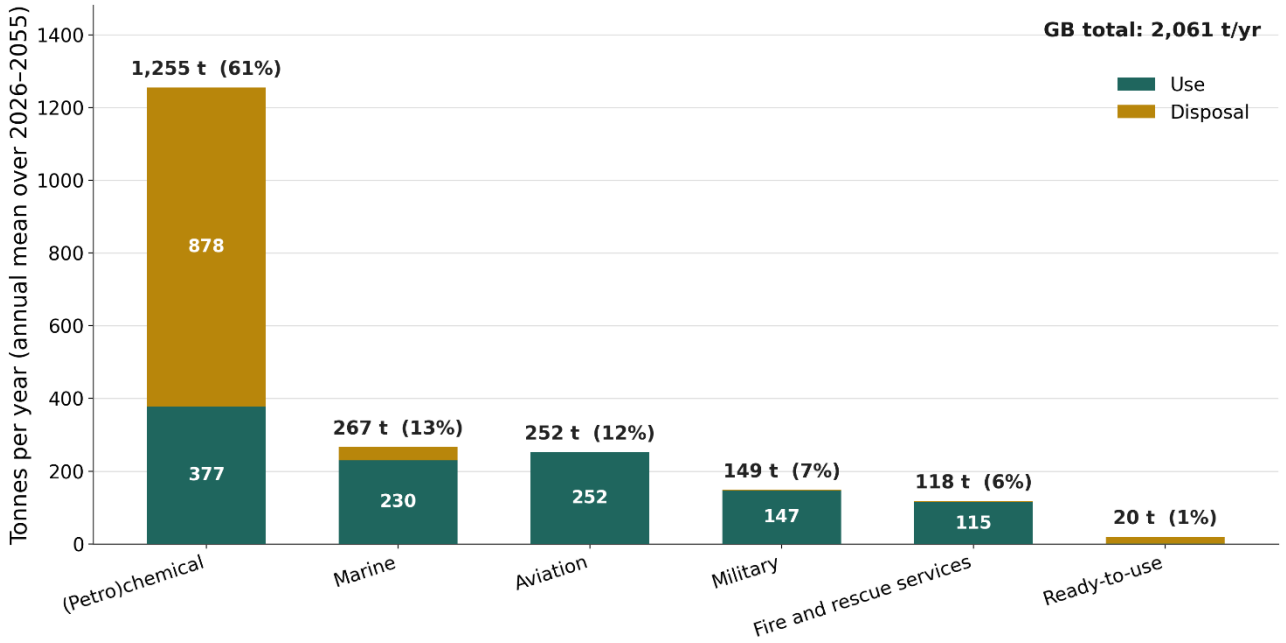
6.4.1.2 Baseline Use and Disposal

A key change from the previous version of the socioeconomic analysis is the baseline assumptions on use and disposal of foam concentrates. In the previous version for consultation, it is assumed that 12% of stock is used every year and no stock is to be discarded due to expiry (assuming 15 years shelf life) in the central scenario (as 100% - 12% x 15 years <0). In the public consultation and stakeholder engagement, stakeholders stated that much lower percentages of stock are used per year. The information supplied by stakeholders also indicates that these use rates vary between sectors and subpopulations. The Agency's desk research shows that the disposal rates (due to expiry) are likely positive, especially when there are strict safety requirements to hold reserve stock in case of incidents (e.g., Incident Response Plan in Large Atmospheric Storage Tank (LAST) sites in the (petro)chemical sector), or when incident occurrence is infrequent (e.g., ready-to-use spray cans). Therefore, this version of the SEA adopts lower and varying use rates (1-15%; central) and positive and varying disposal rates (0-19%; central) by subpopulation.

The foam purchase every year is the sum of use (deployed) foams and disposed (expired) foams.

Figure 6.2 shows the annual baseline use, disposal and purchase by sector over the appraisal period. See Annex G.2 for the values by subpopulation within sectors. These tonnages per year are assumed to be constant over the appraisal period, with the military sector as the exception because Defence Regulations are expected to induce substitution for some subpopulations regardless of the restriction. This is captured in the baseline as the response is not induced by this restriction.

Figure 6.2: Annual baseline use, disposal and purchase of PFAS foam concentrate by sector over the appraisal period



6.4.1.3 Baseline Emissions

The use and disposal of PFAS-containing FFF concentrates are associated with the emissions by sector in the appraisal period as shown in Table 6.3. The total emission under baseline is 1,507t in the appraisal period. Similar to the previous section, these emissions are assumed to be constant over the appraisal period, with the military sector as the exception because Defence Regulations are expected to induce substitution for some subpopulations within the sector. It is assumed that wastes originated from use of PFAS foams and expired stock go into wastewater treatment plant, and wastewater treatment is assumed to have zero efficiency in reducing PFAS emissions. Other assumptions and subpopulation breakdown, including sources are listed in Annex G.3.

Table 6.3: Baseline emissions by sector

Sector	Total emission (tonnes in 30 years)	Emission (tonnes/year)
(Petro)chemical	941	31.4
Military	74	2.4
Marine	200	6.7

Aviation	189	6.3
Fire and rescue services	88	2.9
Ready-to-use	15	0.5
Total	1,507	50.2

6.4.1.4 Baseline Prices

As with the assumed future tonnages of PFAS-containing foams, the Agency assumes that the relative prices of both PFAS-containing and F3 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 (£/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.

In addition, the EU REACH restriction on PFAS-containing firefighting foams may affect the relative price dynamics depending on whether and how much GB users rely on the EU markets. Given the EU demand spikes of F3 foams triggered by the EU restriction, it is unclear whether the GB market will face higher prices.

The Agency has not addressed this uncertainty by modelling the price dynamics in the 30-year appraisal period, but addresses this partially in the sensitivity analysis by using an upper bound and a lower bound of foam prices (Section 6.4.5). The Agency is also seeking additional information in this area in this public consultation on the draft opinion.

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 options.

Costs are 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, and waste management cost associated with use and disposal 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 lower abatement), less stringent or no waste management requirements do the same. 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 6.4.2.12. Due to the heterogeneity of some sectors, a comparison of different transition period options for some sectors are presented in Annex G.4.2 to highlight the potential impacts of adopting different lengths of transition period.

6.4.2.1 Foam Substitution/replacement cost (RO1, RO2a, RO2b)

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 6.4.1), and a larger stock may be required if a larger quantity (or higher concentration) 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/of a larger quantity/ of higher concentration is required. These costs of restriction (like any) are only material for users that would not have undertaken such behaviour under the baseline.

The cost of foam replacement during transition therefore depends on the availability of F3 substitutes (technically or supply volume; see Section 5 and Section 6.4.1.4) and stock requirement of the sectors or subpopulations. Stock requirement incorporates fire safety regulations where some sector subpopulations are required to have a minimum amount of stock on site. Coupling with the constraint that PFAS and F3 foams cannot be mixed in use (such as mixing in the same tank), this implies that some sites may need to top up on PFAS-containing foams during the transition period, until F3 substitutes and their systems for using F3 foams are ready. At one extreme, ready-to-use fire extinguishers are transitioning to F3 foams and it is expected that they will deploy the remaining PFAS-containing stock and top up an equivalent quantity of F3 foams. At the other extreme, some LAST COMAH sites and offshore sites may not have approved or verified F3 alternatives so far and they will need to top up the deployed and disposed stocks by PFAS-containing foams during the proposed 10-year transition period, dispose of the large quantity of PFAS-containing stock at the end of the transition period and replace them with F3 products (if available). These differences in behaviours in stocking and top-up will give rise to very different costs of foam purchase. To estimate these costs, the Agency makes assumptions on purchasing, deployment and disposal behaviours for different subpopulations in each sector as listed in Annex G.

Based on these behavioural assumptions, each sector is attributed an annual cost of replacing their depleted (used or expired) 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 or higher concentration 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 concentrates required to extinguish a given fire relative to a PFAS concentrates) of 1.25,

1.5 and 1.75, as the low, central, and high scenario, respectively, for most sectors. These are the assumptions used by ECHA (2022a) which have been verified by stakeholders. For some specific sectors, a foam multiplier ranging from 1.3 to 3 is used as these values, driven by technical requirement, were suggested in stakeholder engagement or public consultation. A full list of foam multipliers for each subpopulation can be found in Annex G.4.1.1.

The Agency estimates the cost of replacing foam stocks to total to **£201.4m** in present value terms across the 30-year appraisal period.

Note that this cost does not include the cost of replacing the ready-to-use portable extinguishers (only foams), so the cost of this sector is likely underestimated. During the public consultation, stakeholders highlighted the risks when refilling old AFFF extinguishers with F3 as many AFFF units lack aspirating nozzles and the refilling can be costly, on top of the foam costs.

6.4.2.2 Cost of technical equipment changes (capital cost; RO1, RO2a, RO2b)

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 applied a factor of 0.5 and 3 to estimate low and high parameter values, respectively. The Agency uses ECHA's estimates for certain subpopulations of petro(chemical), aviation and fire and rescue services sectors (adjusted to £2024: £529,205 and £5,292 for COMAH and non-COMAH sites, respectively) and makes additional assumptions of other subpopulations, resulting in costs ranging from £0 (ready-to-use) to >£25m (LAST sites). See Annex G.4.1.2 for a full set of cost assumptions and values.

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 (petro)chemical 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.

The 163 COMAH sites are further subdivided into subpopulations in the (petro)chemical sector (except for offshore sites). In some sectors, the units of estimates are per vessel or per vehicles instead of per site, where applicable. These are more appropriate for some subpopulations where the foam stock level is likely to be proportionate to the number of vehicles or vessels. The sizes of each subpopulation within each sector are shown in Annex G.1.

When F3 alternatives are available, technical changes to equipment are assumed to occur uniformly over several years during the sectors' respective transition periods. In certain subpopulations where the availability of F3 alternatives or the perceived efficacy is in question, the cost of technical changes is assumed to incur at the end of the transition period.

Based on the above, the Agency estimates the cost of implementing the technical changes required to transition away to total **£411.8m** in present value terms.

Note that this is a conservative estimate of cost (overestimate) because it is modelled as full replacement cost rather than additional and acceleration of capital cost (on top of regular replacement in the baseline). Due to the lack of data on baseline replacement schedule and asset age distribution, a more granular modelling of accelerated investment (which involves stacking these assumptions) will likely produce spurious cost estimates. Instead, this is simplified and modelled in some sector subpopulations by spreading the capital costs over the transition period, representing that a certain percentage of sites is able to align capital replacement with baseline schedule. In addition, this overestimate has been partly offset in the sector subpopulations where the capital cost is assumed to incur at the end of transition period. The sensitivity analysis also stretches the capital cost assumptions using an upper bound and a lower bound, covering the lower cost estimate representing the acceleration of the baseline capital cost.

6.4.2.3 Disposal cost of unused stock (RO2a, RO2b)

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 (HTI) remains the only technically and economically feasible technology currently available in the UK (see Section 3.1.9).

The total amount of stock disposal includes the disposal of expired stock annually and the disposal of unused stock at the end of transition period.

6.4.2.3.1 Disposal of expired stock (recurring)

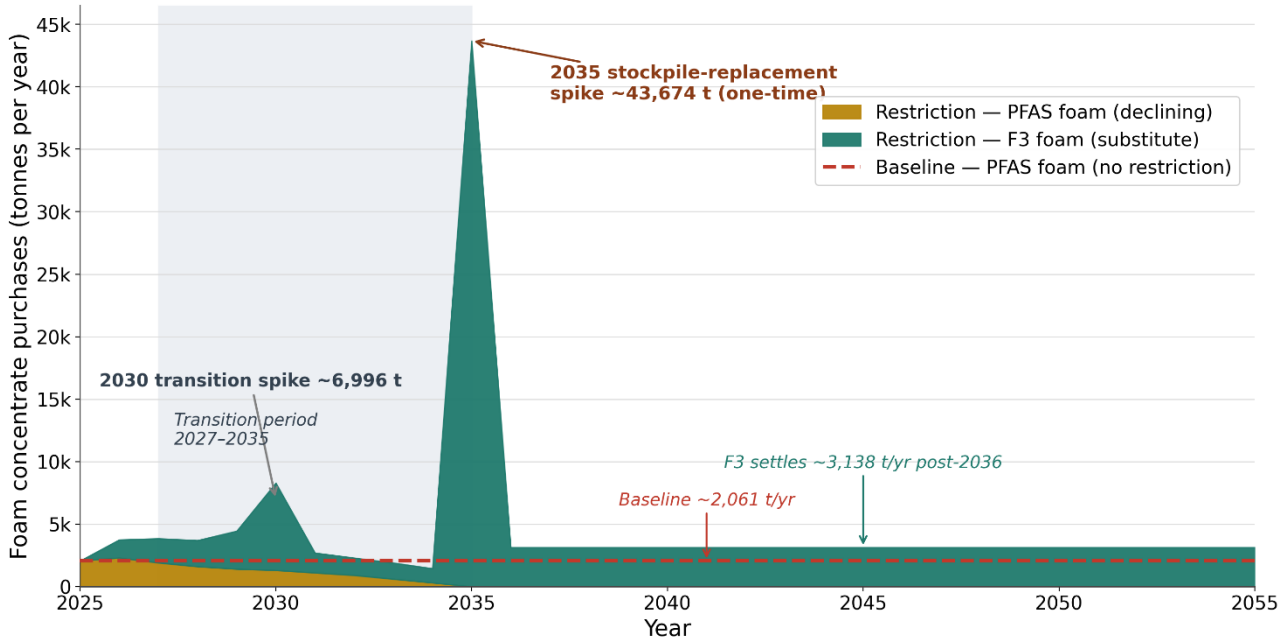
Based on ECHA (2022), the Agency assumes that foams have a shelf life of 10-30 years, with a central estimate of 15 years. With the stock top-up and deployment behavioural assumptions by subpopulation and sector, an average disposal rate of stock can be derived. For example, a deployment rate of 2% and a shelf life of 15 years will give an average disposal rate of (100% - 2% per year x 15 years)/15 years = 70%/15 of stock per year.

Note that it is assumed that in the baseline all expired stock is processed by WwTPs, which have zero efficiency in removing PFAS. Therefore, any costs incurred in managing unused stock as a result of the restriction are attributable to the restriction under this assumption. This can potentially overestimate the cost of restriction. While users could have been incinerating unused stock regardless, this would have been captured under the baseline and thus not attributable to the restriction. Since RO2a and RO2b explicitly requires the appropriate disposal of unused stock under REACH, this cost is attributable to these options.

6.4.2.3.2 Disposal of stock at the end of transition

In addition, users will be required to dispose of any remaining stock by the end of the transition period. The quantity of disposal will depend on the top-up behaviour, and safety or legal requirements on stock holding in the sector. At the extreme case of LAST sites in the (petro)chemical sector, sites are required to hold a physical stock of 100% so they need to top up their PFAS stock after use to meet the safety standards during the transition period, while ready-to-use fire extinguisher users can schedule to deplete their PFAS stock during the transition period and top up F3 stock. As a result, the former sector is expected to dispose of a large stock of PFAS-containing concentrates while the latter is not. Figure 6.3 shows the PFAS and F3 foam purchases under the baseline and restriction over time. See Annex G for a more detailed discussion.

Figure 6.3: Foam concentrate purchases under baseline and restriction



6.4.2.3.3 HTI cost and surge scenario

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).

In the August 2025 public consultation on this dossier, some stakeholders shared the concern that these values were too low and suggested the price per tonne for HTI to be around £3,000/tonne. This was likely due to the capacity constraint of HTI facilities in the UK and thus potential bottleneck, coupled with surge of HTI demand from the recent POPs regulation requirement under Stockholm Convention. To account for this price surge, a surge HTI cost of £3,000/tonne is used to calculate the central[1] and high estimates. In addition, an analysis on the HTI capacity is conducted in Section 6.4.5 Sensitivity Analysis and Annex G.4.1.4. The Agency is also seeking additional information in this area in this public consultation on the draft opinion.

This unit price is then multiplied by the volume of stock, if any, remaining at the end of the restriction transition period.

[1] The high estimate of £3,000/tonne is adopted for the central estimate of restriction cost to account for the possibility of price surge due to capacity constraint. One could argue that this surge price would likely go down as more capacity becomes available over time. The Agency keeps this surge cost because this potential overestimate in costs already gives a favourable ICER at £99/kg – decreasing this cost estimate does not change the main conclusion. See Section 6.4.5 for more discussion on HTI capacity.

Using the central parameters, the Agency estimates this cost to total **£83.2m** in present value terms across the 30-year appraisal period.

6.4.2.4 Cost of managing firewater (RO2b)

Under RO2b, those who continue to use PFAS-containing foams during the transition periods are required to collect firewater run-off from both training (or survey, testing; referred to as training for brevity) and incidents to the extent technically and economically feasible, and ensure the PFAS content is destroyed or irreversibly transformed (Section 6.3.2). In practice, this requires users to capture contaminated run-off via bunding, drainage systems or containment lagoons, then route the collected liquid to processing and HTI (Sections 3.1.6 and 3.1.9). Recognising the difference in feasibility of collecting firewater run-off, sector and subpopulation specific training and incident collection effectiveness and cost assumptions are applied (see Annex G.4.1.5).

Using the central parameters, the Agency estimates this cost to total **£7.6m** in present value terms. It is important to note that **the cost estimates do not necessarily reflect the full picture - where firewater collection may not be possible or monetised, such as incidents in the marine sector, the cost is zero. This cost component might be low for certain sectors or sector subpopulations for this reason, rather than low costs.** The Agency is also seeking additional information in this area in this public consultation on the draft opinion.

6.4.2.5 Savings (RO1, RO2a, RO2b)

Two notable direct cost savings to users may arise as a result of the 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 6.4.2.3, disposal of PFAS-based foams may occur under the baseline if foam stocks are not used up before their expiration date. Some expired PFAS foams are 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 (required by other regulations) but have now transitioned to PFAS free foams, would no longer be incinerating the expired foam because the Agency understands that expired alternative foams are suitable for disposal via other methods. The Agency does not have information on how much of these (previously would be sent for HTI but substituted by F3 triggered by the restriction) foams made up of the total PFAS-containing foams under the restriction. The actual proportion could range from 0-100%. Consider the two extremes: If it is assumed that none of the PFAS-containing foams in scope were sent for HTI (and in fact it is >0%), the emission reduction under the restriction will be

overestimated, at the same time the attributable disposal cost to the restriction will be overestimated as well (savings underestimated). If it is assumed that all the PFAS-containing foams in scope were sent for HTI (and in fact it is <100%), the emission reduction and the attributable disposal cost will both be underestimated (savings overestimated).

For simplicity, it is assumed that 0% of the PFAS-containing foams in scope of this restriction were sent for HTI even before the restriction, recognising that restriction cost and emission reduction are likely overestimated[2]. The saving in HTI cost of expired stock is zero under this assumption.

A second cost saving may arise due to restriction avoiding the need to dispose of firewater. Indeed, this cost saving alone appears to have already prompted transition for some users, notably airports. But for the purpose of this analysis, similar to above, saving in firewater collection and disposal cost is zero.

6.4.2.6 Other costs of cleaning and disposal (not quantified; RO2b)

Other than disposal of unused stock, managing firewater run-off and decontamination of equipment, the EU Guidance for Transitioning to Fluorine-Free Firefighting Foams (2026) highlights that the transition generates several distinct waste streams, each requiring proper identification, classification and disposal under the Waste Framework Directive and POPs Regulation. These include

- PFAS-containing firefighting foam (Section 6.4.2.3)
- PFAS-containing firefighting run-off water (Section 6.4.2.4)
- PFAS-containing water from cleaning of equipment including PPE (Annex G.4.1.7)
- PFAS-containing system components in different parts of the firefighting system (Annex G.4.1.7; capped by cost of replacing components)
- PFAS-containing soil (not monetised)
- PFAS-containing equipment, e.g., PPE (not monetised)

The last two items are not quantified in the Agency's analysis as they are expected to be insignificant compared to the other costs or are highly uncertain (See Section 6.4.3 on remediation cost).

6.4.2.7 Costs of management plan and labelling (not quantified; RO1, RO2a, RO2b)

For all restriction options assessed (RO1, RO2a, RO2b), users are required to set out and keep record of the volumes of PFAS foams on site, use conditions, emission controls, type

[2] A sensitivity analysis has been conducted on the percentage of transition or cost attributable to the restriction (ranging from 0% to 100%). The results confirm the expectation that restriction cost and emission reduction will change proportionately in the same direction. This analysis is not included due to space constraint.

and methods of cleaning and maintenance of equipment, plans in the event of accidental leakage and a strategy for substitution. RO2a and RO2b will require the documentation of collection of unused foam and measures to ensure adequate treatment, and RO2b will require the documentation of collection of other PFAS waste and measures of ensure adequate treatment. In addition, users are required to label the PFAS foams placed on market during the transition period. The Agency has not monetised these costs but do not expect these costs to have significant impacts on the conclusions of the SEA.

6.4.2.8 Manufacture and formulation costs (not quantified; RO1, RO2a, RO2b)

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). It is expected part of the costs are attributed to the EU restriction, nonetheless, because the EU restriction enters into effect before this restriction.

6.4.2.9 Familiarisation, research and training costs (not quantified; RO1, RO2a, RO2b)

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.

6.4.2.10 Enforcement costs to the authority (not quantified; RO1, RO2a, RO2b)

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, but the Agency does not expect these costs to have significant impacts on the conclusions of the SEA.

6.4.2.11 Total costs

The cost total in Table 6.6 is calculated as follows:

- RO1 = replacement cost + capital cost
- RO2a = replacement cost + capital cost **+ cost of appropriate disposal of unused PFAS stock (incineration cost)**
- **RO2b** = replacement cost + capital cost + cost of appropriate disposal of unused PFAS stock (incineration cost) **+ firewater management cost**

Although the intent of RO2b requires the collection and adequate treatment of PFAS containing waste other than firewater, this cannot be costed due to the uncertainties with the volume and type of waste generated (See Section 6.4.2.6).

Table 6.6: Estimate PV costs by type

Cost type	PV estimate (30 years, million)
Foam substitution	£201.3m
Capital replacement	£411.8m
Enforcement (to authority)	Not quantified*
Familiarisation	Not quantified*
Cost to manufacturers	Not quantified*

Cost type	PV estimate (30 years, million)
Administration cost (management plan, labelling)	Not quantified*
Incineration/disposal of unused stocks	£83.2m
Firewater management (where possible and monetised)	£7.6m
RO1 total	**£613.2m**
RO2a total	**£696.4m**
RO2b total	**£704.0m**

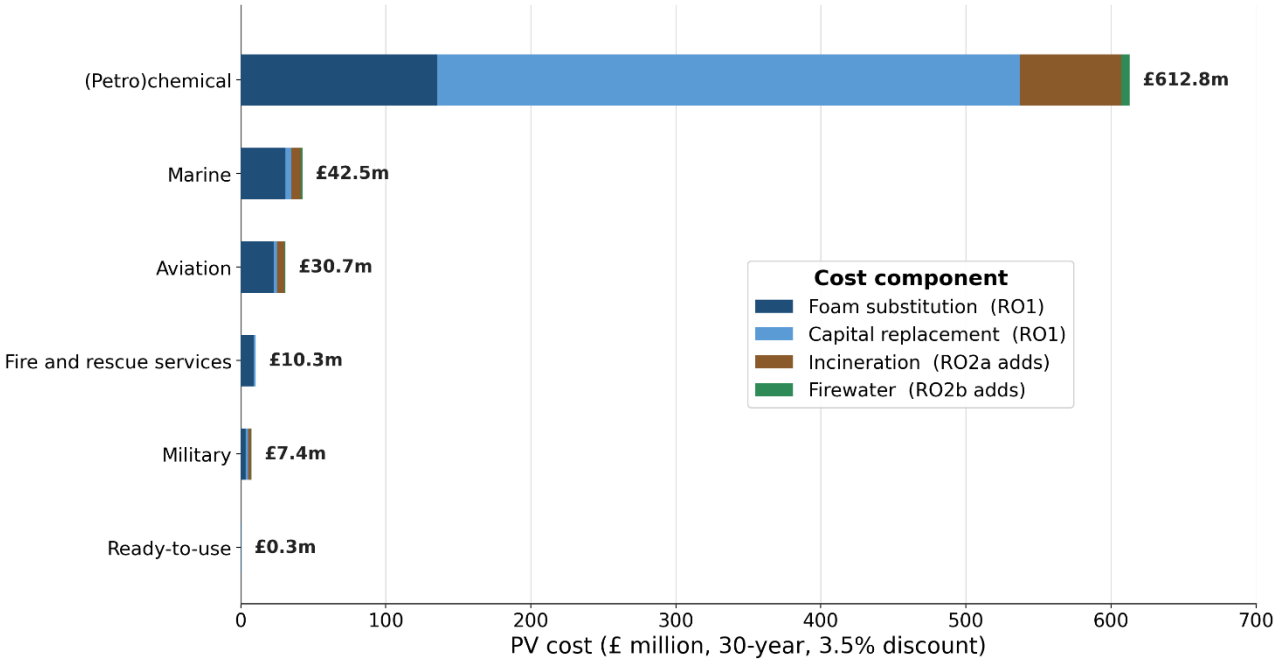
*The Agency has not monetised these costs and expects these costs to be insignificant compared to other monetised costs. (see Sections 6.4.2.7-6.4.2.10)

The Agency estimates the total costs of restriction for RO1, RO2a and RO2b to be **£613.2m, £696.4m and £704.0m**, across the 30-year appraisal period in present value terms, respectively. 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); RO1	Cost (30 years PV, million); RO2a	Cost (30 years PV, million); RO2b
(Petro)chemical	£537.5m	£607.1m	£612.8m
Military	£5.1m	£7.0m	£7.4m
Marine	£34.9m	£41.6m	£42.5m
Aviation	£25.1m	£30.1m	£30.7m
Fire and rescue services	£10.3m	£10.3m	£10.3m
Ready-to-use	£0.3m	£0.3m	£0.3m

Figure 6.4: Types of restriction cost by sector



From the above, one can see that roughly 87% 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 61% of GB consumption), but also in large part due to the high stock holding requirement and more expensive equipment changes being required for COMAH sites under restriction (see Section 6.4.2.2).

The next section explores the emission reduction that the Agency expects to occur under the restriction proposal, which will then allow for the proportionality of intervention to be considered.

6.4.2.12 Emission Reduction

Under the central scenario, the Agency estimates total emissions associated with the scope of this restriction to equal ~1507 tonnes(see Annex G for baseline emissions assumptions). RO1 is expected to bring at least 35% of emission reduction from baseline, while RO2a will reduce emissions by at least 91% and RO2b will reduce emissions by at least 94%.

Figure 6.5 shows how PFAS emissions are expected to evolve within the appraisal period under the baseline and the restriction scenarios. The PFAS emissions under the baseline are expected to be constant over time except for a spike in 2030 due to the constant stock assumption and the expected transition of some subpopulations in the military sector under the baseline (see Annex G). Similarly, the spikes in PFAS emission under RO1 coincide with the end of transition periods (2030, 2035) for some

subpopulations, where they are expected to dispose of unused PFAS-containing stock. The disposal of the large amount of PFAS stock in reserve in the (petro)chemical sector (due to safety regulations) gives rise to the huge spike in 2030. It may appear counterintuitive that the PFAS emissions in RO1 are expected to exceed that for the baseline. The reason is that under RO1, waste management is not mandated under REACH and thus is not attributable to RO1.

Table 6.8 shows the breakdown of PFAS emissions by sector.

Figure 6.5: PFAS emissions in baseline and under restriction

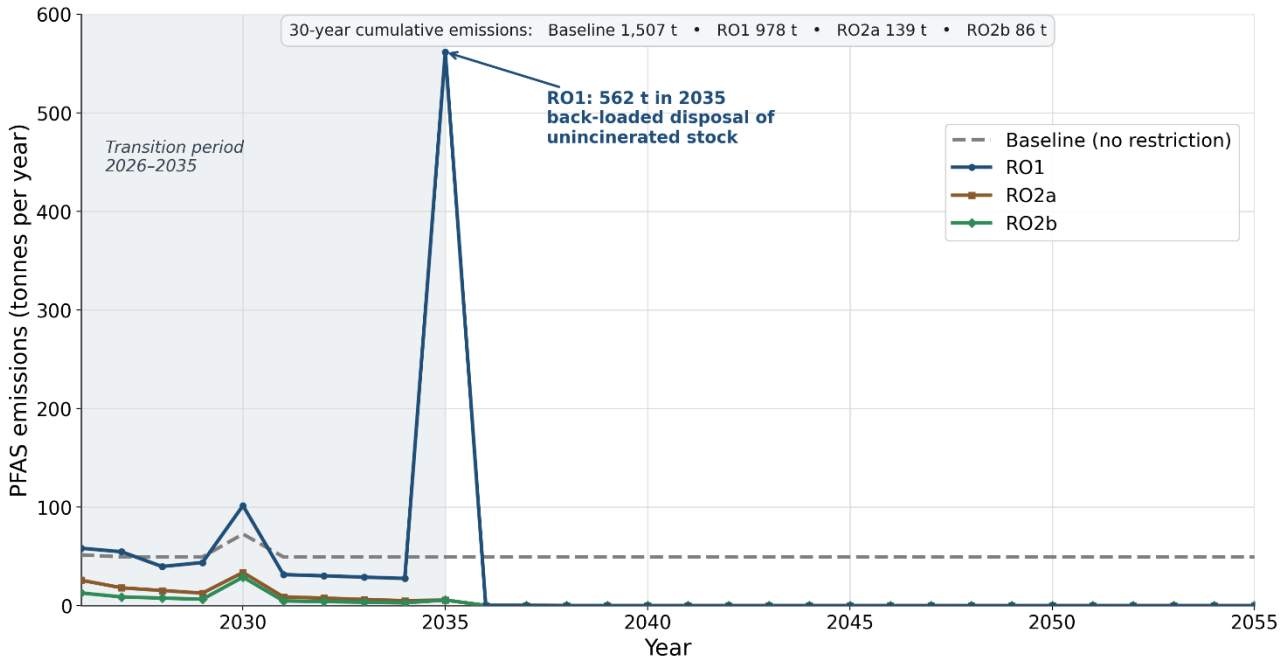


Table 6.8: Sector specific PFAS emissions over the appraisal period

Sector	Baseline PFAS emissions (tonnes, 30 years)	RO1 reduction (tonnes, 30 years)	RO2a reduction (tonnes, 30 years)	RO2b reduction (tonnes, 30 years)
Petrochemical	941.1	202.0	885.1	927.3
Military	73.5	13.4	33.2	33.3
Marine	200.0	105.8	173.4	175.1
Aviation	189.3	132.9	176.7	184.0

Sector	Baseline PFAS emissions (tonnes, 30 years)	RO1 reduction (tonnes, 30 years)	RO2a reduction (tonnes, 30 years)	RO2b reduction (tonnes, 30 years)
Fire & rescue	88.3	62.1	85.0	87.1
Ready-to-use	15.0	13.0	14.9	14.9
GB total	1,507.2	529.3	1,368.3	1,421.6

Emissions 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 has undertaken specific analysis comparing different transition period options. The two examples (comparing transition period of 10 years vs. 5 years in petrochemical sector and marine sector) illustrate a general pattern: shortening transition periods raises total cost and increases emission reduction. The cost-effectiveness ratios also increase as transition periods are shortened. The subpopulations where shortening matters most are those with high capital intensity (chemical/petrochemical, marine) and those where transition cannot easily align with a scheduled capital event. Transition periods have been chosen to minimise these dislocations where consultation evidence supports doing so. Refer to Annex G.4.2. For sector subpopulation specific transition periods, refer to Annex G Table G.10.

Table 6.9: Sector Transition Periods

Sector	Transition period (years)
Aviation	5
Marine	10
Ready-to-use	5
Military	5

Sector	Transition period (years)
(Petro)chemical	10
Fire and rescue services	1.5

6.4.2.13 Cost-effectiveness analysis

With estimates of emission reduction occurring under restriction and the expected costs associated with this, the Agency can estimate cost-effectiveness ratios (CER; £/kg) dividing the expected costs (£) by emission reduction (kg). These can be estimated for restriction as a whole and for individual sectors. Table 6.10 shows the CER of the restriction options.

Table 6.10: Sector specific (average) cost-effectiveness ratios (CER) of restriction options

Sector	RO1 CER (£/kg)	RO2a CER (£/kg)	RO2b CER (£/kg)
(Petro)chemical	2,661*	686	661
Military	381	211	223
Marine	330	240	243
Aviation	189	170	167
Fire and rescue services	166	121	118
Ready-to-use	20	17	17
Total	**1,158**	**509**	**495**

*Red text indicates a CER exceeding the reference point drawn from Oosterhuis and Brouwer (2015).

Most absolute CERs are significantly below (i.e., more favourable) the cost-effectiveness reference point for PBT type substances that Oosterhuis and Brouwer (2015) derive from previous chemicals policy interventions.[3] 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'. 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 that the CER threshold derived loosely reflects societal acceptance of these past decisions.

However, although most absolute CERs are below (more favourable than) the above ECHA-derived reference point, incremental cost-effectiveness ratio (ICER) as opposed to the absolute cost-effectiveness ratio allows a more informed comparison between the ROs. This seeks to answer whether the incremental costs incurred from requiring additional measures (moving from RO1 to RO2a to RO2b) are justified by the incremental reduction in emissions. One can break down the restriction options into different components and evaluate the costs and emission reductions in an incremental manner: substitution from PFAS to F3 foams, disposal of unused stock (HTI), and firewater management.[4] These ICERs can aid the analysis of whether this is deemed a proportionate restriction measure. Table 6.11 shows these ICERs of different measures starting from the baseline.

Table 6.11: Sector specific (incremental) cost-effectiveness ratios (ICER) of restriction options

Sector	Switching from PFAS to F3 ICER (£/kg)	Incineration ICER (£/kg)	Firewater management ICER(£/kg)
(Petro)chemical	2,661	102	134

[3] Although the Oosterhuis and Brouwer study considers policy interventions for PBT and vPvB substances, its findings are considered relevant to PMT-related concerns. While the exposure pathways differ, both regulatory approaches are underpinned by concerns about persistence, uncertain long-term effects, irreversibility, and the need to prevent potentially serious environmental harm before it occurs.

[4] Measures regarding the decontamination of equipment are not assessed as part of the main analysis since decontamination is not an intended requirement of the restriction. They are however considered as a separate analysis in Annex G.4.1.7. This shows that while equipment decontamination (including rinsewater management and testing) prevents rebound emissions to a certain extent, the cost is extreme relative to the risk reduction. The ICER for decontamination is estimated at £130,536/kg, far exceeding the Oosterhuis and Brouwer (2015) informal policy reference point for PBT/PMT substance regulation. Note that these costs will be higher if users are required to regularly collect samples and test to ensure compliance, while the emissions through rebound are expected to trail off over time after transition. These further call the proportionality of a strict end-of-pipe limit into question.

Sector	Switching from PFAS to F3 ICER (£/kg)	Incineration ICER (£/kg)	Firewater management ICER(£/kg)
Military	381	97	4,392
Marine	330	99	575
Aviation	189	115	81
Fire and rescue services	166	n/a	n/a
Ready-to-use	20	n/a	n/a
Total	**1,158**	**99**	**143**

*Red text indicates a CER exceeding the reference point drawn from Oosterhuis and Brouwer (2015).

Some ICER are above the ECHA-derived cost-effectiveness reference point, 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. Although the reference point is an indicator, below which measures are deemed to be societally acceptable compared with other PBT related chemicals policies in terms of cost-effectiveness, that does not necessarily mean that measures whose cost-effectiveness is in the 'grey zone' are not proportionate in terms of their benefits and costs. The (petro)chemical sector ICER of switching from PFAS foams to F3 foams is slightly above the lower bound of 'grey zone' due to the high cost in technical change of the high-tier COMAH (LAST) sites.

Note that the ICERs when requiring firewater collection and disposal are below the reference point but these do not represent the complete picture of firewater management cost-effectiveness. Collection of firewater in some subpopulations may not be possible or monetised, and excluded in the calculation.

A Marginal Abatement Cost Curve (MACC) could similarly be presented for every discrete step of restriction. Figure 6.6 presents the MACC for the restriction as a whole and Figure 6.7 presents the MACC for each sector.

Figure 6.6: Marginal Abatement Cost Curve (MACC) for the restriction as a whole

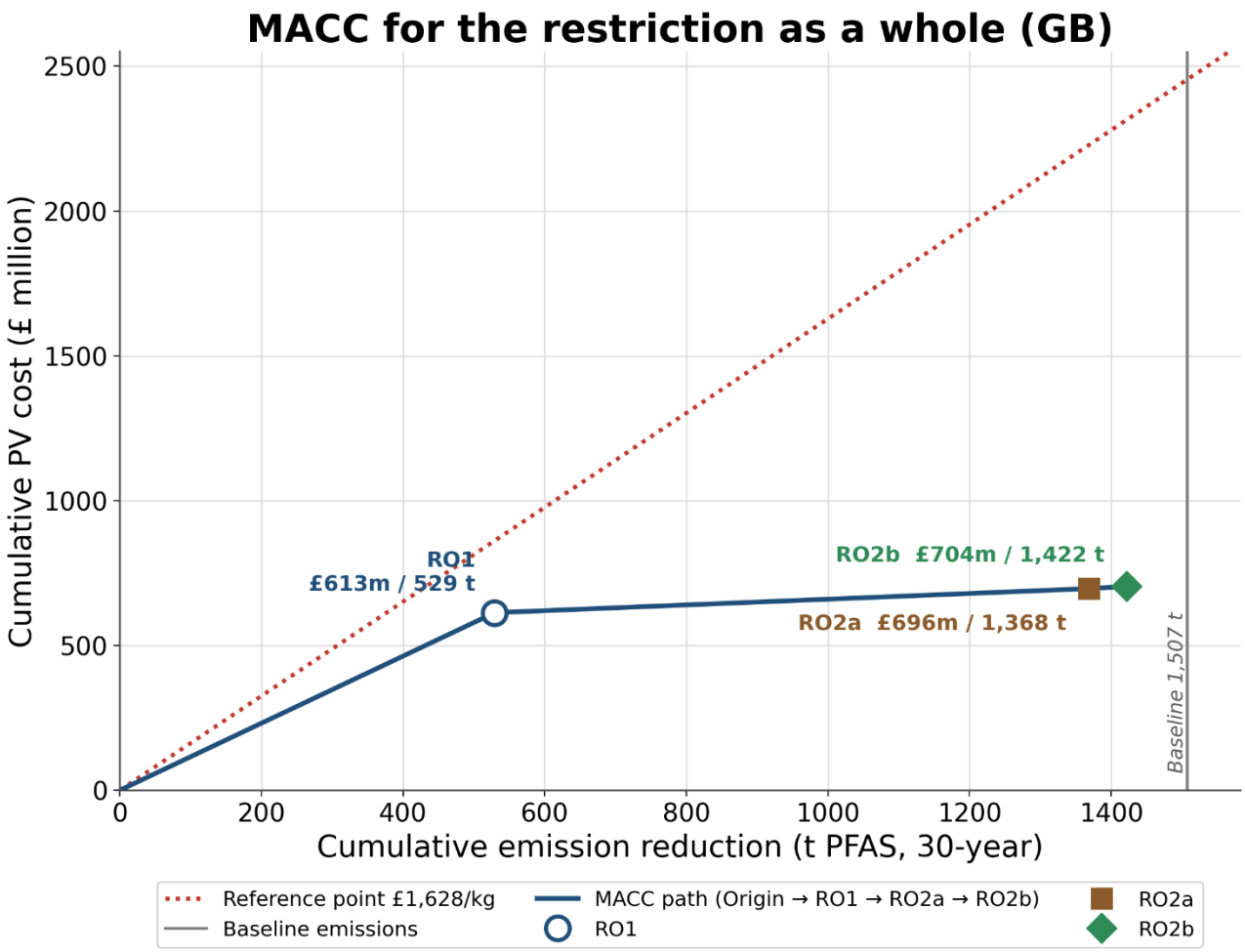


Figure 6.7: Marginal Abatement Cost Curve (MACC) by sector

Note: The remaining emission in the military sector is less than 40t because the emission reductions are not attributable to REACH restriction.

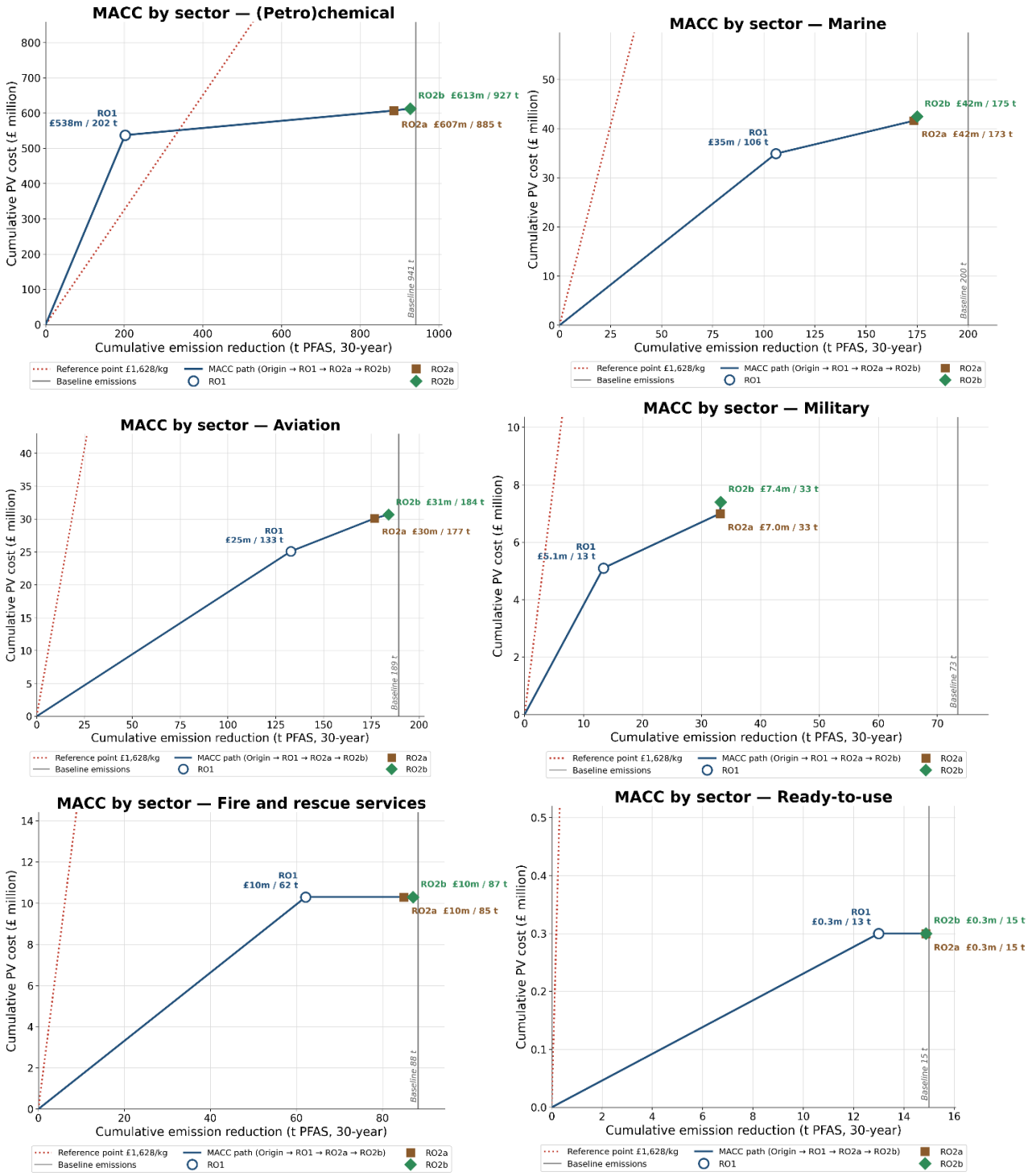


Figure 6.6 shows the costs of restriction, reduction in emissions and cost-effectiveness by different restriction options. Starting from the origin (baseline), RO1 brings an emission reduction of 529.3t (35% of baseline emissions) at a cost of £613.2m. The slope of the line (change in cost divided by change in emission reduction) represents the ICER from baseline to RO1, at £1,158/kg. From RO1 to RO2a, the additional requirement of appropriate disposal of unused stock reduces emissions further by (1368.3t-529.3t=839.0t; 56% of baseline emissions) at an additional cost of (£696.4m-£613.2m=£83.2m). The ICER is £99/kg, represented by the flatter line from RO1 to RO2a. From RO2a to RO2b, the additional requirement of firewater management reduces emissions further by (1421.6t-2368.3t=53.4t; 4% of baseline emissions) at an additional cost of (£704.0m-£696.4m=£7.6m), giving an ICER of £143/kg.

The slope of the dashed line gives the informally established policy reference point for PBT/PMT substance regulation for comparison- regulations on PBT substances with a CER below £1,628/kg have been considered cost-effective from a decision-making standpoint. The ICER of all measures (substitution, unused stock disposal and firewater management) and CER of all three options (RO1: £1,158/kg; RO2a: £509/kg; RO2b: £495/kg) are below this reference point, implying these measures options are considered acceptable in cost-effectiveness grounds based on past policy decisions.

The bottom-up analysis adds a new dimension to the cost-effectiveness assessment by identifying subpopulations where the CER exceeds the reference point (enters ‘grey zone’) in the central case. This does not necessarily mean that measures whose cost-effectiveness ratio is in the ‘grey zone’ are not proportionate in terms of their benefits and costs. See Annex G.4.3 for the cost-effectiveness analysis by subpopulation.

As noted, there are many limitations to using the results of Oosterhuis and Brouwer (2015) as a reference point for demonstrating that a restriction is cost effective. Nonetheless, it provides interesting context relevant to decisions that other authorities have previously made. Further discussion on the limitations is outlined in Section 6.4.4.

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 Options

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, the potential for adverse effects following the 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 (primarily from studies in animals) 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 potential 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 environmental 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 Background Document . 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 exist. Nonetheless, they can be useful to indicate preferences for avoiding such pollution.

No monetised estimate of the benefits of restricting the use of PFAS in FFF has been provided at this stage, owing to limitations in the available evidence on risks and impacts to human health and the environment. On the basis of the current evidence, the Agency considers that any attempt to quantify, and in particular monetise, the environmental and human health benefits would be highly speculative and subject to considerable uncertainty. In these circumstances, the Agency does not consider it proportionate to quantify the benefits of the restriction.

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 thisBackground Document. 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%[5] 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 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 Background Document.

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 (2024b) 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

[5] The authors report these values to be statistically significant at 5% and 1% level, respectively.

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 options

As outlined in Section 6.4.2, the estimated PV costs of restriction, across a 30-year appraisal period, are at least **£613.2m, £696.4m and £704.0m** for RO1, RO2a and RO2b, respectively. Under RO1, emission is reduced by at least **529.3 tonnes**, with RO2a reducing emissions by at least **1368.3 tonnes** and RO2b reducing emissions by **1421.6 tonnes**. A requirement on appropriate disposal of unused stock will result in emission reduction of **839.0 tonnes**. A requirement on firewater management will result in emission reduction of **53.4 tonnes**. 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.

Under RO1, the estimated absolute cost-effectiveness ratio (CER) of the modelled restriction is **£1,158/kg**. The CER under RO2a and RO2b are **£509/kg and £495/kg**, respectively. If incineration of unused stock is required, the incremental cost-effectiveness ratio (ICER) is **£99/kg**. If firewater management is required, the ICER is **£143/kg**. Section 6.4.2.13 showed that all but one individual absolute CERs presented fall within the cost-effective reference point derived by Oosterhuis and Brouwer (2015) (£1,628/kg), loosely implying societal acceptance on cost-effectiveness grounds, that these cost-effectiveness ratios for PBT substances were acceptable to decision makers as reflected by past decisions.

This is a crude measurement of proportionality. 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 reference point 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 less likely to transition voluntarily.

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 reference point in Oosterhuis and Brouwer (2015), though as discussed, this reference point is not necessarily a robust measure.

In line with the above, the Agency does not see a compelling case for concluding that restriction on placing on market and use of PFAS in FFF would be a disproportionate risk management measure. This conclusion is based on the Oosterhuis and Brouwer (2015) reference point rather than a fully quantified cost benefit assessment. Taken together with valuation evidence demonstrating significant benefits (stated, revealed and cost avoidance) associated with avoided PFAS exposure, the Agency concludes that **a restriction is an appropriate measure to address the risk. The requirements to appropriately dispose of unused stock, collect and dispose firewater appear to be proportionate.** However, this should be **interpreted with caution** as this ratio does not reflect the full picture as firewater management in some sectors (e.g., marine or offshore) may not be possible (or monetised) and is not included in the calculation. This ICER of £143/kg **should not be interpreted as a robust measure of cost-effectiveness of firewater management and does not mean that this measure is indeed proportionate**. The Agency recommends **further investigation of the capacity of HTI (or other acceptable methods of disposal) and technical and economic feasibility of firewater management in different sectors and subpopulations**. The Agency is seeking additional information in the public consultation in these two areas.

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

Two sensitivity analyses test the robustness of the central conclusion that the restriction is proportionate at GB and sector levels. Two additional sensitivity analyses including top ten parameters affecting cost-effectiveness, and parameters producing a ‘proportionality flip’ can be found in Annex G.4.4.

6.4.5.1 HTI capacity

The purpose of this analysis is to compare expected available HTI capacity with the expected demand triggered by this restriction, to project the 'pessimistic' scenario of capacity constraint versus demand, in order to stress test the conclusion on cost-effectiveness of requiring appropriate disposal of unused stock (HTI) as a measure. It is important to note that the following analysis focuses on the 'pessimistic' scenario to stress test the conclusion on cost-effectiveness (whether ICER is still favourable despite extreme assumptions), rather than providing a robust forecast of capacity and demand in the appraisal period.

There is steady disposal of 900-1,500 t/year through 2026-2034, which is barely above the no-restriction baseline disposal rate of 938 t/year (the natural shelf-life turnover of PFAS foam concentrate). During these years, the restriction is essentially just channelling normal disposal flows through HTI rather than via the baseline disposal pathway.

Demand surge: A demand surge of 22,472t in 2035 is over 20 times the baseline (steady-state) rate. The demand surge is composed of four subpopulations whose transition paths are configured as fully back-loaded (zero progression in years 1-9 of the transition, then 100% completion in year 10 before the end of transition period): Petrochemical sector (LAST refineries, contributing 19,272t), Marine (UK-flag vessels, 2,400t), Military (Royal Navy vessels, 800t), and Fire and Rescue Services (COMAH tenders, stock held by COMAH sites). There is also a smaller secondary pulse of 3,669t in 2030 driven by the military sector and aviation sector reaching end of their respective transition periods. Note that these are extreme assumptions to stress test the HTI capacity constraint and cost-effectiveness, rather than a robust forecast of demand.

Capacity: Available capacity is inferred from permitting data and OEP (2026):

- According to the hazardous waste incinerator capacity and receipts calculation in Section 3.1.9 using permitting data, a spare capacity of approximately 47,000 tonnes/year is currently available from two facilities, before a new facility becoming operational in 2027. However, this calculation of permitted quantity minus throughput may not be a realistic operational capacity, as it is limited by factors such as planned maintenance.

- According OEP (2026), the two existing facilities have reserved capacity for their existing contracts from competing waste streams: Fawley primarily serves the oil and chemical industries, and Ellesmere Port serves clinical, pharmaceutical and chemical industry. It is expected that there is limited capacity for additional demand from PFAS foams arisen from this restriction. In their analysis, approximately 6,000 tonnes/year is the low estimate of capacity available for POPs, and around 30,000 tonnes/year is the high estimate of capacity available for POPs. This available capacity for POPs AFFF is used as a proxy for the capacity available to the PFAS waste arise from this restriction.

- It is unclear how appropriate it is to use this available capacity for POPs AFFF as a proxy for the capacity available to the PFAS waste arisen from this restriction. This will depend on whether currently listed POPs stockpile will have been processed by the time this restriction enters into force.

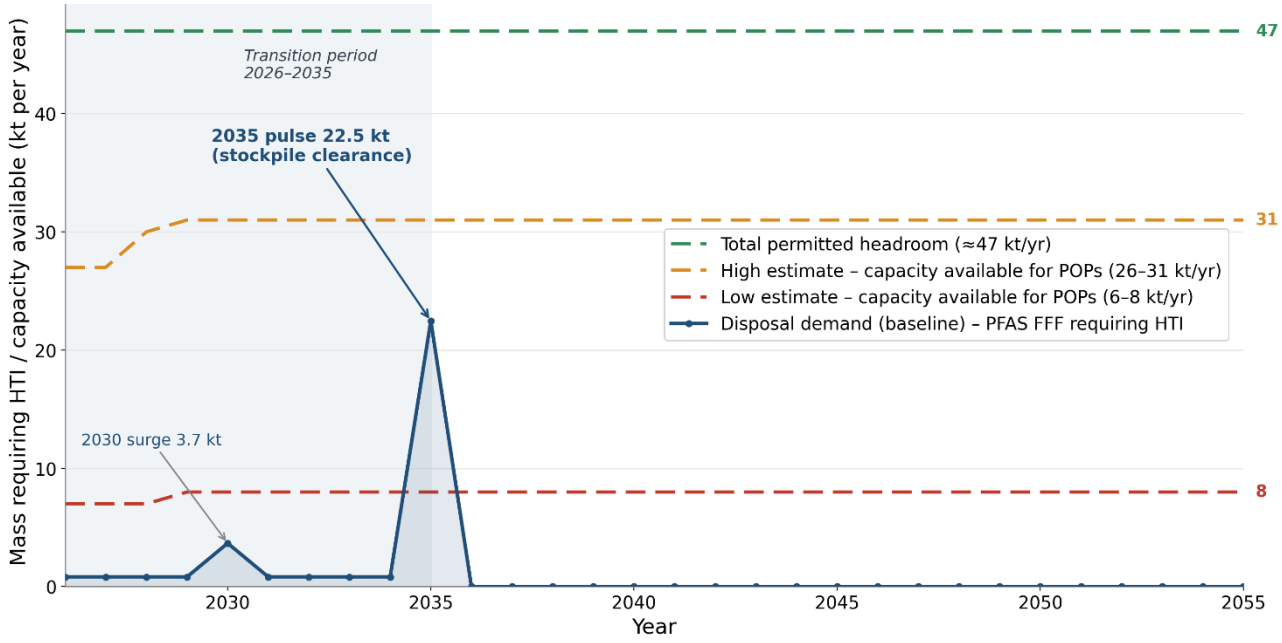
Combining the capacity estimates and the modelled demand of 22,472 tonnes in 2035, it can be concluded that the capacity constraint is more likely to be binding under these conditions:

- The unused stock disposal of some subpopulations with a 10-year transition period lands in a single year (2035).
- Other waste streams take the available capacity first; for example, the facilities are at high utilisation for their core industries and will continue to reserve spare capacity for these clients.
- The facilities will not take PFAS foams, or planned new plant does not become operational as planned.
- Storage is unavailable so the foam cannot be stored to smooth the surge.
- Alternatives, such as exporting wastes to the EU for HTI or alternative technology is not considered by users as feasible, for example, alternative technology does not become commercial in time.

At this stage, the Agency is unable to make more robust conclusion on the capacity versus demand comparison. The Agency is seeking additional information in the public consultation in this area.

The high estimate of £3,000/tonne is adopted as the central estimate of restriction cost to account for the possibility of price surge due to capacity constraint. One could argue that this surge price would likely go down as more capacity becomes available over time. The Agency keeps this surge cost for the following reasons: first, the incineration cost will be incurred within the transition period (i.e., first ten years) so the room for capacity growth is less; second, smoothing and scheduling incineration over the appraisal period will alleviate the surge but this increases storage costs and one could consider that this is included in the estimate; third, this potential overestimate in costs already gives a favourable ICER at £99/kg – decreasing this cost estimate does not change the main conclusion.

Figure 6.8: HTI capacity compared to hypothetical disposal demand surges in 2030 and 2035



6.4.5.2 Comparison with ECHA SEA

Since a large number of parameters are relevant and integral to the analysis outlined above, the upper bound and lower bound of the parameter values have been applied to compute a lower bounds and upper bounds for key results in the GB socioeconomic analysis.

Next, the GB SEA results are compared against ECHA's EU-27 SEA scaled down by five extrapolation methods: population share (14.7%), GDP share (17%), foam concentrate sales share (16%), LAST/COMAH site count share (~14%), and chemical sector size (12%).

Figure 6.9 Panel (a) Total PV cost. The GB SEA range (£137m-£2,821m) fully encompasses the ECHA range (£516m-£2,635m). The GB SEA central (£704m) sits at the lower end of the ECHA range, close to ECHA's lowest extrapolation method but well below the cluster of ECHA centrals (£1,340m-£1,950m, tick marks). The bottom-up calculation is more conservative on cost than any of ECHA's top-down approaches.

Panel (b) 30-year emission reduction. The GB SEA central (1,422t) is just below the ECHA range minimum (1,560t). The bottom-up bottom-line is materially less abatement than ECHA's smallest extrapolation, and 30-60% less than the ECHA centrals (1,730-2,280 t).

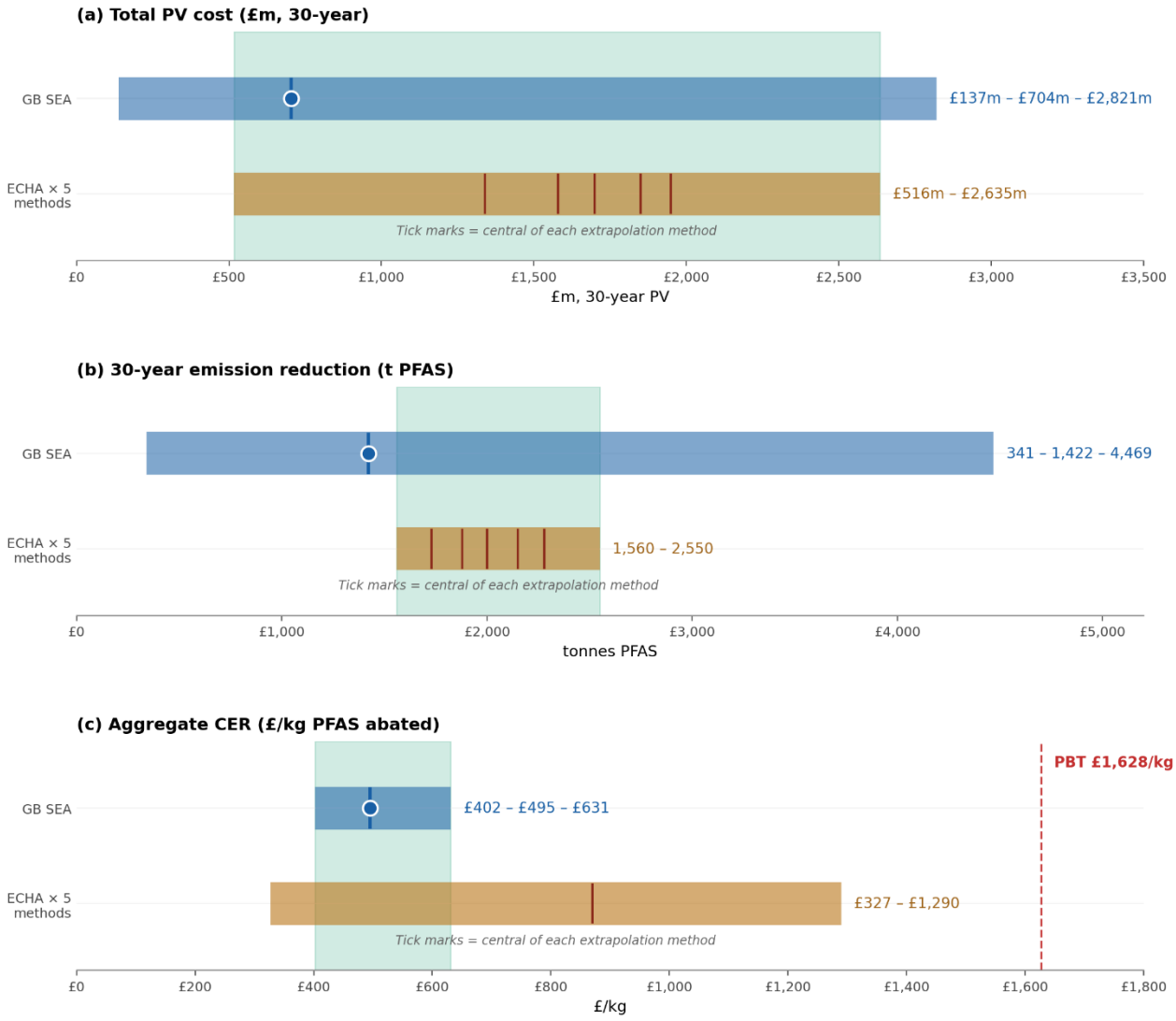
Panel (c) Aggregate CER. The GB SEA range (£402-£631/kg) falls entirely within the lower half of the ECHA methods range (£327-£1,290/kg). Both methodologies independently conclude the restriction is cost-effective by a comfortable margin against the

£1,628/kg PBT reference point, even ECHA's worst extrapolation (£1,290/kg) sits below PBT reference point. The lower cost in the GB SEA and the lower abatement partially cancel in the ratio, so the CER reconciliation is much tighter than either input metric in isolation.

The GB SEA is more pessimistic on abatement and more optimistic on cost than the ECHA extrapolations. Both biases pull the CER toward the centre of the ECHA range, which is why the CER triangulation looks cleaner than the cost or abatement triangulation individually. This is a useful piece of independent validation: even though the bottom-up and top-down approaches disagree by 25-50% on some input metric, they agree to within roughly 30% on the headline cost-effectiveness figure.

Note that the £704m GB SEA central estimate of restriction cost is based on RO2b (Replacement + Capital + Incineration + Firewater costs), excluding the optional decontamination step that adds another £93m. If decontamination is included for comparison with ECHA's full-suite estimate, the GB SEA cost central rises to £797m, still below the ECHA range minimum but the gap narrows.

Figure 6.9: GB SEA ranges against ECHA-extrapolated ranges



6.4.5.3 Main uncertainties in cost and emission assessment of the proposed restriction

Table 6.12 shows the likely direction of each uncertainty on both the estimated cost and the estimated emission reduction, and subsequently on cost-effectiveness ratios. Annex G.4.4 contains the analysis of the main uncertainties individually.

Table 6.12: Main uncertainties in cost and emission assessment of the proposed restriction

Uncertainty / source	Treatment & range in the SEA	Effect on estimated cost	Effect on estimated emission reduction	Net effect on CER & significance
Capital cost per site	Site-specific; ~£0.5k-£250k+ per site (Table G.13)	Either way; overestimated as full replacement cost; can be materially underestimated for some subpopulations	None	High. Most influential single parameter; CER reaches £973/kg (still below £1,628/kg reference point). Only parameter within ~2.4× of flipping proportionality.
Market size (number of sites and stock per site)	Bottom-up 636 / 2,060 / 5,348 t/yr (Table 6.1)	Either way; scales all cost components	Either way; scales baseline and abatement together	High for absolute totals, medium for the CER: numerator and denominator move together, so the ratio is largely self-cancelling.
F3 foam volume multiplier	F3 may require more than 1× the volume of PFAS foam replaced	May understate; higher replacement and disposal cost	Negligible	Medium-high; needs ~40× swing to flip; robust.
PFAS concentration in foam	2.0 / 2.5 / 3.0 % w/w (Table G.8)	Minor; slightly higher incineration mass	Higher concentration → more PFAS abated and more baseline	Medium; near-neutral on the CER; robust.

F3 replacement foam price	£3,600 / 4,000 / 5,000 per tonne (Table 6.5)	May understate; higher substitution cost	None	Medium; needs ~53× to flip; robust.
PFAS foam price avoided	£3,330 / 3,700 / 4,625 per tonne (Table 6.4)	Avoided financial cost; a higher avoided price lowers net cost	None	Low-medium; pushes the CER down.
Foam shelf life	10 / 15 / 30 years (Table G.6)	Shorter life → more purchases → higher cost	Shorter life → more throughput → more abatement	Medium; partially offsetting CER changes.
Incineration (HTI) unit cost and surge capacity	£362–845/t non-surge; up to £3,000/t under the 2030/2035 surge (Figure 6.7)	May overestimate surge pricing if more capacity becomes available	None	Low; reduces CER further, that is, HTI is more cost-effective. Low significance because the conclusion of the HTI measure being cost-effective is unchanged.
Decontamination, rinsate and testing	Excluded from RO2b; would add £75.9m-£159.2m if required	Large upside cost risk if enforcement requires it	Negligible (<1 t abatement)	High as an upside cost risk; would raise the CER sharply if incurred.
Firewater collection efficiency and cost	Efficiency varies by site; firewater-to-foam ratio = 80 (Table G.8)	Minor; small firewater management cost	Small (RO2b firewater capture ≈ 53 t of 1,422 t)	Low; unless firewater collection technical feasibility is disregarded.
Wastewater (other than firewater)	Not monetised	underestimated	underestimated	Low; offsetting CER changes

management cost				
Rebound release factor	6.0e-8 / 8.0e-4 / 1.6e-3 (Table G.8)	None	Higher → more residual leaching → less net abatement	Low-medium; wide range but small absolute effect.
Release assumptions (in-use 100%, WWTP removal 0%)	Conservative fixed values (Table G.8)	None	If true release is lower, baseline and abatement are both overstated	Medium; tends to overstate emission reduction.
Transition-period feasibility	1.5-10 years by sector (Table G.10)	A forced shorter transition raises cost; (petro)chemical 10→5 yr: +£87m	Faster transition brings abatement forward	Medium; a concern flagged by SEAC.
Counterfactual / attribution	Some substitution may occur autonomously; military reductions are not attributable to REACH; baseline on waste management is unclear	Attributable cost may be overstated	Attributable abatement may be overstated	Medium; both numerator and denominator fall (especially Military); near-neutral on CER.
Unquantified costs (enforcement, familiarisation, reformulation,	Set to zero (Table 6.8)	Understates cost	None	Medium; increases CER.

administration)				
Unquantified benefits / avoided costs (remediation, health, liability avoided)	Not monetised	Overstates costs; benefits not netted.	n/a	Medium; increases CER

6.4.5.4 List of parameters

Table 6.13 below contains key modelling parameters used by the Agency in the Annex 15 SEA. See Annex G for a full list and discussion of all parameters. **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 socioeconomic impacts of restriction.**

Table 6.13: Key Modelling parameters used in the Socioeconomic Analysis

Parameter	Low	Central	High	Unit	Table
A. Market and physical parameters					
PFAS concentration in foam	2.0%	2.5%	3.0%	% w/w	G.6
Foam shelf life	10	15	30	yrs	G.6
PFAS foam price	3,330	3,700	4,625	£/t	G.6
F3 foam price	3,600	4,000	5,000	£/t	G.6
F3 volume multiplier (sector-specific)	1.0-1.5	1.1-2.0	1.5-3.0	ratio	G.12
GB annual concentrate sales	1,166	2,061	3,973	t/yr	G.5
Subpopulation site numbers (20 values)	Varies	Varies	Varies	sites	G.2

Stock per site (20 values)	Varies	Varies	Varies	t/site	G.3
Annual use rate (20 values)	Varies	Varies	Varies	%/yr	G.4
B. Emission factors					
In-use release factor	100%	100%	100%	fraction	G.8
Baseline HTI rate	0%	0%	0%	fraction	G.8
HTI destruction efficiency (1,100 °C)	99%	99%	99%	fraction	G.8
WWTP removal efficiency	0%	0%	0%	fraction	G.8
Rebound release factor	6×10^{-8}	8×10^{-4}	1.6×10^{-3}	ratio	G.8
Rebound duration	2	2	2	yrs	G.8
Firewater collection eff. (training, 20 values)	Varies	Varies	Varies	fraction	G.18
Firewater collection eff. (incident, 20 values)	Varies	Varies	Varies	fraction	G.19
Firewater split, training vs incident (20 values)	Varies	Varies	Varies	ratio	G.20
C. Unit costs					
HTI unit cost	£845	£3,000	£3,000	£/t	G.15
Capital cost per site (20 values)	Varies	Varies	Varies	£/site	G.13
Dry-dock proportion (marine A-C)	10%	15%	25%	% fleet	G.14
Dry-dock uplift (marine A-C)	0.5×	1.0×	2.0×	uplift	G.14
Decontamination cost per site (20 values)	Varies	Varies	Varies	£/site	G.21

Rinsewater cost (20 values)	Varies	Varies	Varies	£/site	G.21
Testing cost (20 values)	Varies	Varies	Varies	£/yr	G.21
Firewater training cost (20 values)	Varies	Varies	Varies	£/yr	G.16
Firewater incident cost (20 values)	Varies	Varies	Varies	£/yr	G.17
D. Appraisal and policy parameters					
Social discount rate	3.5%	3.5%	3.5%	%	-
Appraisal period	30	30	30	yrs	-
Base year for present value	2025	2025	2025	year	-
Transition period (20 values)	Varies	Varies	Varies	yrs	G.10
Carbon price (HMT non-traded, central)	£293	£293	£293	£/tCO_2e	-
PBT CER reference point	—	£1,628	—	£/kg	-

Table 6.14 summarises the key results under the lower bound and upper bound parameters. All three CER values for RO2b sit comfortably below the PBT reference point (£402/kg low; £495/kg central; £631/kg high). Even at the high envelope, the aggregate CER has 61% headroom against PBT. The step ICERs from lower bound and upper bound parameters also produce results that are consistent with the earlier conclusion that going beyond substitution to incineration provides the largest marginal value: cumulative abatement nearly triples for ~13% more cost, decreasing the ICER of that step to roughly £100/kg in the central case (lower in the low and high cases). The firewater collection and disposal step adds modest abatement at modest cost as well (ICER ≈ £143/kg central; slightly higher for low and high cases).

Table 6.14: Summary of key results in the central scenario, upper bound and lower bound

Metric	Low envelope	Central	High envelope
Annual PFAS sales (year 1)	636t/yr	2,061t/yr	5,348t/yr
Baseline cumulative emissions (30-yr)	373.9t	1,507.2t	4,662.5t
RO1: substitution only			
Abatement (30-yr)	89.8 t	529.3 t	2,176.1 t
PV cost	£122.4m	£613.2m	£2,612.9m
CER	£1,362/kg	£1,158/kg	£1,201/kg
RO2a: RO1 + incineration			
Abatement (30-yr)	391.2t	1,368.3t	4,295.5t
PV cost	£135.4m	£696.4m	£2,792.4m
CER	£346/kg	£509/kg	£650/kg
RO2b: RO2a + firewater capture			
Abatement (30-yr)	400.4t	1,421.6t	4,468.9t
PV cost	£137.1m	£704.0m	£2,821.4m
CER	£342/kg	£495/kg	£631/kg
ICERs (incremental cost-effectiveness)			

switching to F3	£1,362/kg	£1,158/kg	£1,201/kg
+ incineration	£43/kg	£99/kg	£85/kg
+ firewater capture	£189/kg	£143/kg	£167/kg
PBT reference point	£1,628/kg	£1,628/kg	£1,628/kg

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