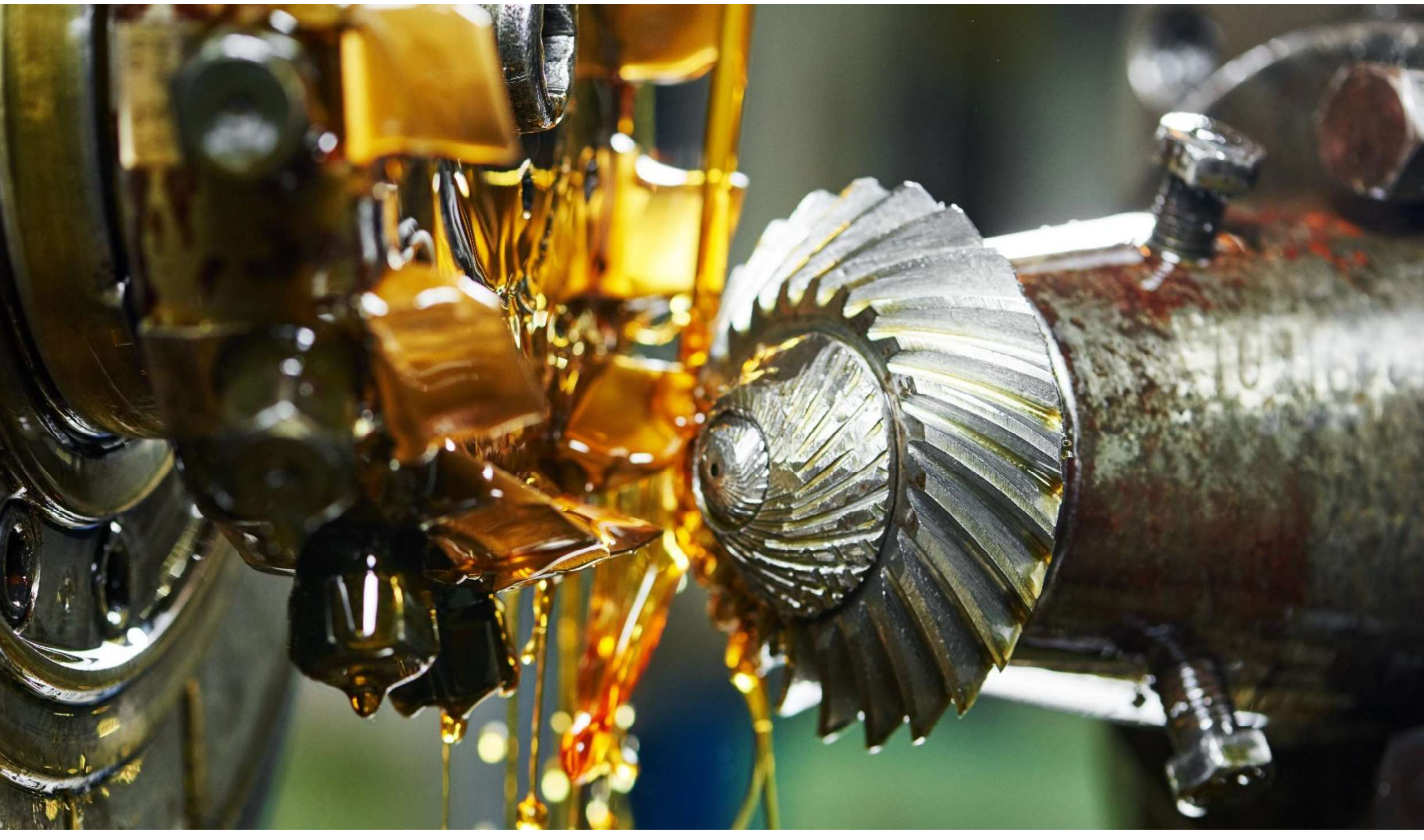
Per- and Polyfluoroalkyl Substances (PFAS) and Alternatives in Hydraulic Oils and Lubricants

REPORT ON COMMERCIAL AVAILABILITY AND CURRENT USES

OECD Series on Risk Management of Chemicals



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Please cite this publication as:

OECD (2025), *Per- and Polyfluoroalkyl Substances (PFAS) and alternatives in hydraulic oils and lubricants: Report on commercial availability and current uses*, OECD Series on Risk Management of Chemicals, OECD Publishing, Paris, https://doi.org/10.1787/fed2872b-en.

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The Inter-Organisation Programme for the Sound Management of Chemicals (IOMC) was established in 1995 following recommendations made by the 1992 UN Conference on Environment and Development to strengthen co-operation and increase international co-ordination in the field of chemical safety. The Participating Organisations are FAO, ILO, UNDP, UNEP, UNIDO, UNITAR, WHO, World Bank, Basel, Rotterdam and Stockholm Conventions and OECD. The purpose of the IOMC is to promote co-ordination of the policies and activities pursued by the Participating Organisations, jointly or separately, to achieve the sound management of chemicals in relation to human health and the environment.

Acknowledgements

This report was prepared under the framework of the Global PFAS Group and developed with financial support from Denmark, Japan and the United Kingdom. A draft report was developed by the consultant WSP with input from the members of the Global PFAS Group. The report was also reviewed and endorsed by the Working Party on Risk Management. This work was approved and declassified by the Chemicals and Biotechnology Committee on 12 June 2025.

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Executive summary

This report examines the commercial availability and current uses of per- and polyfluoroalkyl substances (PFASs) and non-PFAS alternatives in lubricants and hydraulic oils within the framework of the Global PFAS Group. The study considered publicly available information from worldwide sources, including those provided by members of the Global PFAS Group. The information was supplemented by discussions and inputs from experts with stakeholders from a range of backgrounds (academic, regulatory and industry). The key findings of this study are as follows:

- PFASs are used in various lubricant components across a wide range of different sectors and end uses. It is estimated that approximately one third of the PFASs used are in base oils (most notably PFPEs) and two thirds are micro-powder additives (almost entirely PTFE). PFASs are shown to impart wide and unique combinations of properties, that in turn enable a range of technical functions simultaneously. These are associated with key performance qualities that cannot be attained with more 'conventional' lubricants.
- While some progress is being made in substituting PFASs in these uses, and various non-fluorinated alternatives have been identified, manufacturers and downstream users of lubricants have highlighted the technical and economic challenges in developing suitable alternatives in many uses. This is mainly associated with the multi-functional aspect of PFASs in these uses, and it is suggested that, while alternatives can replicate some of the functionality needed, it is technically challenging to replace all desired functionality with one 'drop in' option.
- It is expected that, in the absence of significant market drivers towards substitution, the market for PFAS-based lubricants will expand in the future. It is currently indicated that PFAS-based lubricants are limited to uses that must withstand 'harsh' or 'extreme' conditions (e.g. related to temperature, pressure, corrosive chemicals, radiation etc) and where the use is considered by the user to be 'critical' (e.g. related to safety or reliability of equipment). However, what constitutes 'harsh' or 'extreme' conditions or 'critical' uses is subjective and likely to vary between sectors and users. This report highlights the importance of making an objective assessment of required performance requirements so it can be determined where, and for what functions, available alternatives can currently be used.

Based on the conclusions of this study, a number of specific policy recommendations are made, highlighting specific actions for different actors, in order to address the barriers and challenges associated with substitution of PFASs in lubricant and hydraulic oils. These include:

- **For international organisations**: actions to further understand the potential health and environmental risks of PFASs and non-PFAS alternatives; and systematically collect market data on the use of PFASs and alternatives in hydraulic oils and lubricants.
- **For national and regional governments and agencies**: develop and implement national-or regional-level action plans and risk management measures to minimise the uses and releases of PFASs in

hydraulic oils and lubricants; establish a regulatory approach incorporating requirements for users to report and assess alternatives for identified uses, which could include specific guidance on what a ‘critical’ application is; and prioritise research funding to address current knowledge gaps.

- **For individual companies**: actions to phase out the use of PFASs in lubricant and hydraulic oil products where possible; a more detailed evaluation of uses and performance requirements and targeted comparative tests to fully evaluate the potential alternatives.
- **For industry associations**: actions to better investigate and monitor the uses of PFASs across the full supply chain in different sectors; supporting the sharing of knowledge and data between different users, including data from the evaluation of alternatives and methods or approaches to help users determine if the use of PFASs in specific applications is ‘critical’.

List of abbreviations

Abbreviation	Full terminology
ACEA	European Automobile Manufacturers' Association
ASD	Aerospace, Security and Defence
ATIEL	Technical Association of the European Lubricants Industry
ATSP	Advanced high-bearing aromatic thermosetting polyester
CAGR	Compound Annual Growth Rate
EEA	European Economic Area
EP	Extreme Pressure
EU	European Union
FEP	Fluorinated ethylene propylene
FPs	Fluoropolymers
GNP	Graphene nanoplatelets
HPU	Hydraulic power units

Abbreviation	Full terminology
ICCM	International Conference on Chemicals Management
IPA	Isopropyl Alcohol
LC	Long chain
LOX	Liquid oxygen
MRO	Maintenance, repair, and overhaul
MW	Molecular Weight
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
PA	Polyamide
PAOs	Polyalphaolefin
PASF	Perfluoroalkane sulfonyl fluoride
PAVE	Copolymer of TFE and a perfluoroalkylvinylether
PCTFE	Polychlorotrifluoroethylene
PEEK	Polyether ether ketone
PEM	Polymer Electrolyte Membrane
PET	Polyethylene terephthalate
PFA	perfluoroalkoxyl polymer

Abbreviation	Full terminology
PFASs	Per- and polyfluoroalkyl substances
PFBE	Perfluorobutylethylene
PFCAs	Perfluoroalkyl carboxylic acids
PFHxS	Perfluorohexane sulfonic acid
PFNA	Perfluorononanoic acid
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonate
PFOSF	Perfluorooctanesulfonyl fluoride
PFPAE	Perfluoropolyalkylether
PFPE	Perfluoropolyethers
PFSA	Perfluoroalkane sulfonic acid
POP(RC)	Persistent Organic Pollutants (Review Committee)
PP	Polypropylene
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidene fluoride
R&D	Research and Development
SH	Short chain

Abbreviation	Full terminology
SIA	Semiconductor Industry Association
SPIN	Substances in Preparations in Nordic Countries
UEIL	Union of the European Lubricants Industry
UNEP	United Nations Environment Programme

1 Background

The Global PFAS Group[1]

The Global PFAS Group was established in 2012, in response to the International Conference on Chemicals Management (ICCM) - ICCM Resolution II/5. The group brings together experts from OECD members, non-member countries, academia, governments, industry, and NGOs, as well as representatives from other international organisations, with the aim of continually facilitating the exchange of information regarding PFASs and to support a global transition towards safer alternatives.

One of the key work streams of the group is to gather information on alternatives to PFASs, to understand what they are, what they are used for, their market penetration, feasibility, effectiveness, and cost. The Global PFAS Group has produced a number of reports on PFASs and their alternatives, including the 2013 synthesis report on the use, potential adverse effects, and alternatives to PFASs (OECD/UNEP Global PFC Group, 2013[1]); a set of 15 fact cards on the major groups of PFASs (OECD, 2022a[2]); and reports on the use of PFASs and alternatives in specific sectors, including coatings, paints and varnishes (CPVs) (OECD, 2022b[3]), food packaging (OECD, 2022c[4]) and cosmetics (OECD, 2024a[5]).

Background and aims of the study

PFASs, their uses, hazards and risks

PFASs are a family of synthetic chemicals that have been extensively used in a wide number of different industrial and consumer applications for over 80 years due to their unique physical and chemical properties (such as water-, oil- repellence and high chemical and thermal stability). Since the discovery of polytetrafluoroethylene (PTFE) in 1938, both polymeric and non-polymeric PFASs, have been used extensively and are in everyday use in various industries worldwide.

In general, the highly stable carbon-fluorine bond and the unique physicochemical properties of PFASs make these substances valuable ingredients for products with high versatility, strength, resilience and durability. PFASs are used to fulfil a wide range of functions across industrial, professional, and consumer settings, including applications in textiles and leather; cosmetic products; food contact materials; paper and board; firefighting foams; household articles and consumer mixtures; construction products; lubricants, hydraulic oils and greases; industrial chemicals used in chrome plating; use in electronics such as the manufacture of semiconductors; mixtures for treatment of skis; medical devices and apparel; inks, dyes, and paint coatings, applications within the oil, gas and mining industry; refrigeration and cooling applications; transportation

[1] Previously called the OECD/UNEP Global Perfluorinated Chemicals (PFC) Group

(automotive, aviation etc.); and photographic surface layers (Glüge et al., 2021[6]); (ECHA(a), 2023[7]). PFASs are also reportedly used in medicines[2] and pesticides (Donley N, 2024[8]).

Over the past 25 years, there have been growing concerns that the unique physicochemical properties of PFASs that have made them so useful and popular in their wide-ranging uses, can also result in negative impacts on the environment and human health (ECHA(a), 2023[7]) (OECD, 2023[9]). An environmental concern for PFASs, and/or their degradation products, is their very high persistence (ECHA(a), 2023[7]). Some PFASs can be, or can degrade to, extremely persistent chemicals that accumulate in humans, animals, and the environment (European Environment Agency, 2022[10]). Their resistance to degradation, and high mobility in the environment mean that some PFASs are now ubiquitous in the environment, including remote environments such as the Arctic (Hartz et al., 2023[11]) (Muir et al., 2019[12]). These PFASs have been observed to contaminate water and soil in most European Union (EU) countries, and it is extremely difficult and costly to clean up such contamination (Nordic Council of Ministers, 2019[13]).

With regard to human health impacts, a number of PFASs are known to display potentially hazardous and/or bioaccumulative effects. Health effects in humans associated with exposure to certain PFASs include increased cholesterol levels, impact on infant birth weights, effects on the immune system, increased risk for certain types of cancers, and thyroid hormone disruption (Ministers of Denmark, Luxembourg, Norway & Sweden, 2019[14]). Some PFASs are classified in the EU as toxic for reproduction, for the liver, and as suspected carcinogens (HBM4EU, 2022[15]) (ECHA(a), 2023[7]). However, while there are several thousand known PFASs only a relatively small number of PFASs has been assessed for their health effects.

Some OECD countries have, therefore, taken the first steps to address all PFASs as a class. For example, the Government of Canada (2021) published a notice of intent (Government of Canada, 2021[16]), outlining several actions to assess and address PFASs as a class, and subsequently collected and examined information on PFASs, and published a final State of PFAS Report (Environment and Climate Change Canada, Health Canada, 2025[17])), which concluded that the class of PFAS, excluding fluoropolymers, as defined in the report, is toxic under the *Canadian Environmental Protection Act, 1999* (CEPA). At the same time, the Government of Canada has published a Risk Management Approach (Environment and Climate Change Canada, Health Canada, 2025[18]) for a 60-day public comment period (ending 7 May 2025). Australia has also developed regulatory, policy and voluntary approaches to regulating PFASs, so that importers and manufacturers of PFASs must comply with legal obligations under the Industrial Chemicals Act 2019 (Australian Government, 2019[19]).

The European Commission has recommended that actions at the EU level should be taken to ensure that the use of PFASs is phased out unless proven essential for society (European Commission, 2020[20]). In February 2023, an EU restriction proposal was published, regarding around 10,000 PFASs compounds across a wide range of different sectors and uses (including lubricants and hydraulic oils). This proposal was prepared by authorities of Denmark, Germany, the Netherlands, Norway, and Sweden, with the aim of limiting the risks to people and the environment (ECHA, 2023a[21]).

[2] As indicated by the European Federation of Pharmaceutical Industries Associations (EFPIA), see:

https://www.efpia.eu/news-events/the-efpia-view/statements-press-releases/evidence-shows-more-than-600-essential-medicines-at-risk-and-manufacturing-in-europe-will-grind-to-a-halt-if-wide-ranging-chemical-ban-is-implemented/

Aim of this report

The current study is intended to support and further advance the work of the Global PFAS Group by looking at the commercial availability and current uses of alternatives to PFASs used in hydraulic oils and lubricants. It is expected that this work will support the Global PFAS Group in achieving its key goals of understanding what alternatives are available for these applications, what are they used for, their market penetration, feasibility, effectiveness, and the costs associated with the use of such alternatives.

Definition of PFASs

The definition of what constitutes 'PFASs' differs between publications and authors, and is discussed comprehensively elsewhere, for example in OECD/UNEP Global PFAS Group (OECD/UNEP Global PFC Group, 2013[1]), OECD (OECD, 2021[22]), Buck et al. (Buck et al., 2011[23]) and Buck, Korzeniowski, Laganis, & Adamsky (Buck et al., 2021[24]). For the purposes of these reports, the discussion of PFASs and their alternatives uses the structural-based definition from the OECD report "Reconciling Terminology of the Universe of Per- and Polyfluoroalkyl Substances: Recommendations and Practical Guidance" (OECD, 2021[22]):

"PFASs are defined as fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I 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 PFASs" (OECD, 2021[22]). It is noted that the EU restriction proposal for PFASs (ECHA(a), 2023[7]) uses a broadly similar definition.

The term 'PFASs' is a broad term and the exact number of individual chemical substances in the PFAS family varies between various studies conducted by different authors, depending on the specific definition used. In general, the number of PFAS compounds will be in the order of several thousands. Publications by the USEPA (USEPA, 2021[25]) and Buck, Korzeniowski, Laganis, & Adamsky (Buck et al., 2021[24]) suggest that the number PFASs that are actively used commercially is in the order of several hundreds.

PFASs can be divided into subgroups in several ways, e.g. based on the chemical moieties present, the carbon chain length, and non-polymeric vs polymeric structures (ECHA(a), 2023[7]). According to their definition, 'PFASs' are typically divided into two key categories:

- **Non-polymeric PFASs** comprise a range of diverse molecules and include two broad sub-groups defined by their fluorinated carbon chain length, which can be either short chain (SC) or long chain (LC). As outlined in (OECD, 2021[22]), these have been historically described as follows:
    - Long-chain (LC) includes:
        - Perfluoroalkyl carboxylic acids (PFCAs) with seven or more perfluoroalkyl carbons, such as perfluorooctanoic acid (PFOA) (with eight carbons or C_8 PFCA) and perfluorononanoic acid (PFNA) (with nine carbons or C_9 PFCA);
        - Perfluoroalkane sulfonic acids (PFSAs) with six or more perfluoroalkyl carbons, such as perfluorohexane sulfonic acid (PFHxS) (with six perfluoroalkyl carbons, or C_6 PFSA) and perfluorooctanesulfonic acid (PFOS) (with eight perfluoroalkyl carbons or C_8 PFSA); and
        - Substances that have the potential to degrade to LC PFCAs or PFSAs, e.g. through various degradation processes (aerobic, anaerobic, biodegradation) from precursors such as perfluoroalkane sulfonyl fluoride (PASF) and fluorotelomer-based compounds.
    - Short-chain (SC) includes: PFCAs with six or fewer perfluoroalkyl carbons and carbon chain lengths of less than C_7, and PFSAs with carbon chain lengths of less than C_6.

- **Polymeric PFASs** can be divided into three major groups, as described in (OECD, 2021[22]):
  - Fluoropolymers (FPs): fluorinated polymers consisting of carbon only backbone with fluorine atoms directly attached to this backbone (e.g. PTFE; polyvinylidene fluoride (PVDF); fluorinated ethylene propylene (FEP); perfluoroalkoxyl polymer (PFA); etc.). FPs are not made from PFCAs or their potential precursors (except perfluorobutylethylene (PFBE) that can be used as a comonomer). PFCA homologues are, however, used as processing aids in the polymerisation of some FPs.
  - Side-chain fluorinated polymers: fluorinated polymers consisting of variable compositions of non-fluorinated carbon backbones with polyfluoroalkyl (and possibly perfluoroalkyl) side chains. The fluorinated side-chains, including PASF- and fluorotelomer-based derivatives, are potential precursors of PFCAs.
  - Perfluoropolyethers (PFPE): fluorinated polymers consisting of backbones containing carbon and oxygen with fluorine atoms directly attached to carbon. They are not made from PFCAs or their potential precursors; and PFCAs or their potential precursors are not involved in the manufacturing of PFPE.

It should be emphasised that the specific terminology, definitions and distinctions used to describe PFASs differ between studies or the regulatory actions in different regions. For example, more recent language in European and Canadian publications and regulatory actions indicate the term 'LC' usually refers to ≥8 carbons for PFCAs. 'LC PFCAs' have been nominated for restriction under the Stockholm Convention, using the range C_9-C_{21} (UNEP, 2022[26]) and C_9-C_{14} PFCAs have been restricted in the EU/EEA since 2023[3]. In Canada LC-PFCAs, under Schedule 1 of the Canadian Environmental Protection Act, 1999 are considered 'Perfluorocarboxylic acids that have the molecular formula CnF2n+1CO2H in which 8 ≤ n ≤ 20 and their salts'.[4]

Scope of this report

This report focuses on the uses of PFASs and their alternatives in lubricants and hydraulic oils, considering both the direct use of PFASs as lubricating agents themselves (e.g. in base oils, greases) and as additives to other lubricant products.

This report follows the definitions as used in (OECD, 2017[27]), where 'lubricants' are defined as "chemical substances used to reduce friction, heat generation and wear between solid surfaces that are intended for consumer or commercial use". Examples of lubricants and greases include engine oils; transmission, brake and hydraulic oils; gear oils; and calcium, sodium, lithium, and silicone-based grease. This report covers the uses defined in (OECD, 2017[27]) product use categories including liquid, paste, and spray lubricants. However, 'degreasers', defined in (OECD, 2017[27]) as "product that remove greases or oils from hard surfaces, machinery, or tools", are not in the scope of this report.

The terminology and definitions used for lubricant applications are not always uniformly defined in across different data sources, geographies, and industry sectors. Investigating the use of PFASs in lubricants is challenging because the term 'lubricant' can encompass myriad different specific uses and functions. For

[3] See: https://echa.europa.eu/registry-of-restriction-intentions/-/dislist/details/0b0236e18195edb3

[4] See: https://www.canada.ca/en/environment-climate-change/services/evaluating-existing-substances/supporting-document-ecological-state-science-report-sc-pfcas-sc-pfsas-lc-pfsas.html

example, lubricants can include mineral base oils, combustion engine lubricants, lubricant additives, hydraulic and transmission fluids, gear lubricants, lubricating greases, metalworking and machining fluids (Rizvi, 2009[28])).

As discussed by Rizvi (2009), lubricants are generally used for the following actions: (1) lubrication (reducing friction and wear between mechanical moving parts); (2) cooling (heat transfer; dissipates the heat away from the critical moving parts of the equipment); (3) cleaning and suspending (facilitates smooth operation of equipment by removing and suspending potentially harmful products); (4) protection (lubricant prevents metal damage due to oxidation products, corrosion, and wear); (5) transfer power (lubricant is used as a power transfer medium in some applications). A further complication in the assessment of PFASs and alternatives in lubricants is that some studies consider lubricants as a separate discreet sector, while others discuss lubricants (and/or lubricant additives) as a sub-use under broader sectors (e.g. transport, energy, industry etc).

Similarly, hydraulic oils can be referred to under a range of different definitions and terminologies across different sources. In this report, the (OECD, 2017[27]) definition is used for hydraulic oils: *"chemical substance, typically liquid or gaseous, used for transmitting pressure and extreme pressure-additives; and to transfer power in hydraulic machinery"*. However, it is noted in (OECD, 2017[27]) that these are also commonly referred to by other terms such as 'hydraulic fluid', 'transmission fluid'; 'brake fluid'; 'power steering fluid' etc. For purposes of this report, the terms 'hydraulic fluids' and 'hydraulic oils' are considered interchangeable.

In some cases, hydraulic oils are considered as a subset of lubricants, in others, e.g. (ECHA(a), 2023[7]), they are considered separately as a discreet use under the transport sector. In the (ECHA(c), 2023[29]) restriction proposal, hydraulic oils are discussed mainly in the context of their use in the aviation industry. While the report title here refers to hydraulic oils and lubricants as separate products or applications, for the purposes of this study, hydraulic oils are considered as a category of use under the broader consideration of the use of lubricants.

The use of PFASs in lubricants and hydraulic oils is complex, covering a wide range of industry sectors and applications. As a consequence, it has been necessary to adjust the structure of this report, to seek an optimal way to present the diverse information and to focus on selected key areas. For example, it has not been possible to carry out an efficacy and market analysis for all individual uses within lubricants and hydraulic oils that have been identified here. Instead, a focus has been placed on specific uses or sub-categories of uses, which are shown to be significant (e.g. in terms of market share, value or the challenges or drivers to alternatives) and where there was a greater availability of evidence.

For the purposes of this study an 'alternative' refers to substances and mixtures that do not meet the OECD definition of PFASs (see above) that are used to perform the same functions. This report discusses both 'chemical' and 'non-chemical' alternatives. Chemical alternatives are chemical substances that can be used as replacements for PFASs in mixtures or articles and can perform at least to some extent the same function(s) of PFASs. Non-chemical or 'technical' alternatives refer to changes to the product or systems to avoid the use of PFASs (or even the use of any chemical substances), which includes changing or modifying equipment or parts of completely.

Within the past decade several 'long-chain' PFASs[5] (e.g., PFOS, PFOA, PFCAs C_9-C_{14}) have been restricted or banned under national or international legislation. Such restrictions have led to a shift towards short-chain PFASs for a number of uses that have been increasingly used as an 'alternative' to the long-chain PFASs for some applications. Information indicating where a shift from LC to SC PFASs may have occurred in the

[5] See above for a discussion of LC and SC PFASs

lubricants and hydraulic oils sector is included as part of this report, as part of the consideration of 'alternatives', however this should not be taken as indication that such a switch is considered acceptable in the context of 'regrettable substitution'[6].

Geographically, the scope of this report focuses on OECD countries and related regions and was developed on the basis of available data. Attempts to provide a broad geographic coverage has been made, but this has not been possible in all cases since the evidence base of available literature is wider for some regions compared to others. For example, there is a strong evidence base in regions that have or are in the process of developing legislation on PFASs. Gaps in the knowledge with respect to geographical coverage are highlighted where appropriate in the report.

Generally, only substances and mixtures that are commercially available are considered in this report. However, identified information relating to ongoing research and development (R&D) is also discussed where relevant and has been included. This report is not intended to be comprehensive or an exhaustive survey of what is commercially available. Instead, the report summarises the findings of the research carried out for this project and the subsequent analysis.

This report is exclusively intended to be a market analysis. As such, the potential health and environmental implications of PFASs and the alternatives identified, as well as wider life-cycle analyses of the alternatives, are outside the scope of this study.

Structure of the report

This report presents the overall findings on PFASs and alternatives in hydraulic oils and lubricants. The outline of the report is as follows:

- Introduction, including the context of the study, its scope and aims (Chapter 1);
- The market and technical function of PFASs in lubricant and hydraulic fluid applications; and the commercial availability and market trend of alternatives to PFASs in lubricants and hydraulic oils/lubricants, (Chapter 2) including:
    - The use(s) and function(s) of PFASs in hydraulic oils and lubricants;
    - The specific PFASs identified in hydraulic oils and lubricants;
    - The identity and commercial availability of chemical and non-chemical (technical) alternatives.
- Efficacy of alternatives to PFASs in lubricants and hydraulic oils (Chapter 3), including:
    - The technical feasibility of identified alternatives;
    - The associated costs (both unit cost and lifetime/operating cost) of using alternatives.
- Uptake and market penetration of alternatives (Chapter 4), including;
    - The overall market for lubricants and hydraulic oils;
    - The market share of alternatives and geographical coverage;
    - Timeframes for implementation of alternatives;
    - Challenges (technical, economic, regulatory) and drivers (market, regulatory) for alternatives.

[6] A scenario where a chemical substance is used to replace a chemical of concern also ends up being problematic

- Status of the shift to alternatives and its sustainability (Chapter 5);
- Policy recommendations and areas for further work (Chapter 6);
- Uncertainties and limitations resulting from the study (Chapter 7);
- References – a full list of references used in the report.

Methodology

The report is based on a review of publicly available information[7], supplemented by information provided by the members of the Global PFAS Group and additional stakeholder consultation. The literature reviewed includes reports and papers published by national and international authorities, academic institutions, and industry, as well as information on individual company websites, and media articles. The information from the literature has been obtained either directly or indirectly (i.e. using information from the references cited).

This work was further supplemented through interviews and targeted information requests to Global PFAS Group members, as well as key stakeholders identified through the information gathering process. Targeted stakeholder consultation included inputs from expert stakeholders from research institutions, industry associations, companies and NGOs. It should be noted that where information is presented based on inputs from this further consultation, specific opinions or information are not attributed to named individuals or organisations in the report text. As such they are fully anonymised. A full list of stakeholders consulted is available in Annex A.

In the development of this report, it has been reflected that the recent reports published by ECHA (ECHA(c), 2023[29]) and Danish Environmental Protection Agency (Danish Environmental Protection Agency, 2024[30]) represent relatively comprehensive reviews of available literature related to this topic, hence this report draws regularly from these two key resources.

Additional literature relating to any key gaps from those reports e.g. relating to the market for, and technical/economic feasibility of, available alternatives has been reviewed and included. It is also noted that further input in addition to the published ECHA and Danish Environmental Protection Agency reports has been provided as part of ECHA's public consultation for the REACH restriction proposal on PFAS[8]. Therefore, this information has also been reviewed and relevant inputs (in the public domain) have been cited. This includes submissions or position papers submitted by relevant industry associations, e.g. representing the manufacturers or users of lubricants and hydraulic oils.

[7] In this context, publicly available is referring to sources that are in the public domain and free of change to access

[8] https://echa.europa.eu/comments-submitted-to-date-on-restriction-report-on-pfas

2 Overview of the commercial availability and market for PFASs and alternatives in hydraulic oils and lubricants

The identity, uses and market for PFASs in hydraulic oils and lubricants

Identity and uses of PFASs in lubricants and hydraulic fluids

For purposes of clarity and consistency throughout this report, reference is made to the following aspects regarding the use of PFASs and alternatives in hydraulic oils and lubricants:

- **Lubricant component –** lubricant products can be considered on the basis of the combination of different components. In general, three key categories can be described: (1) base oils (the base component of the lubricant itself); (2) chemical additives (additional chemical substances added to impart enhanced or additional physical or chemical properties); and (3) solvents (i.e. a carrier and deposition solvent as part of a lubricant dispersion). As this section discusses in more detail, PFASs are associated with each of these components, and in some products, they can be used in multiple components of the same product.
- **Lubricant type –** this refers more directly to the lubricant product itself, and the specific type of use for which these are marketed, and for what purpose or scenario they are used.
- **Lubricant use –** this refers specifically to the end-use of the products, providing a description of the downstream sector or the type of component or equipment in which they are used, and specific location or scenario of application for that product.

Understanding each of these three aspects is important in understanding how, why, and where PFASs are used in hydraulic oils and lubricants, and when considering the efficacy of potential alternatives that can be used in place of them.

This report has identified many specific PFASs used in lubricants and hydraulic oils. A detailed table of specific PFASs (including CAS numbers and an indication of the lubricant components in which they are used) is provided in Annex B. A table is also provided in Annex C to indicate which end use sectors these PFASs are associated with. It is emphasised that the list is based on available literature (and informed by the Zero PM database[9])) so is not to be considered a definitive or exhaustive list.

Further discussion on the use of PFASs in base oils, additives and solvents is provided separately in the sections below. Based on EU data (ECHA(a), 2023), it is estimated that approximately one third of the PFASs used are (part of) base oils and two thirds are micro-powder additives (almost entirely PTFE), with much lower volumes for solvents and other types of additives.

Lubricant components

Base oils and greases

All lubricants contain a base oil, which represents the foundation of the lubricant before it is blended with additives and/or a thickener. Base oils are commonly classified as either mineral, synthetic, or plant-based (Rizvi, 2009[28]). PFAS-containing base oils have been highlighted as examples of synthetic base oils that are used for specific 'high performance' applications. For example, it is considered that synthetic base stocks can possess certain advantages over 'conventional' mineral base stocks, which make their use more suitable in lubricants that are employed in applications that experience extreme temperatures or extreme operating conditions, or both (Rizvi, 2009[28]).

Many PFASs have been identified as being used as (or in) base oils (see Annex B). The most commonly highlighted examples are PFPEs, PCTFEs, and fluorosilicone oils, which can be used directly as lubricants, or they can be used as base oil for greases (ECHA(a), 2023[7]). Many variations of commercial products using these PFASs as base components are marketed by a wide range of manufacturers and suppliers globally.

For example, commercial PFPE polymers are fractionated by distillation to produce a series of products of different grades, based on their viscosity (Chemours, 2015a[31]). PFPE oils are reported to be considerably more compressible, with lower bulk modulus, than conventional petroleum hydraulic fluids (Moffett, 2020[32]). In the case of greases, commonly used thickening agents for PFPE-greases include inorganic substances such as silica, 'attapulgus clay', montmorillonite, ammeline, boron nitride, talc, calcium carbonate and zinc oxides, but also PFAS additives including micro-powder PTFE and FEP (Rudnick, 2020[33]).

As discussed in (OECD, 2024[34]), PFPE fractions employed in lubricant applications have molecular weight of 2000–10,000 Da, corresponding to the number of monomer units in each chain of 12–60. It is noted that specific PFPE identities, structures, usage volumes, or formulations are seldom provided, so often the extent of specific PFPEs used remains unclear. However, for some lubricants and greases, CAS numbers have been indicated[10].

PCTFE-based greases (base oil of oligomer/low-molecular weight PCTFE), commonly thickened with silica, micro-powder PTFE and/or high-molecular weight (MW) PCTFE, are commercially available (Rudnick, 2020[33]). Greases based on fluorosilicone oils can be thickened with amorphous fumed silica, PTFE and organics.

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[9] https://zeropm.eu/alternative-assessment-database/

[10] These miscellaneous or unspecified lubricants and greases include CASRNs 156559-18-1, 161075-00-9, 161075-02-1, 161075-14-5, 370097- 12-4, 51798-33-5, 60164-51-4, 69991-67-9, and 76415-97-9

Additives

Chemical additives in lubricants are used either to enhance the existing properties of the base fluids or to impart new properties that they lack, e.g. wetting agents to assure particle suspension, anti-wear additives, and rust inhibitors (Dias et al., 2024[35]). In particular, extreme pressure (EP) additives have been highlighted as an important area of innovation with respect to the use of PFAS compounds (Dias et al., 2024[35]). These EP additives, mixed with engine oils, gear oils, and greases, form a protective film on metal surfaces, which can reduce friction during high-pressure interactions. This protective action can be key to preventing severe wear and potential machinery failures (Diaz et al., 2024).

Several PFASs identified are used as lubricant additives (see Annex B and C). The most commonly highlighted example is nano- or micro-powder PTFE. Incorporating PFAS as additives in lubricants, especially using nano- and micro-sized PTFE particles, has been shown to greatly enhance friction and wear performance (Dias et al., 2024[35]). For example, recent advancements in EP additives involve integrating nanosized PTFE particles into lubricants to enhance their physical and tribological properties or act as hardening thickeners in greases, forming an effective protective film even under higher loads (Dias et al., 2024[35]).

Besides nano or micro-powder PTFE, many types of low-molecular weight PFASs may also be used as additives for lubricants; including fluorosurfactants and fluorinated or partially fluorinated alkanes, ethers, amines, esters, and metal salts of alkyl phosphates (Annex B and C). For example, the use of PVDF nanospheres in commercial lubricating oils and greases (0.1%wt) has also been reported (Dias et al., 2024[35]).

Solvents

Various PFAS-based solvents (functional fluids) are applied in relation to lubrication, which uses can be divided into two types: (1) PFAS-based carrier and deposition solvent as part of a lubricant dispersion; (2) cleaning agents for the cleaning of parts/articles to be lubricated (e.g. to avoid contamination of the lubricant). The latter application is not in the scope of this report. Application of PFASs in carrier and deposition solvent processes are considered to take place in closed systems where the evaporated solvent is captured.

Lubricant types

The most commonly identified PFASs in lubricants are identified as polymeric PFASs, such as micro-powder PTFE (solid additive), PFPE (base oil) and PCTFE (base oil) (ECHA(a), 2023[7]). According to (Ebnesajjad, 2019[36]) other polymeric PFASs such as polyfluorosiloxane/ fluorosilicone oils (base oils or additives), FEP, and PAVE (copolymer of TFE and a perfluoroalkylvinylether) additive are occasionally also present in lubricants. Non-polymeric PFASs, are also sometimes used as dispersants/wetting agents in lubricants and solvents in lubricants and lubricant applications (e.g. cleaning before adding a lubricant).

Most of the available data on the use of PFASs in lubricants and hydraulic oils has come from evidence in Europe. Data from other OECD countries is relatively scarcer. A number of specific types of lubricant where PFASs are used have been highlighted in existing reviews, e.g. Danish Environmental Protection Agency (2024) and ECHA(a) (2023) reports, as summarised below.

Low viscosity lubricants (incl. engine oil)

Low viscosity lubricants (incl. engine oils) can be 100% base oil (either mineral or synthetic), but in many cases also contain additional additives, e.g. wetting agents to assure particle suspension, anti-wear additives and rust inhibitors. PFASs such as fluorosilicone oils can be used as base oils in these applications. Solid additives, such as e.g. micro-powder PTFE are also sometime used. However, the use of PTFE in engine oils is rather limited due to its inherent instability in oil, the risk of oil filter clogging, as well as difficulties with recycling (ECHA(a), 2023[7]).

Grease

Greases are typically produced using mineral, synthetic, or plant-derived oils and a thickening agent (ECHA(a), 2023[7]). Micro-powder PTFE can be used as thickener/solid additive/fortifier alone or in combination with other thickeners. However, most greases based on mineral oils do not use fluoropolymers as thickeners (Ebnesajjad, 2019[36]). The use of PFASs as thickeners is more common for some synthetic oils (PFPEs, oligomer PCTFE, polyalphaolefin oils, fluorosililicone oils). Using a fluorinated thickener gives the grease a similar temperature and chemical stability as the base oil, allowing it to be used also in harsh, demanding conditions (Chemours, 2015a[31]). Micro-powder PTFE is usually only used as a thickener in PFPE-based greases, with the main combination often being silica, micro-powder PTFE, and/or high-molecular weight PCTFE as a thickener. Used on its own, the PTFE level in lubricant products ranges from 20-40% and when used together with other thickeners the range is from 3-40% (Ebnesajjad, 2019[36]). Micro-powder PTFE is often used as thickener in PFPE-based greases. Silica, micro-powder PTFE, and/or high-molecular weight PCTFE is commonly used as thickener in PCTFE-based greases (ECHA(a), 2023[7]).

Solid/ dry films and release-agents

Dry film lubricants, when applied to a surface, provide a layer of solid lubrication. Unlike traditional liquid or semi-liquid lubricants, they provide a continuous, thin layer of solid particles, and as such they do not rely on oils or greases to provide lubrication. There are some greases and lubricants that use dry film lubricants in combination with standard oil and greases, and in such cases, the standard lubricant almost only acts as a delivery agent for the dry lubricant.

Solid/dry films usually need to have high volatility to be functional. Easy volatilisation of the liquid is usually important for these applications, therefore, the fluid phase for dry films can be oil but is more likely to be water, a very low-MW hydrocarbon, or a polar organic compound such as isopropanol or acetone, as these will evaporate before end use. After evaporation of the solvent, the solid additive (e.g. graphite or micro-powder PTFE) will be left as a dry film (ECHA(a), 2023[7]).

Release agents are considered a special case of dry film use. The release agents are mainly used in manufacture or modification of (thermo)plastics and elastomer shapes, preventing build up/sticking of resins on process equipment. Polymerics PFASs are used here (e.g. micro-powder PTFE (solid additive), PFPE (base oil), and PCTFE (base oil) or even polyfluorosiloxane/ fluorosilicone oils (base oils or additives)). FEP (copolymer of TFE and hexafluoropropylene), and perfluoroalkyl vinyl ether PAVE (copolymer of TFE and a perfluoroalkylvinylether) additives are occasionally also present in lubricants (ECHA(a), 2023[7]).

Hydraulic oils

Hydraulic fluids are used in the transportation sector to actuate moving parts of aircrafts such as wing flaps, ailerons, the rudder, and landing gear (Glüge et al., 2021[6]) and in steering systems, brake systems or other special applications such as systems for lifting and lowering of vehicle parts or cargo.

There are three main types of hydraulic fluids: a) mineral-based fluids, b) polyalphaolefin-based fluids and c) phosphate ester-based fluids (Aeronautics Guide, 2019[37]). Hydraulic fluids based on phosphate esters are used in most commercial aircrafts and are extremely fire-resistant (Aeronautics Guide, 2019[37]). However, they can absorb water and the subsequently formed phosphoric acid can damage metallic parts of the hydraulic system (Glüge et al., 2021[6]).

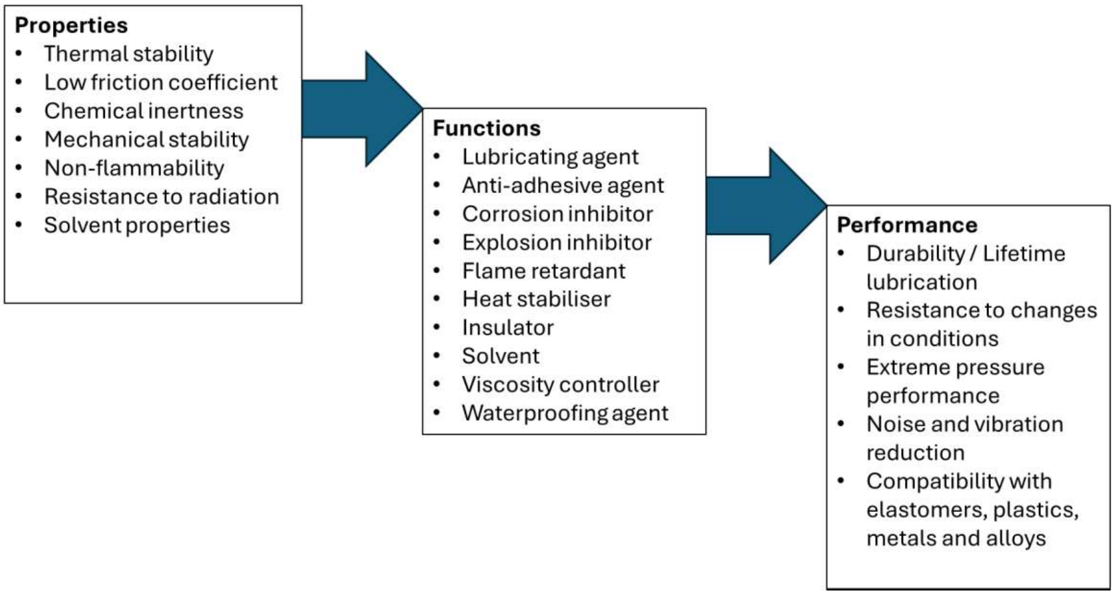
PFASs are used primarily as an anti-erosion additive in aircraft hydraulic oils (ECHA(a), 2023[7]). For example, fluorinated surfactants in phosphate ester-based hydraulic fluids inhibit the corrosion of mechanical parts of the hydraulic system by altering the electrical potential at the metal surface (POPRC 2019). The fluorinated surfactants can also prevent fire and evaporation of the hydraulic fluid (KEMI, 2015[38]).

The function(s) of PFASs in hydraulic oils and lubricants

Overview of key properties, functions and performance qualities

Manufacturers of lubricants, e.g. Chemours (2015a); Chemours (2015b), and downstream lubricant users e.g. ATIEL (2023); UEIL (2023); ACEA (2023); ASD Eurospace (2023), highlight that PFASs are used in lubricants and hydraulic oils due to a wide and unique range and combination of physical and chemical properties. These properties are associated with a number of specific technical functions in lubricant applications, that in turn enable a higher level (or wider range) of performance qualities in those lubricants for specific applications. The properties, functions and performance qualities of PFASs in lubricants (as indicated in the above-mentioned sources) is shown in Figure 2.1 below:

Figure 2.1. Properties, functions and performance characteristics related to PFASs in lubricants and hydraulic oils



There is a wide range of potential end use applications for PFAS-based lubricants, however, a number of key properties, encompassing many different end uses and sectors of application, are highlighted by the manufacturers and end-users of lubricants e.g. Chemours, (2015a); ACEA (2023); ASD Eurospace (2023); UEIL (2023). These include the following:

- **Thermal stability –** the heat stabilising function of PFASs allows fluorinated lubricants to withstand extreme high and low temperature conditions, a key property across many different uses, for example where they are used in harsh outdoor environments such as in aerospace and offshore applications and/or in equipment which can become very hot (e.g. ovens, heaters, corrugated paper machinery, steel mills and printers). For example, it is considered that most petroleum products begin to degrade above 99 °C (210 °F) and are too viscous at temperatures just below –18 °C (0 °F), while PFPE-based lubricants are demonstrated to have much longer durability at test conditions of 177 °C (350 °F) (Chemours, 2015a[31]).

- **Low friction coefficient –** PFASs are known to be excellent lubricating agents. They contribute to reducing friction between moving parts, enhancing the efficiency of machinery and engines (New Tech Lubes., n.d.[39]). This is attributed to the molecular architecture of PFAS - a fluorinated hydrocarbon chain arranged in a parallel manner, which results in a remarkably smooth surface at the microscopic level, reducing mechanical interlocking and enabling sliding between contacting surfaces, reducing intermolecular entanglement, and thereby providing a stable, low-friction interface (Dias et al., 2024[35]). For example, the extremely low coefficient of friction of (micro-powder) PTFE in combination with its good thermal stability makes it attractive as a solid lubricant additive.
- **Chemical inertness –** PFASs are considered resistant to oxygen, but they are also demonstrated to be inert to virtually all chemicals used in a variety of industries. They are insoluble in most solvents but soluble in highly fluorinated fluids and some supercritical fluids, such as CO2 (Chemours, 2015a[31]). For example, at elevated temperatures and pressures, PFPE oils are highly resistant to attack by gaseous and liquid oxygen. The chemical inertness of PFASs enables a number of key technical functions in lubricants and hydraulic oils. The inert nature of PFASs in lubricant oils and greases allows them to outlast and outperform competing hydrocarbon products.
- **Mechanical stability –** PFAS-based lubricants are popular because they do not readily break down under mechanical stress, so they reduce wear and tear on component parts, reducing the chances of component failure.
- **Non-flammability –** Conventional lubricants that contain mineral oils or conventional synthetics can react with oxygen and halogens; thus, increasing the potential for explosion, fire, and premature deterioration (Chemours, 2015a[31]). Therefore, a key technical function of PFASs in lubricants is their flame retardancy (as well as explosion inhibition). For example, the absence of hydrogen in the molecular structure of some PFASs (e.g. in the case of PFPE) increases the stability of the lubricants and renders them non-flammable with no flash point.
- **Resistance to radiation –** PFAS-based lubricants are considered remarkably stable to radiation when compared with many materials used as lubricants or power fluids (Chemours, 2015a[31]). This is particularly important in aerospace and nuclear power plant applications.
- **Solvent properties –** The use of PFASs as solvents is associated with their non-flammability, thermal and chemical stability, dielectric properties, compatibility with dissolved materials, low surface tension and viscosity, high liquid density, and low toxicity (ZeroPM database). For example, the poor electrical conductance of PFAS-based solvents means they can be used safely in contact with electronics.

The specific technical functions of PFASs in lubricant or hydraulic oil applications, enabled by the key physical and chemical properties described above, are outlined in Table 2.1 below. The range of functions enabled or required in lubricant uses, can vary considerably depending on the specific end user and the application. In general, it is indicated that PFAS-based lubricants are used in relatively ‘extreme’ applications where the technical function(s) are needed to provide superior technical performance compared to more conventional lubricants and/or where other types of lubricants would not be technically feasible. For example, it has been highlighted that PFPE greases are especially used for applications that require performance over a significant temperature range and wherein oxygen-resistance is needed (ECHA(a), 2023[7]).

Manufacturers and users report that PFAS-based lubricants are generally highly coveted in certain applications because they simultaneously impart most, if not all the properties highlighted above. For example, as discussed in (ECHA(c), 2023[29]), PFPE are fluids known to be chemically inert, have low outgassing, are thermally stabile (service temperature range from approx. -80 ºC to approx. 350 ºC), are non-flammable and radiation resistant. The vapour pressure and volatility of the PFPE oils vary with average molecular weight so that higher-viscosity oils generally have lower volatility losses (Rudnick, 2020). PCTFE lubricants are known to have good lubricity, to be chemically inert to a high number of aggressive chemicals, be non-flammable, have low outgassing, are thermally stabile, radiation resistant, have high dielectric strength, high density and low compressibility (Rudnick, 2020). PCTFE is used directly as a lubricant as it has high lubricity properties, chemical inertness to aggressive chemical environments, low flammability, and low compressibility (Danish Environmental Protection Agency, 2024). Fluorosilicone oils (polyfluorosiloxane oils) can resist oxidation, harsh chemicals, fuels, have a low evaporation and a wide service temperature range (-40 to 200 °C).

Utilising PFASs in lubricant additives, particularly nano- and micro-sized PTFE and PVDF particles, helps enhance their friction and wear performance (Diaz et al., 2024). Furthermore, PFAS additives in lubricants are considered to offer enhanced performance and greater protection within extreme pressured environments, useful for use within a wide range of industrial applications where traditional lubricants have been found to be insufficient.

Table 2.1 Overview of PFAS functions in hydraulic oils and lubricants[1]

Technical Function	Associated Performance qualities	Category of use	Key PFASs used	Alternatives (category)[2]	Application(s)[3]	Source
Lubricating agent	Reducing friction between two moving surfaces to reduce frictional loss; provide better durability/lifetime lubrication; and minimise wear;	Base oil/grease;	PFPE PCFTE	Silicone-based Synthetic organic chemical	Consumer mixtures; Food sector Aviation and aerospace; Automotive	ECHA (2023a); Zero PM database
		Lubricant additive	PTFE PVDF	Inorganic / other	Trains; Nuclear powerplants, Watch making; Hearing loss applications, Electronics and semiconductors; Laboratory supplies, equipment, and instrument actions, Hospital equipment; Renewable energy, Oil & gas; Chemical industry; Bulk gas industry; Metal working industry Steel industry; Wastewater treatment, Diving equipment; Paper; Plastics, Rubber/Tire industry; Textile, Pharmaceutical industry; Laboratory supplies, equipment, and instrument actions	
Anti-adhesive agent	Low friction; Good slide ability; Non-stick properties; preventing adhesion to another material/ substance	Lubricant additives	PTFE PVDF	Silicone-based Synthetic organic chemical	Automotive	ECHA (2023a); Zero PM database

Technical Function	Associated Performance qualities	Category of use	Key PFASs used	Alternatives (category)[2]	Application(s)[3]	Source
Corrosion inhibitor	Chemical stability/ resistance to harsh chemicals; Thermal stability, Low vapor pressure	Lubricant additives	PTFE	Silicone-based Synthetic organic chemical	Aerospace and Defense; Automotive Trains; Energy (incl. Nuclear power) Electronics and semiconductors; Renewable energy; Oil & gas; Chemical industry	ECHA (2023a); Zero PM database
		Hydraulic oils	PTFE (oil) Potassium decafluoro(pentafluoroethyl)cyclohexanesulphonate	None identified	Aviation (Aerospace and Defense)	ECHA (2023a); Zero PM database ; (Glüge, et al., 2021)
Explosion inhibitor	Do not react with oxygen; prevents risk of fire, auto-ignition and explosions to improve safety.	Base oil/grease;	PFPE	Silicone-based Synthetic organic chemical	Chemical industry	ECHA (2023a); Zero PM database
		Lubricant additive	PTFE	Inorganic / other		
Flame retardant	Prevent ignition when exposed to heat or a flame, improve safety against fire hazard, low flammability	Base oil/grease;	PFPE	Synthetic organic chemical	Aerospace and Defense Oil & gas	ECHA (2023a); Zero PM database
		Lubricant additive	PTFE	Inorganic / other		
Heat stabiliser	Thermal stability; Resistance to broad range of temperatures	Base oil/grease;	PFPE	Silicone-based Synthetic organic chemical	Food sector; Aerospace and Defense Automotive; Trains Watch making; Hearing loss applications Electronics and semiconductors; Oil & gas	ECHA (2023a); Zero PM database
		Lubricant additive	PFTE	Inorganic / other		

Technical Function	Associated Performance qualities	Category of use	Key PFASs used	Alternatives (category)[2]	Application(s)[3]	Source
					Paper; Plastics; Rubber/Tire industry; Textile	
Insulator	Reduction of noise; Provide arc-resistance	Base oil/grease;	PFPE	Silicone-based Synthetic organic chemical	Automotive; Renewable energy Electronics and semiconductors	ECHA (2023a); Zero PM database
		Lubricant additive	PTFE	Inorganic / other		
Solvent	Non-flammability, thermal and chemical stability, dielectric properties, compatibility with dissolved materials, low surface tension and viscosity, high liquid density, and low toxicity	Carrier solvent	Various – see Annex B	Synthetic organic chemical	Not specified / multiple	ECHA (2023a); Zero PM database
Radiation resistance	Provide resistance to degradation by radiation to lubricant	Lubricant additive	PTFE PFPE	Inorganic / other	Nuclear powerplants; Aerospace	ECHA (2023a); Zero PM database
Viscosity controller	Regulating viscosity of the lubricant	Lubricant additive	PTFE PFPE	Inorganic / other	Automotive	ECHA (2023a); Zero PM database
Waterproofing agent	Water repellency	Base oil/grease;	PFPE	Silicone-based Synthetic organic chemical	Watch making Automotive	ECHA (2023a); Zero PM database

Notes:
[1] PFAS in hydraulic oils serve only an anticorrosion function (see 'category of use' in the table).
[2] The performance limitations of the alternatives identified are detailed in Chapter 3.
[3] As indicated in the Zero PM database. This should not be interpreted as a definitive or exhaustive list.

The physical and chemical properties of PFASs, and the technical function(s) these properties are associated with in lubricant and hydraulic fluid applications, enable a number of key performance qualities in the lubricant products or the components/equipment in which they are applied. The main performance qualities highlighted by manufacturers and users include:

- **Lifetime lubrication –** the use of fluorinated lubricants means the need and frequency for maintenance and re-lubrication is reduced or avoided completely. Due to their inert nature, PFAS-based lubricants provide a much longer usable life compared with conventional hydrocarbon oils and greases. They reduce the number of lubricants changes and thus reduce the volumes of lubricants used leading to cost savings related to reduced need for replacement and maintenance (see Chapter 3). Their enhanced durability can also lead to relatively long storage life of products.
- **Resistance to changes in conditions –** the use of fluorinated lubricants is associated with uses that experience significant range in use conditions, mainly related to the temperatures experienced at different times and location – e.g. maintaining good durability under certain loads and harsh environmental conditions such as shock, vibration, heat and pressure, aggressive chemical environments and intense radiation exposure.
- **Extreme pressure performance –** PFASs are used in heavy-duty greases used for high load-carrying conditions, where they are able to provide good lubrication characteristics under boundary and mixed friction conditions (Chemours, 2015a).
- **Noise and vibration reduction –** their low friction coefficient will in turn reduce noise and vibrations in various components e.g. in the automotive industry.
- **Compatibility with elastomers, plastics, metals and alloys –** PFAS-based lubricants are considered compatible with all elastomeric seal materials and engineering plastics, as well as metals and alloys (e.g. steels, stainless steels, titanium alloy, nickel alloy, and cobalt alloy). This allows PFAS-based lubricants to be applied to reduce friction between plastic parts e.g. in electronics, electromechanical applications, and in plastic gears.

The market for PFASs in lubricants and hydraulic oils

Overview

The past 75 years has seen a rising interest and demand for high performance synthetic lubricants. Conventional lubricants are subject to oxidation, attack by harsh chemical or solvents, flammability, and volatilisation of the base oil, leading to failure of the lubrication system and associated hazards (Chemours, 2015a[31]). Conventional lubricant properties are often not considered adequate for critical systems where failure is not an option, for example when ensuring safety of people, vehicles, or infrastructure.

While it is challenging to identify precisely when PFASs were first used in lubricant applications, this is likely to have commenced as early as the 1950s, when PFASs were first documented as being produced and used commercially in lubricant applications (Danish Environmental Protection Agency, 2024[30]). Technological advances in the second half of the 20th century have seen the demands on the availability and performance of machinery rapidly increase (Dias et al., 2024[35]). For example, military and defence requirements during and after the Second World War drove the development of new lubricants and lubricant additives, largely due to the innovations in new faster-running engines (e.g. the advent of the jet engine), which placed a heavy demand on the performance of lubricants (Rizvi, 2009[28]) .The combination of advanced PFAS additives and EP technology has been the crucial driver in lubrication science, offering enhanced performance and greater protection in a wide range of industrial, commercial and professional applications where traditional lubricants were found to be insufficient (Dias et al., 2024[35]).

A key driver behind the incorporation of PFASs in lubricants and hydraulic oils has been developments in the automotive and aerospace industries, which have opened new environments for the operation of engineering systems, and corresponding performance requirements for lubricants (such as withstanding large temperature gradients, oxidising environments, harsh chemicals, radiation, weight and volume limitations, and the absence of replenishment) (Dias et al., 2024[35]).

It has previously been identified that lubricants and grease formulations (based on PFPE) were first developed for market by Dupont in the 1960s, in conjunction with NASA and the United States Air Force for military and aerospace applications (Dias et al., 2024[35]). In the 1980s, the United States Air Force Wright Aeronautical Laboratory put forward several candidates for the expansion of the use of various classes of fluoropolymer base materials for lubricant and fluid materials during a symposium on fluoropolymers (Dias et al., 2024[35]).

Key sectors of PFAS use in hydraulic oils and lubricants

As discussed in Chapter 1 and illustrated by the data compiled in the ZeroPM (2023) database and discussed in ECHA(a) (2023), ATIEL (2023), and UEIL (2023), there is a wide range of different applications for PFAS-containing lubricants, across many different sectors including:

- Transport (aerospace, rail, automative, marine);
- Weapons, military and defence;
- Power generation (renewables, nuclear) and energy storage, energy transmission and connection systems;
- Electronics and semiconductors;
- Various industry sectors (e.g. oil and gas, iron and steel production, cement, lime, gypsum, food and drink production, plastics, chemical processing, pharmaceuticals, paper. refineries, rubber, plastics and leather industry);
- Consumer and professional uses (e.g. hospital and medical equipment, bicycle chains, watchmaking).

There is limited quantitative data on estimates on how the volume of use for PFAS-containing lubricants breaks down between these different end-use sectors globally. However, it is indicated by the lubricant manufacturing industry that the primary consumer of PFAS-containing lubricants by volume is the automotive sector. In this section, a brief overview of each of the key use sector is provided.

Automotive

PFASs lubricants are widely used in high-performance mechanical systems of vehicles such as combustion engines, electric motors, batteries and charging systems, power electronics, thermal management systems, and many others (Dias et al., 2024[35]); (ACEA, 2023[40]). The performance of the lubricants used in these applications is important because these components are subject to challenging conditions such as mechanical loading, cyclic stresses, and high temperatures.

The use of PFASs based lubricants (e.g. PFPE oils and PTFE additives) has been highlighted for various automotive components (ECHA(a), 2023[7]); (Chemours, 2015b[41]); (Chemours, 2015c[42]), including:

- Under hood mechanical components: e.g. fan clutch bearings, emission air pumps, spark plug boots, clutch release bearings, antilock brake systems, windshield wiper motors, exhaust gas re-circulating (EGR) valves, belt pulleys, O-rings in fuel connectors (combustion engines) oil pressure sensors, alternator bearings, and sintered bearings in motors;
- Chassis components: e.g. wheel bearings, CV/universal joints;

- Interior parts: e.g. weather stripping, sunroof seals, window lift mechanism, leather seats, consoles and trim, flocked and unflocked window seals and channels, door handles, switches, air vents, controls, and airbag covers.

Fluorinated lubricants are also used in gearboxes where they have the advantage that they do not degrade at high temperatures and do not form sludge or varnish that is often the cause of bearing and gear failures (Glüge et al., 2021[6]).

The use of PFAS-based lubricants is associated with a number of key performance benefits in these applications, including: prevention of wear and noise from vibration; durability and resilience against tough exterior conditions (e.g. rain, snow, ice, dust, and grit), and harsh internal conditions (e.g. withstanding the fuel, coolant, brake fluid, and washer solvent of the harsh under hood environment); overall longer lasting performance, which helps to extend the service life of a variety of car and truck parts.

Hydraulic oils are also used in the automotive sector for steering/ braking systems. Stakeholders from the USA also highlighted that hydraulic oils are used in industrial maintenance, repair, and overhaul (MRO) applications for hydraulic power units (HPU) and in the construction, agricultural machinery as well as in marine applications.

Aerospace, defence and military

Lubricant manufacturers, e.g. (Chemours, 2018[43])highlight aerospace and military applications as having some of the most demanding requirements with respect to lubrication, e.g. with extremely broad temperature ranges encountered in operation.

An initial advent of developing PFAS-containing lubricants was for the aerospace sector. For example, Gschwender (Gschwender, 2009[44]) noted that the perfluoropolyalkylether (PFPAE) liquid lubricant has been used by the U.S. Air Force Research Laboratory (AFRL) since the 1960s, with the potential uses envisioned then included lubricant for the MACH 3+ turbine engine, hydraulic oil, rocket gear box lubricant. In 1964, new Krytox™ (PFPE-based) grease formulations were developed jointly with the U.S. Navy and Air Force, resulting in military specification MIL PRF-27617, which was developed specifically for Krytox™.

Uses of PFASs in both hydraulic oils and lubricants in these applications have been highlighted (ASD Eurospace, 2023[45]); (ATIEL, 2023[46]); (UEIL, 2023[47]):

- **Hydraulic oils –** PFASs are used in civil/military aircraft and the aerospace sector for applications such as flight control systems, landing gear systems, and as defence parts such as steering mechanisms, munitions loading systems, turrets and actuators.
- **Lubricants –** in particular PFPE and PFTE containing lubricants **–** are used in a wide range of aerospace, defence and military applications, including in: bearings, seals (valves, pumps pneumatics), O-rings, oxygen systems (e.g. in valve and pump packing seals, mechanical seals, regulators, seals and connectors), rocket engines, liquid fuelled turbines, gimbals, pumps, gears, ground support systems, gyroscopes , actuators (e.g. electro-mechanical/gear-type actuators for control valves and systems), mechanical components (e.g. spline shafts, control linkages; leadscrews and ball screws), engine ancillary gearbox spline couplings; anti-friction mounts, engine oil tanks; non-conducting lubricant for sealing of electrical connectors. The ASD Eurospace (2023) also highlighted the use of PTFE bulk composite material with special adds-on for bearing cages in space applications.

The use of PFAS-based lubricants is associated with a number of key performance benefits in these applications, including: reliability and long service life of mission-critical mechanical components in the face of high vacuum, temperature extremes, contact with fuels and oxidizers, and radiation exposure; reduced maintenance requirements, improved safety and reliability, compliance with a wide range of military specifications (ECHA(a), 2023[7]) (Chemours, 2015a[31]). PFPEs are used as lubricants in aerospace jet engines, high temperature turbine engines and satellite instrumentation because of their long-term retention of viscosity, low volatility in vacuum and their fluidity at extremely low temperatures (Glüge et al., 2021[6]).The low outgassing of PTFE allows for low contamination contributions. For example, PFPE oils, greases obtained by thickening of PFPE oils with PTFE, and PTFE composite materials are considered 'critical' to lubrication of satellite components and allow for fulfilment of an aerospace mission (ASD Eurospace, 2023).

Semiconductors and electronics

PFAS-containing lubricants and greases (e.g. PFPE, PCTFE and PFTE) are used in semiconductor manufacturing. This industry involves many moving parts that require lubrication, e.g. those associated with robotic systems, photolithography applications, gears and bearings, linear guides and ball screws, chains, mechanical pumps, compressors, valves, O-rings and seals, as well as other components (SIA, 2023[48]); (Chemours, 2015a[31]).

For example, semiconductor manufacturing operations contain many vacuum pumps that require lubrication of the moving parts within them. PFAS-based lubricants are used in wet and dry vacuum pumps and vacuum system sealants. PFPE is used as sealing and working fluids in vacuum pumps exposed to aggressive environments (chemical and thermal). PFPE and PTFE-based lubricants are also used for low outgassing applications: in vacuum applications, optical instruments and light housings where lubricant condensation must be minimised (UEIL, 2023[47]).

PCTFE oils and greases are also used as a vacuum pump oil for equipment used to plasma-desmear multilayer printed circuit boards and for semi-conductor manufacturing equipment (ECHA(a), 2023[7]). PFASs are also reportedly used in grease for sliding contacts in electric switch and for pushbuttons, rack and pinion disk drive lubricant, spindle and actuator bearings, and top coating lubricant on computer disc drives (ECHA(a), 2023[7]).

Energy and power generation

PFPE- and PTFE-based lubricants are used in nuclear power plants, operating in an area where they are exposed to radiation, for example as a bearing lubricant for pumps and other moving parts, critical bearings, fuel manufacturer equipment, compaction equipment, etc. (ECHA(a), 2023[7]). Radiation quickly degrades ordinary lubricants, but PFPE-based lubricants function for long periods without significant degradation (UEIL, 2023[47]).

PFAS-based lubricants (e.g. PFPE, PTFE) are also used in renewable energy applications, e.g. in wind power (for lubrication of screws, nuts, magnetic anchors, bolts, bearings); fuel cell technology (e.g. grease for O-rings) and in energy storage and energy conversion via hydrogen such as Polymer Electrolyte Membrane (PEM) (ECHA(a), 2023[7]).

Food processing industry

PFASs, including PFPE (90-99%; 30-70%) and PFPE (60-75%; 30-70%) are used in chains and bearings, e.g. in high temperature applications ovens (ECHA(a), 2023[7]). H1-approved base oils include white oils (highly refined mineral oils), Polyalphaolefin-based fluids (PAOs), several silicone oils, polybutenes, alkylated naphthalenes, synthetic esters and PFPE (McGuire, 2019[49]). PFASs are associated with lifetime lubrication in micro-amounts in closed parts; moving mechanical parts, semi-closed; and lubricants and lubricant sprays for incidental food contact (ECHA(a), 2023[7]). PTFE (2.5–100%) is used as a lubrication additive on the inside coating of metal food and beverages containers (ECHA(a), 2023[7]).

Oil and gas production

PFASs have been highlighted as being used, for example in lubrications of screws, nuts, magnetic anchors, bolts, bearings*, c*asing/tubing sealants for high-definition threads in high chrome steel, sealing systems for centrifugal and rotary pumps, and anti-seize lubricant for drilling tools in hydrogen sulphide environments (ECHA(a), 2023[7]).

Chemical and bulk gas industry

PFAS-based lubricants are used in the machinery and equipment associated with chemical production and processing, as well as bulk gas production. For example, they are used in valves, fittings, couplings, O-rings, and seals exposed to reactive and corrosive chemicals, sealing systems for centrifugal and rotary pumps, sealing systems for rotary agitators and mixers in reactive chemical processes, and sealants for flange faces (ECHA(a), 2023[7]). PFASs are also used in vacuum pump oils for evacuating oxygen cylinders and bulk (cryogenic) storage tanks, vacuum pump oils for oxygen plasma cleaning, bearing grease for liquid oxygen (LOX) pumps and lubricant for compressors in portable oxygen plants (ECHA(a), 2023[7]).

Other industrial applications

Due to oxidation stability and suppression of deposits, PFPE- and PTFE-based lubricants are used in general industrial applications, for example for heavily loaded bearings and pivots, including uses in valves, fans, pumps, agitators, reactors, centrifuges, push-button and sliding-switch contacts and other components (UEIL, 2023[47]) (Chemours, 2015a[31]) (Glüge et al., 2021[6]).Polymeric PFASs are used within bearings in ovens for heat treatment of plastic films or to lubricate the rolling bearings of corrugating machines or the vulcanising rubber operations to manufacture tyres, both of which have high temperatures and humidity prevailing simultaneously. Similarly, polymeric PFASs can be used in the bearings of automated furnaces which are lubricated with food-grade PFPE-based lubricants (UEIL, 2023).

PFPE- and PTFE-based lubricants are also used for emergency applications when machinery needs to start quickly after years of stoppage (for example: fire doors that need to close, emergency power generators, gear boxes). PFASs are also used to dissolve and deposit lubricants on a range of substrates during the manufacturing of hard disk drives (Glüge et al., 2021[6]).

Other commercial and professions applications

PFAS-based lubricants are used in bike chain lubricants, watch making, and musical instruments, diving equipment and handicap assistance equipment (e.g. prosthesis, orthosis, wheelchair, exoskeleton etc.; piston and gear wheel applications; plastic components) (ECHA(a), 2023[7]); (ZeroPM, 2023[50]). PFASs based lubricants are also used in hospital equipment, e.g. valves, fittings, O-rings, pressure gauges in oxygen enriched environment, medical injection device (syringe, pumps, pens), hospital (and home oxygen systems/units), hyperbaric oxygen chambers, anaesthesia machines, nitrous oxide systems (ECHA, 2023a[21]).

Identification and commercial availability of alternatives to PFASs in hydraulic oils and lubricant

Identification of chemical alternatives to PFASs

Non-fluorinated (chemical) alternatives

Overview

Alternatives to PFASs have been identified through a number of recent studies and initiatives, including the Danish Environmental Protection Agency (2024)[11], ECHA(b) (2023)[12], (ZeroPM, 2023)[13] and the Open Public Consultation for the Annex XV PFASs restriction (ECHA(c), 2023[29])[14] as well as via information collected directly from stakeholders in this study.

Specific chemical alternatives identified are shown in Tables 2.2, 2.3 and 2.4. The presentation of alternatives has been split three categories, using the same convention used in the ZeroPM database:

i. Silicone based alternatives;
ii. Synthetic organic/organic alternatives; and
iii. Inorganic/other alternatives.

The information presented in Tables 2.2, 2.3 and 2.4 is presented according to the following headings:

- **Material/substance type**: Description of the alternative/ material type which makes up the alternative.
- **Alternative**: The name of the alternatives identified using the databases/reports listed above.
- **Cas no**: The CAS number of the alternative identified.
- **Category of application:** For some alternatives, the category of lubricants that the alternative would be replacing were listed (e.g. the Danish EPA report and ZeroPM database). For example, an alternative could be replacing PFASs as a micro-powder additive but may not be able to replace an application of PFASs such as a base oil.
- **PFAS compound replaced:** The type of PFASs that will be replaced by the alternatives, as identified in the Danish EPA report.
- **Commercial availability** (mainly based on the indication in the ZeroPM database)**:**
  - Yes - The alternative is indicated to be currently on the market and already in use.
  - No - The alternative is not currently commercially available in sufficient volumes.
  - Lack of data - no information identified.

While a number of different chemical alternatives have been identified, it is challenging to establish which specific properties or technical function(s) those alternatives provide, and to what extent they are capable of

[11] Using section 2.1.3 of the report

[12] Section E.2.14.2.3 of Annex E

[13] Using their long list of alternatives in the alternative tab of the excel

[14] Using several publicly available responses to alternatives to PFASs in lubricants

replacing PFASs in all applications. PFASs provide multiple technical functions in several sectors and currently, there is very limited data available that specifies precisely which (or to what extent) the alternatives identified could replace those functions for different applications. At the current stage of knowledge, there are no substitutes that meet the same performance levels as PFPE- and PTFE-based lubricants. Possible options such as silicones and esters are available while they require product redesign (UEIL, 2023[47]). Chapter 3 of this report covers in more detail the technical feasibility of the alternatives identified below, where possible, on the basis of technical functions.

Silicone-based alternatives

Table 2.2 provides an overview the silicone-based alternatives that were identified through the literature sources highlighted above. These alternatives cover both base-oils and additives. The majority of the alternatives are currently available on the market for several categories of applications. A more detailed discussion on the technical and economic feasibility of these alternatives is provided in Chapter 3.

Synthetic organic/organic alternatives

Table 2.3 provides an overview the synthetic organic/organic alternatives that were identified through the literature sources highlighted above. The majority of the alternatives are currently available on the market for several categories of applications. The alternatives identified cover base-oils and solvents. more detailed discussion on the technical and economic feasibility of these alternatives is provided in Chapter 3.

Inorganic/other alternatives

Table 2.4 provides an overview of the synthetic inorganic/other alternatives that were identified through the literature sources highlighted above. The majority of the alternatives are currently available on the market for several categories of applications. The alternatives identified cover lubricant additives only. A more detailed discussion on the technical and economic feasibility of these alternatives is provided in Chapter 3.

2D materials (e.g. graphene, WS2 and MoS2) were also flagged to reduce friction as part of an integrated additive in composite material, this can be done for the automotive, aerospace, marine and defence sector, which are seeing increasing applications of these 2D materials (Sahoo, 2020[51])

An advanced high-bearing aromatic thermosetting polyester (ATSP) coating filled with PTFE and graphene nanoplatelets (GNP) respectively was also identified for lubricating systems, with the GNP-filled coatings showing a decrease in friction, an improvement in wear resistance and doing better at extreme temperatures of 300°C (Bashandeh et al., 2019[52]).

Table 2.2 Overview of the silicone-based alternatives

Alternative	CAS no	Category of application	PFAS replaced for some technical functions/categories of use (if known) (see Chapter 3)	Commercial availability (see following section)	Sources
Silicone oil / Polydimethylsiloxane	63148-62-9	Base oil	PFPE	Yes	(ECHA(b), 2023[53])
Silicone oil (with polyurea additive)	63148-62-9 / 37955-36-5	Micro-powder additive	PTFE	Lack of data	(Danish Environmental Protection Agency, 2024[30])
Amorphous silica	7631-86-9	Micro-powder additive	PTFE	Yes	(Ebnesajjad, 2019[36]); (ECHA(b), 2023[53])
Silicone alternatives	63148-62-9	Lubrication systems	Not specified	Yes	(Danish Environmental Protection Agency, 2024[30])

Table 2.3 Overview of the synthetic organic and organic alternatives identified

Alternative	CAS no.	Category of application	PFAS replaced (for some technical functions/categories of use) (if known) (see Chapter 3)	Commercial availability (see following section)	Sources
Isopropyl alcohol (IPA)	67-63-0	Carrier solvent	Not specified	Yes	(Exponent International, 2021[54]); (ECHA(b), 2023[53]); (ZeroPM, 2023[50])
Trichloroethylene (TCE)	79-01-6	Carrier solvent	Not specified	Yes	(Exponent International, 2021[54]); (ECHA(b), 2023[53]); (ZeroPM, 2023[50])
Perchloroethylene (PER)	127-18-4	Carrier solvent	Not specified	Yes	(Exponent International, 2021[54]); (ECHA(b), 2023[53]); (ZeroPM, 2023[50])
Hydrocarbons (Hexane)	110-54-3	Carrier solvent	Not specified	Yes	(Exponent International, 2021[54]); (ECHA(b), 2023[53]); (ZeroPM, 2023[50])
Hydrocarbons (Heptane)	142-82-5	Carrier solvent	Not specified	Yes	(Exponent International, 2021[54]); (ECHA(b), 2023[53]); (ZeroPM, 2023[50])

Alternative	CAS no.	Category of application	PFAS replaced (for some technical functions/categories of use) (if known) (see Chapter 3)	Commercial availability (see following section)	Sources
Hydrocarbons (Benzene)	71-43-2	Carrier solvent	Not specified	Yes	(Exponent International, 2021[54]); (ECHA(b), 2023[53]); (ZeroPM, 2023[50])
Hydrocarbons (Acetone)	67-64-1	Carrier solvent	Not specified	Yes	(Exponent International, 2021[54]); (ECHA(b), 2023[53]); (ZeroPM, 2023[50])
n-Propyl bromide (nPB)	106-94-5	Carrier solvent	Not specified	Yes	(Exponent International, 2021[54]); (ECHA(b), 2023[53]); (ZeroPM, 2023[50])
Dichloromethane (DCM, Methylene chloride)	75-09-2	Carrier solvent	Not specified	Yes	(Exponent International, 2021[54]); (ECHA(b), 2023[53]); (ZeroPM, 2023[50])
Trans-1,2-dichloroethylene	156-60-5	Carrier solvent	Not specified	Yes	(Exponent International, 2021[54]); (ECHA(b), 2023[53]); (ZeroPM, 2023[50])
Dec-1-ene, homopolymer, hydrogenated Dec-1-ene, oligomers, hydrogenated	68037-01-4	Base oil (PAO)	Not specified	Yes	(ECHA(b), 2023[53]); (ZeroPM, 2023[50])
Fatty acids, C16-18 and C18-unsatd., Me esters	67762-38-3	Base oil	Not specified	Yes	(ECHA(b), 2023[53]); (ZeroPM, 2023[50])
Natural sources (oils, fats and waxes)	n/a	Base oil	PFPE	Yes	
Graphite	7782-42-5	Micro-powder additive	PTFE	Yes	(Ebnesajjad, 2019[36]); (ECHA(b), 2023[53]); (ZeroPM, 2023[50])

Table 2.4 Overview of the inorganic and other alternatives identified

Alternative	CAS no.	Category of application	PFAS replaced (for some technical functions/categories of use) (if known) (see Chapter 3)	Commercial availability (see following section)	Sources
Molybdenum disulphide (MoS_2)	1317-33-5	Micro-powder additive	PTFE	Yes	(Ebnesajjad, 2019[36]); (ECHA(b), 2023[53]); (ZeroPM, 2023[50])
Boron nitride	10043-11-5	Micro-powder additive	PTFE	Yes	(ECHA(b), 2023[53])

Alternative	CAS no.	Category of application	PFAS replaced (for some technical functions/categories of use) (if known) (see Chapter 3)	Commercial availability (see following section)	Sources
Other inorganics (layer building zinc phosphates, talc etc.)	n/a	Micro-powder additive	PTFE	Yes	(Ebnesajjad, 2019[36]); (ECHA(b), 2023[53]); (ZeroPM, 2023[50])
MoS_2 or boron nitride with Black Phosphorus	MoS_2: 1317-33-5 Boron nitride: 10043-11-5 Black phosphorus: 7723-14-0	Micro-powder additive	PTFE	Yes	(ECHA(b), 2023[53]); (Wang, 2018[55]); (ZeroPM, 2023[50])
MoS_2 or boron nitride with Tungsten disulfide (WS_2)	MoS_2: 1317-33-5 Boron nitride: 10043-11-5 Tungsten disulfide; 12138-09-9	Micro-powder additive	PTFE	Yes	(Ebnesajjad, 2019[36]); (ECHA(b), 2023[53]); (ZeroPM, 2023[50])
Premium esters	n/a	Lubrication systems	Not specified	Lack of data	(Danish Environmental Protection Agency, 2024[30])
Ionic lubricants tetrafluoroborate (BF_4) with an organic cation.	BF_4: 13755-29-8	Lubrication systems	Not specified	Lack of data	(Somers et al., 2013[56]); (Danish Environmental Protection Agency, 2024[30])
Ionic lubricants hexafluorophosphate (PF_6) with an organic cation	PF6:21324-39-0	Lubrication systems	Not specified	Lack of data	(Somers et al., 2013[56]); (Danish Environmental Protection Agency, 2024[30])
Lubrication free bearings : • Polyamides (PA) • Sulphonated polyetheretherketone (PEEK) • Polyethylene terephthalate (PET)	29658-26-2 (PEEK) 25038-59-9 (PET) 9003-07-0 (PP)	Lubrication systems	Not specified	Yes	(ZeroPM, 2023[50])

Alternative	CAS no.	Category of application	PFAS replaced (for some technical functions/categories of use) (if known) (see Chapter 3)	Commercial availability (see following section)	Sources
• Polypropylene (PP)					

Commercial availability of non-fluorinated chemical alternatives

It is indicated in Tables 2.2 to 2.4 above that several of the alternatives to PFASs are currently available commercially and are these are denoted in the Zero PM (2023) database as being 'already in use', with the exception of some that are currently in the R&D phase. It has not been possible to identify information for alternatives where multiple materials are used e.g. for "other inorganics" and MoS_2 or boron nitride with black phosphorus/MoS_2 or boron nitride with tungsten disulfide (WS_2) etc. Chapter 4 of this report covers a more detailed focus on the market availability and additional factors that impact uptake of the alternatives to PFASs in lubricant and hydraulic fluid applications.

The following paragraphs contain information on the alternatives listed above, and their current market growth prediction. The information gathered on the identify and commercial availability of alternatives does not necessarily provide an indication of the technical or economic feasibility of the alternatives to replace PFASs in all uses and scenarios. It is likely that if the alternatives are deemed by the user to be feasible to replace PFASs, the market for such alternatives will grow in the future.

Base oils and greases

Looking at the commercial availability of alternatives to base oils, the global silicone oil market stood at approximately 820 thousand tonnes and is expected to grow at a compound annual growth rate (CAGR) of 6% up until 2032 (Chemanalyst, 2023[57]). The reason for this expansion is due to the increasing growth of the automotive, chemical, and electronics industries, and the role that silicone oils play as lubricants in these sectors. For natural sources e.g. oils and fats, the market is expected to robustly grow between 2021-2026 with new and innovative activities in the sector being used to find new natural sources (S&P Global, 2021[58]).

Micro-powders/additives

Several alternatives were identified for micro-powders/additives, with their commercial availability varying. For graphite, the global market is expected to grow in the next few years, but this is mainly due to the electric vehicle sector. Both synthetic graphite and natural graphite will be a key element of lithium batteries in the next decade, although it is unclear how much of this demand will be used to supply alternatives to PFAS in micro-powder PTFE (Barrera, 2022[59]). For MoS_2, it expected that the market will expand with its use in the automotive industry as a lubricant (Mordor intelligence, n.d.[60]), The highest growth rate for MoS_2 will likely come from Asia and Oceania (Mordor intelligence, n.d.[60]).

Similar to the alternatives outlined above for micro-powder PTFE, the amorphous silica market is expected to grow due to the rising demand for high-performance materials and the increase for sustainable products. The main sectors where amorphous silica will be used include electronics, automotive, and the construction sector (Verified market reports, 2024[61]). It is unclear how these sectors utilise the amorphous silica for its lubricating properties. Boron nitride is another alternative that has a CAGR of 7.5% from 2023 to 2028, with its main lubrication use being in engines, alongside other uses in other sectors such as the cosmetic and personal care sector (Global Market Estimates, 2024[62]).

When looking at the graphene market, it is likely to significantly grow in the next few years, with a CAGR of 35.1% from 2024-2030 and a market of USD 195.7 million in 2023 (Grand View Research, 2023[63]).

Solvents

For solvents/ additive, several synthetic substances were identified. Isopropyl alcohol (IPA) was valued at USD 3.2 billion in 2022 and was growing at a CAGR of 7.5% between 2023-2031, showing potential availability as an alternative solvent (Straits research, 2024[64]). Trichloroethylene is expected to follow a similar trend, with a market of USD 3.8 billion in 2023 and a CAGR of 7.2% up to 2028 (Reports and data, 2023[65]).

Perchloroethylene had a smaller market in 2022 of USD 1.67 million, and a smaller CAGR of 3% between 2022-2032, making it a potentially less feasible alternative because of the size of the market (Future market insights, 2022[66]). Hydrocarbons also have a much smaller market size of USD 71.6 million and are expected to grow at a slower rate of 3.5% compared to IPA and trichloroethylene (Data bridge market research, 2023[67]).

Out of the alternative solvents identified, nPB has the lowest predicted CAGR of 2% between 2020- 2030, mainly due to its hazardous properties as identified by ECHA, therefore this alternative is likely infeasible (Fact.MR, 2022[68]). Other alternatives such as dichloromethane are expected to have a CAGR of 4.5% between the period 2018-2028 (Data Intelo, n.d.[69]). The final alternative identified for solvents was trans-1,2-dichloroethylene which is poised to have the most significant market growth with a CAGR of 11.8% between 2024-2021 with a rising demand from several sectors although it is highlighted that stringent regulatory frameworks could hamper production and utilisation (Reliable research reports, 2024[70]).

Hydraulic fluids

As discussed above, no alternatives were identified that are currently available on the market to replace PFASs used in hydraulic fluids for aviation (ZeroPM, 2023[50]); (ECHA(a), 2023[7]).

Available alternatives from retailers

Several companies are actively marketing PFAS-free lubricant products, firstly, FUCHS[15] are advertising a product named the “RHEOLUBE 460P series”, this product is said to be a next generation additive technology for advanced lubricity. The product is designed to replace PTFE lubricants in the automotive industry. FUCHS have also started to investigate several other alternatives to PFASs in lubricants, these alternatives were not identified on the FUCHS website.

Similarly, Kluber are marketing the Klübersynth PTB 2-24[16], a PFAS-free, high-performance lubricant that shows good oxidation resistance. The product has several other properties key for lubricity, although they do not give the applications for this alternative.

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[15] https://www.nyelubricants.com/fuchs-develops-non-pfas-based-alternative-to-ptfe-containing-lubricants [Accessed: 11th December 2024]

[16] https://www.klueber.com/in/en/products-service/products/kluebersynth-ptb-2-24/303993/ [Accessed: 11th December 2024]

Technical alternatives

Identification of technical alternatives

Lubricants

Alternative technologies

Modifying the lubricating system or the materials used, in order to avoid or reduce the use of lubrication completely have also been identified as potential alternative technology-based solutions. For example, the ZeroPM (2023) database includes the application of 'Lubrication free bearings based on using alternative materials (e.g. polyamides (PA), sulphonated polyetheretherketone (PEEK), polyethylene terephthalate (PET), and polypropylene (PP)). However, it is also indicated that these alternatives may not flexible enough to be used for required applications or is degraded at high temperature. Research is also on-going in relation to whether liquid lubrication could in some situations be substituted with non-liquid lubrication (Danish Environmental Protection Agency, 2024[30]).

Another system includes self-lubricating coatings is described by Feng, Zou, Li, Dou, and Huang (Feng et al., 2020[71]). The technique is achieved through, (1) using self-lubricating coating systems with two-dimensional early transition metal carbides and carbonitrides which have been seen to improve systems with their low shear strength, high mechanical strength and self-lubricating properties; (2) Intelligent coatings such as microcapsules which can make the composite show the characteristics of fluid lubricants in the friction process as well as avoiding defects of fluid lubrication; (3) Modifying current solid lubricants e.g. inorganic nanoparticles, to increase compatibility with polymer matrices.

Hydraulic oils

For hydraulic oils, there is a lack of information on technical alternatives.

Commercial availability of technical alternatives

While the specific materials associated with lubrication-free bearings (e.g. PAs, PEEK, PET, PP) are all common polymers and widely available on the market in different regions, their availability for specific applications where they can act as a substitute for materials where PFAS-based lubricants are used, is unclear from publicly available data.

3 Efficacy of alternatives to PFASs in hydraulic oils and lubricants

Technical feasibility of alternatives to PFASs in hydraulic oils and lubricants

Overview

Chapter 2 has highlighted the identity and overall commercial availability of potential alternatives to PFASs in a limited number of lubricant and hydraulic oil applications. When considering the efficacy of these alternatives, the information available in the public domain has focused predominantly on how a restriction on the manufacture and use of PFASs could lead to loss in lubricant technical performance. However, studies investigating the technical feasibility and providing a detailed comparison of performance qualities of 'drop in' alternatives replacing PFASs are not widely available for specific uses in publicly available assessments to date.

ATIEL (2023) has provided a specific (quantitative) comparison between PTFE lubricant additives and alternatives (including graphite molybdenum disulfide and boron nitride). This included a consideration of price, friction coefficient, working temperature, chemical stability and performance in various 'harsh' conditions. Similarly, a comparative assessment was conducted by SIA (SIA, 2024[72]), assessing the performance (wear, temperature resistance, outgassing) of PFAS-based and non-PFAS based products on the market. The results from these studies are discussed in this section. However, relatively few such studies were found in the public domain.

The automotive industry has indicated (based on input from the ACEA) that there is ongoing work to identify alternatives. However, at this time they have been unable to find an alternative that provides the life-time usage that PFPE provides in lubricants as well as providing all the same range of functionalities that PFPE does. Conversely, the food packaging industry has found success in phasing out the use of PFAS, having reviewed the necessary functionalities for food packaging and identifying alternatives that provide those functions.

From an assessment of publicly available literature, it is suggested that in order to achieve an entirely PFAS-free alternative and achieve comparable performance, a new formulation of lubricants or hydraulic oils all together will be necessary, as the substitution of PFASs and replicating the full range of functions and performance qualities has been highlighted as being very challenging or not currently possible in many cases.

Hydraulic oils

While specific PFASs that have been used in aviation hydraulic oils (e.g. PFOS and PFHxS) have been banned under the Stockholm Convention, a UNEP assessment suggested that this resulted in other PFASs, e.g. fluorinated phosphate esters being used as alternatives to PFOS in aviation hydraulic fluids (UNEP, 2018[73]).

It has been emphasised (from industry inputs to this study) that aviation hydraulic oils must meet rigorous aviation industry standards or specifications for safety and reliability[17], and are formulated to function across extreme temperature variations, from very cold at high altitudes to hot during operation. These applications often also require fire-resistant properties due to the high-risk environments typical in aviation. This is in contrast to more 'standard' or 'conventional' hydraulic oils, which are designed for moderate temperature ranges found in industrial or automotive environments. Hence, it has been concluded that so far, no acceptable non-PFAS alternatives in hydraulic oils have been approved for use in the aviation sector (ECHA(b), 2023[53]).

The ZeroPM (2023) database also indicates that there are no alternatives for hydraulic fluids, while there are a number of alternatives for lubricants. At this time, no substantiated information on alternatives for PFAS in hydraulic oils could be identified.

Lubricants

Many of the alternatives identified in Chapter 2 for PFASs in lubricants may not be technically feasible or fully replace the functionality for many of the relevant uses identified, based on the conclusions of the available literature and stakeholder inputs (Danish Environmental Protection Agency, 2024[30]); (ECHA(a), 2023[7]); the Open Public Consultation for the Annex XV PFASs restriction (ECHA(c), 2023[29]). This section further discusses the potential technical feasibility of the alternatives that have been highlighted in different lubricant components, as identified in Chapter 2.

Base oils, additives used in greases and grease thickeners

- ***Silicone oils*** could be used as an alternative to PFAS base oils in some applications. According to the Danish EPA report, silicone oil has a promising temperature services range between -70 ºC to approx. 200 ºC. The voltage breakdown of silicone is poor compared to PFPE, and while silicone oil is not considered a flammable material it can burn if it reaches certain temperatures, which is not the case of PFPE formulated lubricants (Danish Environmental Protection Agency, 2024[30]). Silicone alternatives can be used with most elastomers; however, they do not afford the same functional properties as PFPE base oils. Silicone-based alternatives have been found to remain on a finished article which in turn can hamper the technical performance of the product and some stakeholders had highlighted that silicone oil may not provide the same level of performance as PFPE base oils, especially under harsh conditions. Other issues such as the potential risk of exothermic reactions leading to explosions from the use of silicone alternatives were also flagged, although the respondent did not provide evidence of how/when this occurs (Halocarbon response ID #8045, 2023[74]).

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[17] Specific examples, highlighted in the ECHA (2023c) report include: Boeing Material Specification (BMS)3-11: Hydraulic Fluid, Fire Resistant; MIL-PRF-8328: Hydraulic Fluid, Fire Resistant, synthetic hydrocarbon base, metric, NATO code number H-537; M1L-PRF-87257: Hydraulic Fluid, Fire Resistant, synthetic hydrocarbon base, low temperature, aircraft and missile; SAEAS1241: Fire-Resistant Phosphate Ester Aviation Hydraulic Fluid.

  - The ATIEL noted in their consultation response for the PFAS restriction proposal that while silicone oils can be used in some applications, the lower temperature range as compared to PTFE, as well as the lack of flammability resistance and poor breakdown of voltage make it inaccessible from some applications.
  - The Semiconductor Industry Association found through laboratory testing that the use of silicone oils deposited a silicone dioxide layer onto the optical surface of the lens they were testing on, resulting in a significant decrease in the optical clarity that could not be reversed (The Semiconductor Industry Assosiation, 2023[75]).
- Grease clays such as ***bentonite*** may be used in combination with PTFE to thicken synthetic base oils such as polyalphaolefin oils, esters, and PFPE oils. Silicon oil (polysiloxane) greases are thickened with a mixture of amorphous fumed silica and PTFE. Molybdenum disulphide, graphite, talc and zinc oxide can also be used as grease additives. However, all these additives still require PFASs. Molybdenum disulphide is suitable for high loads but does not do the job in applications where sliding ability is a factor. Micro-powder PTFE is said to lead to cleaner conditions.
- For ***silicon base oil formulated with polyurea thickener***, the polyurea oils provide good properties for applications with high bearing speeds, although they do not perform well in harsh conditions and degrade quicker at elevated temperatures. The 'high performing' lubricant with silicon oil with polyurea produced by Chemie-Technik GmbH have been used in the food sector and has worked efficiently. No further information has been found on the technical feasibility of this lubricant in other applications (Elkalub, 2020[76]).
- ***Premium esters*** could be an alternative but would require 15-25 times the volume to be used due to more frequent lubrication.
- ***Silanes*** are noted to have specific functional ability of water and oil repellence. Silanes may not always reach the high-performance levels of other PFASs in certain aspects such as low friction coefficients or chemical resistance (Dias et al., 2024[35]).
- ***Ionic lubricants*** are currently the subject of R&D, and usually consist of large, asymmetric organic cations and usually an inorganic anion. These alternatives have been highlighted as potentially being toxic, sometimes corrosive and expensive.

Lubricant Additives

- **Graphite** and **molybdenum disulphide** were highlighted as alternatives that can be used depending on the application but are currently missing several key properties which made them inadequate thickeners, such as their chemical/water resistance and their plastic/elastomer compatibility. Graphite requires water to activate its low friction properties, making it unusable for low temperature applications such as refrigerant circuits. Molybdenum disulphide has electrically conductive properties whereas PTFE is resistive. Currently, this additive combination requires further tuning to be a suitable alternative for PTFE micro powders.
- **Boron nitride** is highlighted as a potential alternative in Table 2.3. However, it is indicated that this can only be used with PTFE micro powders and not on its own due to incompatibility with the other lubricant components. It has been found that boron nitride has completely different lubrication behaviour than PTFE micro powders. This alternative, however, was quoted as the most promising inorganic alternative, but not for all applications, as well as it being limited in performance compared to micro-powder PTFE.
  - The ATIEL notes that the above lubricant additives are not suitable alternatives for some PTFE applications in lubricants. Also, boron nitride is considered to be hazardous. Graphite has been

used in heavy duty applications but created carbon oxide during use, and molybdenum disulphide is electrically conductive while PTFE is not (ATIEL, 2023[46]).

- **Other inorganic substances** (e.g., layer building zinc phosphates, talc and silica) are fine when mixed with PTFE. However, when added to graphene both silica and zinc compounds have completely different properties. Silica thickened greases underperform in high shear applications, and some customers do not allow the use of these alternative substances (such as the automotive industry) (ECHA (b), 2023):
    - ***MoS_2 or boron nitride with black phosphorous, WS_2 and a (modified) graphene*** as a thin two-dimensional (2D) lubricant can potentially replace micro-powder PTFE in some applications. However, graphene can have the tendency to agglomerate. To avoid this and to be more efficient graphene can be modified via a hydrogenation or fluorination (Liu L.C., 2019[77]). The latter, seeming to be advantageous, is however also to be considered a PFAS as they contain CF_2 and CF_3 groups.
    - The ***TiO_2 nanoparticle/fluorinated reduced Graphene Oxide Nanosheet Composite*** showed good wear resistance and promising friction reduction although it does contain a fluorine group as well as nanomaterials that will require further investigation (noting PTFE can be nano). When looking at zinc/silica compounds, they have different lubrication properties compared to micro-powder PTFE, and in the electronic industry, it is difficult to use graphene as an alternative due to its hardness and its potential for electrical effects when released.
    - ***FUCH's™ PAO grease[18] thickened with lithium soap and non PFAS-based additives*** as an alternative to PTFE can be used in the automotive industry. The company highlights that the alternative has comparable performance to PTFE, as well as improved friction reduction, low temperature performance, and oil separation.

Within the aerospace industry, lubricants are typically used within a closed system. These lubricants therefore must function through the entire lifetime of the part, and to date, the industry has not identified an alternative to PTFE that has the 40-50 year lifespan deemed necessary.

Solvents

For alternatives to PFASs-based solvents and additives, limited information was identified and most stakeholders cited in Danish Environmental Protection Agency (2024) concluded that the PFASs are necessary due to functionality and cannot be substituted.

Summary on the technical feasibility of alternatives

Alternatives to PFAS in lubricants have been identified and can replicate some of the functionality of PFASs to some extent. However, these alternatives do not possess all the functionalities that PFAS do. Because of this, no single "drop in" alternative has been identified and combinations of alternatives are necessary to reach the same functionality as the original PFAS. This can require specific formulations to be developed for different end applications, which can be costly and time consuming. The overall feasibility of an alternative depends on the precise application, resulting in case-by-case considerations being necessary.

[18] High Quality Lubricating Greases | FUCHS

For example, for PFAS base oils a suitable alternative for all applications has yet to be identified. As PFAS base oils offer low vapor pressure, resistance against aggressive media and oxygen, not being flammable, and various other properties, it has been difficult to identify a one size fits all alternative for PFPE in many applications (e.g. automotive and aerospace applications).

The key area where alternatives are lacking is for conditions determined to be 'harsh' or 'extreme.' These conditions are typically at ultrahigh or subzero temperatures or at high pressures. Stakeholders have highlighted that this is an area where the use of PFAS is 'critical', and without a suitable alternative many applications will no longer be possible. Stakeholders have also expressed concerns with alternatives to PFASs based products contaminating or remaining in finished products (Danish Environmental Protection Agency, 2024[30]).

At this point in time, it is not possible to fully understand the feasibility of all alternatives for all uses within each individual sector. Currently, stakeholders can use PFAS lubricants, such as PFPE, in a number of applications within their industry. The automotive industry uses PFPE as it is a lifetime lubricant, meaning the lubricant outlasts the lifetime of the part without needing to be replaced. When required to develop alternatives, there is no feasible single alternative that compares to PFPE in all applications, resulting in several different alternative formulations being necessary. Stakeholders such as ATIEL and ASD have responded to the ECHA consultation stating that alternative chemistries do not guarantee the performance, reliability, safety or durability that PFAS lubricants do in industry applications.

However, other industries are actively working to find PFAS alternatives. The food packaging industry has done significant work to phase out the use of PFAS and has found success in their efforts (Kluber Lubricants). More customers are approaching lubricant manufacturers to find alternative solutions, and as the demand grows additional R&D efforts are being put forward to find these solutions.

In order to understand the feasibility of alternatives, more *in situ* research is necessary. It can take as little as five years to implement an alternative to market, and much longer for niche or high safety demand uses such as military. While on paper alternatives may seem feasible, testing and recertification is necessary to identify where alternatives are truly feasible. Feasibility testing will need to be done over a range of applications within various sectors to truly understand if an alternative provides the same functionality as the original PFAS.

Costs of using alternatives to PFASs in hydraulic oils and lubricants

The sections below cover the capital cost and the operating cost of using alternatives to PFASs in lubricants and hydraulic oils. The capital costs include the cost of obtaining the alternatives/the costs which could occur for the operator from having to research, develop and implement the alternatives into a product. The operating cost covers the increase or decrease in cost when using the alternatives within the lubricant/hydraulic oil in an application.

There was a lack of relevant information regarding the cost of using alternatives to PFASs in hydraulic oils and lubricants, other than the Annex E document (ECHA(b), 2023[53]) which gave an overview of the cost of PFASs from an EU perspective. Therefore, the costs of alternatives could vary outside of the EU.

The ATIEL noted in their consultation response to the PFAS restriction proposal that PTFE does not have the lowest relative price compared to alternatives. Both boron nitride and graphite fluoride have higher costs, but graphite and molybdenum disulfide come in at a lower cost than PTFE. The industry continues to use PTFE despite this, as the lifetime performance of the lubricant outweighs the decreased costs alternatives may provide (ATIEL #4423, 2023).

Additionally, a lack of readily available information was found on the cost of operating with different alternatives in lubricants/hydraulic oils. Only one response gave a partial overview of using an alternative to PFASs in the semiconductor sector.

The Semiconductor Industry Association responded to the ECHA consultation to highlight the significant costs associated with the changeover of manufacturing due to the use of alternatives. SIA suggests there will be costs associated with new manufacturing processes, a decrease in throughput, an increase in part failure, an increase in mechanical part failure of processing lines, and the downtime to clean all existing parts that use PFAS lubricants (The Semiconductor Industry Assosiation, 2023[75]).

Capital and operating costs of alternatives to PFASs

There was a lack of information on the capital cost which could occur from using alternatives to PFASs. However, there is a likely increase in costs for both the research and development of new alternatives (ECHA(b), 2023[53]), while current fluorinated lubricants are typically, but not always, of higher cost than non-fluorinated lubricants:

- Due to their high costs, PFASs-based grease is only selected when no alternative is available. E.g. fluorinated lubricants may cost the end-user 300-600 US$/kg, whereas non-fluorinated lubricants have a purchase price of about 15-40 US$/kg. Silicone greases are a little bit more expensive than other non-fluorinated lubricants.
- There was a lack of information on the cost of PFPE-base oils. PFASs-based lubricants are more expensive and, therefore, natural substitution occurs where possible. However, PFPE is very difficult to substitute out and, therefore, these lubricants are the most cost-efficient solutions. PFPE lubricants have a longer lifetime and have a lower need for re-lubrication which reduces cost. Finally, as PFASs need to be reapplied less frequently, there are cost savings in terms operations/maintenance.
- For PTFE micro-powders it was highlighted that alternatives are more expensive or that no cheaper alternative is available to PFASs, e.g. boron nitride and nitride are more expensive than the PTFE. Alternatives may also need to be tailored to the relevant applications. Graphite is of lower cost to micro-powder PTFE, although the technical feasibility can be questioned.
- For PFASs-based solvents and additives other than micro-powder PTFE, there were no technical or economically feasible alternatives to PFASs. One stakeholder highlighted that PFASs containing materials cost up to 10 times more than non-fluorinated containing materials and, therefore, they are only used when necessary.

Using alternatives to PFASs is likely to cause an increase in operating costs over the full lifetime of the equipment or parts/components. One stakeholder gave an example of the cost to replace PFASs in lubricants in the semiconductor sector, with the need for an extensive redesign and retrofit of all semiconductor manufacturing equipment being considered cost prohibitive. The following costs would occur according to the semiconductors PFAS consortium (2023):

- A decrease in product throughput in the manufacturing process and an increase in the defects of products.
- An increase in likelihood of failure of the products, such as the lubricated seals and O-rings that would then lead to the compromise of products not being able to contain chemistries, leading to safety concerns and potential increase of environmental exposure.

- An increase in the mechanical failures of moving parts, resulting in an increase in maintenance costs, shorter lifetimes of semiconductors, and a need to update the design of products to incorporate additional redundancy.
- An increase in maintenance costs due to the shorter lifespan of the alternative technology lubricant used.
- An increase in maintenance costs due to number of manufacturing lines necessary to produce various alternative technologies specific to application.
- An increased lifetime cost for products, as the lifetime of the lubricant decreases with alternatives and the need for reapplication increases.

Although the above highlights the cost for lubricants used in semiconductors, it is likely that this scenario is similar for other sectors, with the alternatives to PFASs containing lubricants failing to reach the same level of technicality.

The situation is similar for the PFASs used in the hydraulic systems in the aviation industry, with hydraulic oils not containing fluorochemicals being quoted to have led to metal components being damaged and the need for the degree of acidity of the alternative to be constantly monitored so that its lifetime can be determined. There were no alternatives found that appeared to address these issues.

Additional costs to downstream users of alternatives to PFASs

It is apparent that the alternatives to PFASs in lubricants could lead to increased costs for several stakeholders in the lubricant sector including the manufacturers of the products. The knock-on effect of this is the higher costs which could come to the downstream users. It is likely that per application, the development of the new technologies will cost in the order of hundreds of thousands of Euros (Danish Environmental Protection Agency, 2024[30]).

As noted in the section above, the raw costs of alternatives are often lower than the cost of the PFAS itself. Then why aren't alternatives already employed if they save costs? The response lies in the point mentioned above, that there is no single drop in alternative that completely replaces PFASs in the various hydraulic fluid and lubricant applications. While individual raw materials may come in at a lower cost than PFASs, developing an alternative combination that replaces PFASs to the same functional standards can lead to costs above the raw PFASs cost. This, coupled with the necessary changes to production as well as the potential need for multiple production lines based on various alternative combinations, drives both the capital and operating costs up, resulting in alternatives becoming more expensive than PFAS.

PFPEs are one of the least common and most costly lubricants on the market as they are capital-intensive and have complex supply chains. While alternatives may be cheaper to purchase, there are additional costs to consider over the lifecycle, including changes to production lines and performance changes and associated failure costs.

Outside of material and production costs, there are also the safety/regulatory costs to consider. PFAS are currently used as they ensure end articles meet standards and uphold functionality. Should alternatives be introduced, there will be additional costs to recertify these alternatives to the same safety and regulatory standards. There is also a potential of increased costs due to standards not being adequately met for some time or failures that occur when alternatives are introduced.

Stakeholders have indicated that for uses considered 'critical' they will pay higher costs associated with PFASs rather than the lower costs of alternatives. This is due to the nature of these applications, which are usually safety related. Stakeholders indicate that they would absorb fines for continuing to use PFASs in these critical applications over switching to alternatives in some cases, as the functionality the PFAS affords a material or product cannot be matched by alternatives.

The higher cost associated with PFASs is also accepted when the cost is extended out over a longer lifespan of a component or part than if an alternative were used.

Summary of relative performance of identified alternatives

From the information presented in this section, on the technical feasibility of alternatives as well as the cost to replace PFASs in both lubricants and hydraulic oils, it is noted that further research should be done for several alternatives. A few of the alternatives are already in their R&D phase, for example ionic liquids, copper-based paste and vegetable oils, although these are having to overcome issues such as temperature resistance.

Users of hydraulic fluids and lubricants need to assess the functionality they expect in order to understand if substitution is possible. For some applications, the functionality the PFAS provided to the lubricant or hydraulic fluid can be provided by an alternative substance. A one size fits all alternative will most likely not be possible, but rather tuned alternatives that focus on the performance and functionality expected of the lubricant or hydraulic fluid. It is key that users of lubricants and hydraulic fluids understand what level of performance is needed and if the use of PFAS is truly needed to achieve that level of performance.

Furthermore, the potential increase in costs related to purchasing the alternatives and implementing them into new systems, the increased volume of substance used can also sometimes lead to an increase in costs. Further efforts should be made to decrease the overall cost.

Overall, it appears that there are several substances, all of which have been flagged as potential alternatives to PFASs in several lubrication applications. There are some limitations, and the alternatives may need some further development to fully replace PFASs in lubricants, although some industries have already shown promising signs of doing this.

When it comes to alternatives, understanding if the use of PFASs is critical to the functioning of the material/article is key. For critical applications, stakeholders are not prepared to sacrifice the properties PFASs afford to develop a new combination of alternatives. The cost of PFASs over the lifespan of the article is justifiable rather than switching to a lower upfront cost alternative.

4 Uptake and market penetration of alternatives

Overview of the market for PFASs and alternatives in hydraulic oils and lubricants

Market for PFAS-based lubricants

As discussed in Chapter 2, PFAS-based lubricants are used within multiple sectors globally.

Information regarding the market for PFAS-based and alternative lubricants (including quantitative estimates of total or relative volumes of use, or value) at a global level, even at the level of individual sectors of use, is not widely available in the public domain. Information is available at the national scale in some countries. It has been indicated by some individual stakeholders that overall, the PFAS based and PFAS containing lubricants constitute a relatively small proportion of all lubricants used globally.

Stakeholders (manufacturers and users of lubricants) suggested uses of PFAS-based lubricants are generally limited to 'extreme' cases where performance requirements are high and specific, and no established alternative has been found. One report highlighted that PFAS-based greases are only used when no alternatives are present, predominantly due to their high costs with some fluorinated lubricants costing the end user up to $600/kg (ECHA(b), 2023[53]). This is compared with non-fluorinated lubricants that can cost as little as $15-40/kg. Potential alternatives such as silicone greases cost a fraction more than that of non-fluorinated lubricants. Based on limited inputs from industry stakeholders, the majority of use by volume globally is expected to be within automotive, aerospace, and military sectors, where well established markets for such PFAS-based lubricants exist.

It is estimated that, on average, in the European Economic Area (EEA) roughly 1,600 tonnes of PFAS are used in lubricants annually (Danish Environmental Protection Agency, 2024[30]). The Danish Environmental Protection Agency (2024) highlighted that the use of PFAS-based lubricants has historically been increasing, along with a shift towards synthetic lubricants. Similarly, the demand for fluorinated lubricants is increasing, with PFAS suppliers and lubricants producers suggesting a yearly increase ranging between 1 and 15%, while other stakeholders suggesting a 5% increase between 2021 and 2030 (Danish Environmental Protection Agency, 2024[30]). In terms of turnover, it is estimated that the fluorinated lubricants market makes up about 300 million euros per year, corresponding to roughly 20% of the overall EU lubricants market (Danish Environmental Protection Agency, 2024[30]).

The overall volumes of use for PFAS in hydraulic oils is expected to be much lower than for lubricants. Global market estimates for fluorinated substances within hydraulic oils for aircraft has been estimated at roughly 2 tonnes per year (European Commission, 2015[78]), with roughly 730kg used within the EU per annum.

PFPE Base Oil

Four companies Chemours, Syensqo[19], Daikin, and NOK are estimated to collectively produce more than 1,000 tonnes of PFPE base oil per year. Other companies (e.g. Miller-Stephenson Chemical) are also known to produce and market PFPE-based lubricant, but no data on volumes of products was available).

Most manufacturers sell the PFPE oils or greases directly or through partners. They are also sold to speciality lubricant suppliers who formulate their own lubricant and distribute under their own name (Danish Environmental Protection Agency, 2024[30]). It is estimated that currently, PFPE-based lubricants constitute 0.015% of the lubricants market globally, however this is expected to increase in the future (although no expected time scale for the increase in PFPE oils has been specified) (Danish Environmental Protection Agency, 2024[30]). The relatively low proportion of PFPE within the total use of lubricants worldwide is attributed to the price and volume required compared with other base oils (ECCO Gleittechnik GmbH, n.d.[79]).

Micro-powder PTFE (as an additive)

The following manufacturers have been identified as suppliers of micro-powder PTFE additives: Asahi Glass, Central Glass, Daikin, Dyneon (part of 3M), Chemours and Syensqo, Other companies (e.g. Clariant, Laurel Products, Micro-powders Inc., Shamrock Technologies, Heroflon, and Maflon) obtain FPs (usually PTFE) from secondary sources, and then convert them into micro-powders. However, this should not be considered an exhaustive list and it is expected other manufacturers and suppliers exist.

In 2010 the global market for micro-powder PTFE was approximately 7,000 to 10,000 tonnes per year, with the total EU volume estimated to be roughly 4,000 tonnes per year (Danish Environmental Protection Agency, 2024[30]).

Market for alternatives in lubricants

While it is indicated in Chapter 2 that several alternatives are currently commercially available and in use, very limited information is available in the public domain to compare the market (e.g. total volumes, total values) of the identified alternatives with the PFASs they can potentially replace in specific lubricant applications.

Future market trends

It is noted above that the use of PFAS-based lubricants represents only a relatively small subset of the wider global lubricants market, and the industry has indicated that these uses are generally limited to where the level of performance is deemed to be necessary and can only be provided by PFASs such as PFPE (oils) or PTFE (additives) (see further discussion below).

Nevertheless, the market for PFPE lubricants is expected to grow in the future and as discussed in Chapter 2, the use of PFAS-based lubricants including PFPE has now proliferated into a wide range of sectors of use. Moreover, it is indicated that producers could look to expand their markets for PFPE in wider, more 'mundane' lubricant uses[20]. These trends should be considered in conjunction with wider trends in material demands in

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[19] Previously trading under the name "Solvay Solexis".

[20] https://miller-stephenson.com/comparing-industrial-lubricants/

markets that are likely to expand in future (e.g. green energy, electric vehicles, semiconductors and electronics).

As noted in Chapter 2, several suppliers of PFAS-free alternatives are identified. One company consulted in this study has indicated that interest in investigating PFAS-free solutions is growing (see below) but currently it is very difficult to predict the future market demand for such products, and this may vary considerably between different sectors of use.

Challenges to substitution

Technical challenges

The most common aspect, raised by several industry stakeholders (including both lubricant manufacturers and downstream users) for the substitution of PFASs in lubricants and hydraulic oils relates to technical performance of the alternatives. As discussed in detail in Chapter 2, PFASs are used in lubricant and hydraulic oil applications due a wide (and unique) range of specific properties that in turn impact a number of key technical functions simultaneously, allowing for a level of performance greater than could be achieved with more 'conventional' lubricants.

Industry stakeholders have indicated that the key technical challenge is finding a replacement for a single chemical substance that allows comparable performance. In practice, the available alternatives (as detailed in Chapter 2) are considered not to constitute a single drop-in replacement for most applications or would need to be under synergistically with other alternatives or the original PFAS itself (e.g. in the case of PTFE additives).

A common consideration from the inputs of industry stakeholders, is that alternatives have been widely researched for many decades, and if viable alternatives to PFASs were available, they would have been implemented already. For example, it has been noted that the search for suitable alternatives has been ongoing for the last 30 years, but no suitable alternatives have been identified that achieve the required level of performance (KEMI, 2015) (ECHA(b), 2023[53]).

Given the wide range of different properties and functions PFASs are shown to impart in lubricant products (and the wide range of specific applications for which lubricants are used), this raises the question of what level of performance is strictly required in a particular application, the extent to which available alternatives can provide that performance, and the level of performance 'loss' that could be accepted in a particular use.

In many cases, industry stakeholders emphasise that PFAS-based lubricants are used in situations that require a higher level of performance and reliability than under 'normal' circumstances. The terminology used to describe these conditions varies between different sources. In some cases, stakeholders have indicated that PFASs are used only in 'critical' or 'essential' situations. It is commonly noted that PFAS-based lubricants are used in 'extreme' or 'harsh' conditions, and it is for these cases that finding alternatives has not been possible.

There is no set definition for the above-mentioned terms, so it is challenging to objectively or generically determine when use of PFAS-based lubricants is strictly required and how technically feasible identified alternatives could be. Commonly, the terms 'harsh conditions' can be taken to refer to one or a combination of the following factors: extreme temperature, extreme pressure, presence of corrosive chemicals, exposure to radiation or oxygen. Across the extensive range of uses for PFAS-based lubricants (see Chapter 2), what is considered 'harsh' or 'extreme' conditions will vary (ATIEL, 2023[46]), and will be subjective to each individual user.

Lubricant manufacturers have indicated, in general, that lubricant users who wish to phase out PFAS will still desire to achieve the same level of performance as they did when using PFAS-based lubricants. This presents a significant challenge for manufacturers to solve and is likely to be more challenging for some sectors rather than others. For example, for uses where stringent safety standards apply (e.g. aerospace, military, automotive), it may be difficult to fully replicate the PFASs based performance with available alternatives.

Investments in R&D and the technological development have the potential to explore alternatives to PFASs in the hydraulic oils and lubricants sector with comparable properties to PFAS-based products. In some industries, such as aerospace and defence, the time required to develop an alternative, the timescale of funding cycles, and the recertification process are barriers to substitution. The recertification process is not only time consuming but technically challenging as it is meant to uphold safety standards and ensure products are more than fit for purpose.

Stakeholders noted that they often do not have visibility of alternatives or control over the standards that dictate what substances are used in articles. While stakeholders may be motivated to find alternatives for PFAS applications, they are faced with the challenges of needing new standards/certifications for new formulations. It is indicated that for many sectors (notable aerospace and defence), the process of requalification can be very time consuming and costly. Some stakeholders at the end of the supply chain have the expectation that suppliers have done the research into alternatives when this may not actually be the case.

Moreover, several stakeholders have noted that the visibility of PFASs across the full supply chain is often very challenging. This applies both to the manufacturers of lubricant products (where they may supply to a formulator of articles/components/equipment but then do not know the ultimate end user) and the downstream end users (who may not have access to information on precisely which chemicals are present in the articles, components or equipment they purchase).

Another potential technical challenge for chemical substitution in the lubricants sector, raised by several stakeholders, is if the use of an alternative chemical or technical lubrication method requires a new or adapted design of existing equipment, this can take considerable time and involve significant cost (ATIEL, 2023[46]); (UEIL, 2023[47]).

Economic challenges

Economic costs associated with the development of PFAS-free alternatives are predominantly due to R&D, with estimates suggesting the cost could range from 50,000 to 1,000,000 euros depending on the application (Danish Environmental Protection Agency, 2024).

In addition to R&D costs, from the literature reviewed, it appears that users of PFAS-free lubricants need to use significantly more lubricant to achieve the same performance as PFAS-based lubricants, which result in additional costs. Other economic impacts include the potential for higher maintenance costs, as some machineries would require more lubrication, which in turn could affect productivity due to down time and maintenance. Estimates for the costs of reformulation and testing of new alternatives range from 100,000 to 500,000 euros (Danish Environmental Protection Agency, 2024).

It can also be costly to undertake the R&D process, as it takes as much as five years to identify, test, and place on market a new formulation. During these processes there may be additional costs associated with developing new standards/certifications which is an additional cost. Often times, the funding cycles are not long enough to fully fund R&D for alternatives, resulting in partially researched formulations that did not make the cut for further funding. Funding is often politically driven, even if the funding is not coming from public funds. Different political administrations will have different economic goals, and industry and R&D operations may need to reallocate funds to other areas to align with those economic goals.

Economic challenges also exist in making the change to non-PFAS alternatives within the manufacturing space and the technical specific space. For manufacturing, there could be significant upfront costs necessary to make changes for non-PFAS alternatives, including the need for additional products to be manufactured as the technical performance of non-PFAS alternatives has to be tuned to the end application and is not a one size fits all case. When new products need to be developed, there can also be costs associated with generating new technical specifications for these products or even revising safety and performance standards so new technologies can be used.

Regulatory challenges

One of the main regulatory challenges for alternatives is to meet safety standards particularly within the automotive and aerospace industry.

Due to the ‘harsh’ conditions that are often present in these sectors for which PFAS-based products are used (including temperature and chemical resistance), the certification process for the use of alternatives could take considerable time. This is also relevant for lubricants and hydraulic oils used within the nuclear energy sector, as strict compliance standards are in place to ensure operational safety, with costs for development and testing reaching tens of thousands of Euros (Danish Environmental Protection Agency, 2024).

Within the aerospace industry, there are standards that specify the use of PFAS based materials. Due to these specifications, alternatives cannot easily be swapped in. Instead, the standard would need to be revised with the alternative material undergoing significant testing to ensure that the alternative provides the same functionality and safety as the original standardised material.

For each alternative formulation, new standards/certification will need to be developed. These can be costly to develop and are also time consuming. In order for articles to be placed on the market, they must meet safety standards to ensure consumer safety, and many alternatives are not included in current standards. These standards need to not only meet safety requirements within industry but also to be meet national or international regulation, such as aerospace standards.

The regulatory approval required for new products is also a key barrier. Relatively limited information has been identified as to the regulatory authorities approving or restricting the use of PFAS alternatives. However, the following information was collated from the Open Public Consultation for the Annex XV PFASs restriction (ECHA(c), 2023[29]). It is important to note that, while there are international/national level regulations, there are also industry level standards and specifications that need to be taken into consideration.

According to some stakeholders, alternatives to PFASs in electric vehicles will need to be produced and approved otherwise the EU targets set for electric vehicle capacity and production would be difficult to reach. Another respondent highlighted that any alternatives to the use of PTFE powder in lubricants must conform with the ASTMF1545 standard which covers factory-made plastic-lined ferrous metal pipe, fittings, and flanges intended primarily for conveying corrosive fluids (Zhejiang Green New Materials Co, 2023[80]).

As highlighted in the sections above, there are various industry regulations and standards that need to be considered for alternatives as well. These regulations and standards need to be reviewed in the case of each alternative formulation, and additional testing will be required to ensure that the alternative meets the requirements.

Anticipated time frame for alternatives to eliminate the use of PFASs

Based on the discussion in Chapter 3 and above, it is suggested that fully eliminating PFASs from uses in lubricants and hydraulic oils across all uses where they are currently applied may not be feasible in the short or medium term. Investigating, testing and implementing alternatives to PFASs in lubricants is expected to be a very lengthy and costly process for many sectors of use. The available literature and inputs from stakeholders also suggest that the timeframe will vary considerably between different uses.

In the medium-to-long term, where substitution is technically possible, using known available alternatives, the timescales can still be significant, especially where alternatives need to undergo extensive testing and qualification before they can be approved by the end user. In the aerospace sector for example, it was indicated by one stakeholder that the qualification process could take 3-5 years for testing then commercial evaluation of 5-10 years especially for aircraft. The process can vary depending on the desired lifetime of the product/component and is subject to customer review and approval.

Timescales for uptake of alternatives are also dependent on funding cycles and government administrations. Often, the timescale to find an alternative is longer than the funding cycle or government administration and therefore can be further pushed back as regulatory priorities change over time.

Drivers towards substitution

Market Drivers

Some lubricant manufacturers have indicated that there is a growing demand from original equipment manufacturers (OEMs) to have PFAS-free lubricants and the design and development of new equipment being manufactured may be starting to incorporate this. However, there is limited information to indicate this is being widely pursued currently at a global scale, and the demand or tendency to investigate PFAS-free options will vary between different sectors and regions.

For many uses there is a common driver to not change to alternatives. The end user tends to be primarily concerned with ensuring required performance and availability of the materials that enable performance, particularly when the safety, durability and reliability of the equipment or components must be maintained or is stipulated by stringent standards or specifications.

In many cases, it is possible the end users do not always know what chemicals are in the product. Instead, the end user tends to rely on the supplier to make regulatory changes when it comes to chemical alternatives while expecting the product to remain the same. For example, within the automotive industry the safety of products is key and therefore any alternatives will need to comply with the same safety standards as that of PFASs that are currently used within automotive parts (Doerken Coatings GmbH & Co. KG ID, 2023[81]).

Regulatory Drivers

As discussed above, there is currently a lack of a driver towards PFAS-free alternatives in lubricants other than through regulations, e.g. based on the technical challenges and/or current market factors. The main driver, therefore, to switch to an alternative, will be increasingly stringent regulations, which will require the manufacturers of lubricants or hydraulic oils to phase out specific chemicals, resulting in the reformulation or obsolescence of products.

Regulatory drivers are related to global, national, or state/regional-level restrictions for the use of PFASs, either in general or with a focus on specific uses or sectors, or on the production and imports/ exports of PFASs more broadly. Such restrictions could drive the substitution of PFASs in lubricants and hydraulic oils.

Globally, certain PFASs and their salts / related compounds are restricted under the Stockholm Convention (UNEP, 2023[82]). PFOA and PFHxS are listed in Annex A of the Convention, meaning that countries who have ratified the Convention must take measures to *eliminate* the production and use of these substances. PFOSs are listed in Annex B, meaning that countries who have ratified the Convention must take measures to *restrict* the production and use of these substances. More recently, the approach to listing PFASs under the Stockholm Convention has expanded to considering groups of substances together. In 2024, the POPs Review Committee also recommended to list Long-chain PFCAs under Annex A of the Convention.

Furthermore, when PFOS were originally listed in Annex B of the Stockholm Convention, the use in aviation hydraulic fluids was listed as an approved 'acceptable purpose'. Following a review of the acceptable purposes and specific exemptions for PFOS, based on the assessment and the availability of alternatives and the withdrawal of a number of Parties from the register of acceptable purposes (see UNEP/POPS/POPRC.14/INF/13), the POPs Review Committee recommended that the acceptable purpose for the use of PFOS, their salts and PFOSF for aviation hydraulic fluids no longer be available under the Convention, suggesting this regulatory action (on PFOS) has acted (at least in part) as a driver to develop and implement alternative non-fluorinated chemical alternatives.

At national- or regional- level, OECD countries are implementing legislation and wider policy measures targeted at PFASs, that go beyond the requirements of the Stockholm Convention and that are driving a move away from their use and increases in substitution to alternative across a wide range of different sectors, potentially including uses in lubricants and hydraulic oils.[21] This includes regulatory measures to prohibit or restrict the production, uses, emissions, and presence of PFASs in the environment, food and drinking water. While historically actions have focused on PFASs individually, more recently the focus has shifted to PFASs as a larger collective group (see Chapter 1). These combined actions can be expected to act as a significant driver for phasing out the production of PFASs and their use in specific sectors, including in lubricants and hydraulic oils.

While historically, in most countries, regulatory efforts to address the risks associated with PFAS have focused on the restriction or ban of specific PFASs (e.g. PFOS, PFOA, PFHxS), as discussed in Chapter 1, an emerging focus of regulatory action in some OECD areas (e.g. in EU and Canada, for example) looks to address PFASs as a wide group rather than a case-by-case basis, and covering all production and uses. It is expected that this approach will encourage producers and users of PFASs in lubricant and hydraulic oil applications, to consider more carefully their full product range and investigate their use of (all) PFASs across the full supply chain and the potential for PFAS-free alternatives. It is intended that such an approach will help prevent regrettable substitution when phasing out PFASs from use.

For example, at EU-level, a proposed universal PFAS restriction, which would cover the full range of PFASs in the scope of this report (see ECHA, 2023a) includes a specific discussion of uses of PFASs in lubricants and hydraulic oils. It is highlighted in that proposal, that restriction of PFASs in these uses is challenging due to the lack of currently available alternatives. Nevertheless, action taken at the level of the 'full' range of PFASs is likely to drive action to research, develop and commercialize fluorine-free alternatives in these uses.

[21] See: https://www.oecd.org/en/topics/sub-issues/risk-management-risk-reduction-and-sustainable-chemistry/per-and-poly-fluorinated-chemicals.html

Similarly, Canada's final 'State of PFAS' report (Environment and Climate Change Canada, Health Canada, 2025[17]) concludes that the class of PFAS, excluding fluoropolymers as defined in the report, is toxic under the Canadian Environmental Protection Act, 1999. A targeted and phased approach to the risk management of the class of PFAS, excluding fluoropolymers has been proposed. Fluoropolymers are planned for consideration in a separate assessment. It is also noted that the New Substances Notification Regulations (Chemicals and Polymers) (NSNR) means that new substances that are imported into or manufactured in Canada are subject to notification requirements. It is highlighted that this has already identified uses of PFASs in lubricants.

Other countries[22] have developed detailed action plans to target certain PFAS (PFOA, PFOS and PFHxS) pollution under national level legislation, including actions to study, assess and survey LC-PFASs and consider other selected PFASs to study.

A common feature across regulatory measures in different regions or at different scales, is the inclusion of derogations for specific uses. These are typically allowed for when the socioeconomic implications of a restriction for a use are deemed disproportionate and/or there are not considered to be viable alternatives available. Derogations are typically time-limited, such that continued research and development of alternatives continues. The aspect of derogations, and how these are defined, is likely to be relevant in the case of lubricants and hydraulic oils, given the discussion on the importance their application in many sectors (see Chapter 2 and 3). This also presents a challenge, given the discussion above relating to the how different sources may define or describe 'critical' or 'extreme' conditions where PFAS-based lubricants are often needed to provide the desired level of performance.

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[22] For example: https://federation.gov.au/about/agreements/intergovernmental-agreement-national-framework-responding-pfas-contamination

5 Status of the shift to alternatives and its sustainability

The following section synthesises the information from Chapters 1-4 to provide an overview of the current state of play regarding the shift from use of PFASs to non-PFAS alternatives in the lubricant and hydraulic oil sector.

PFASs are used in lubricants and hydraulic oils due to a wide and unique range and combination physical and chemical properties, associated with a wide range of specific technical functions in their applications – including: extreme temperature resilience, low friction coefficient, extreme pressure performance, chemical inertness towards harsh chemicals and oxygen, mechanical stability, non-flammability, resistance to radiation, and compatibility with elastomers, plastics, metals and alloys. Because of this unique combination of properties and technical functions, PFAS-based lubricants are generally used in 'critical' applications, where the technical function(s) are needed to provide superior technical performance e.g. due to regulation, certification, or standards. For example, manufacturers and users have indicated these 'critical' uses are associated with applications in more 'extreme' or 'harsh' conditions and where the use is associated with ensuring levels of safety or reliability.

In general, it is indicated that currently, only limited action is being taken to actively substitute PFAS-based lubricants with alternatives. Industry stakeholders have indicated that they consider PFAS-based lubricants are limited only to those 'critical' uses, so represent a relatively small subset of the global use of lubricant products. The consideration is that, if viable alternatives were available, they would already be in use as there is a substantial cost incentive to do so. However, the market for PFAS-based lubricants is expected to expand, potentially into wider markets in future. Moreover, it is reflected that PFASs are not always fully visible across the supply chain so the manufacturer of the PFAS-containing lubricant may not always know all the end-users for that product.

Alternatives to PFASs in lubricants, covering different lubricant components (base oils, additives, solvents) have been identified for some uses and are indicated in many cases to be commercially available and already in use. There is some indication that substitution has already started taking place for certain uses. For example, it is suggested that, compared to PFPEs, there seems to be more activity related to possibly substituting PTFE, at least in some applications (Danish Environmental Protection Agency, 2024). In other cases, it has been suggested that there may not be a need for PFAS-based lubricants at all, for example in bicycle chains[23]. Moreover, there is a suggestion that OEMs are increasingly investigating eliminating PFAS from their equipment at the beginning of the R&D cycle. However, at the same time, OEMs still require the associated level of performance to be maintained, and avoid having to make costly upgrades or redesign of current

[23] https://www.ri.se/en/there-are-no-justifiable-reasons-to-use-ptfe-in-bike-lubes

equipment. The ideal scenario is to allow customers to use the same equipment, and optimise existing options for alternatives, rather than having to investigate 'new' options.

It is highlighted in this report that there are very few incentives for lubricant users to switch to PFAS-free alternatives. Users are primarily driven by a required level of performance, especially where safety, durability and reliability are paramount to the use in question (e.g. aerospace, automotive, military) applications. The main driver that can therefore catalyze the research, development, commercialization and implementation of alternatives, is regulatory actions, as this will potentially limit or remove the availability of PFASs in lubricant manufacture and use. It is indicated that, in general, the industry aims to foresee upcoming regulatory actions and mitigate the risks this may pose (e.g. removal of certain products from the market), for example by targeting research and development to particular uses or products.

In general, it is considered that identified alternatives currently do not possess all the functionality that PFASs provide simultaneously. Because of this, no single 'drop in' alternative has been identified for most uses where the same level of functionality or performance can be achieved. However, the number of specific comparative assessments available in the public domain is relatively limited. Given the wide range of specific uses for PFAS-based lubricants, each with their own unique performance requirements, there is significant complexity in determining for which uses alternatives can be implemented, and where this will be more challenging. The further investigation of the efficacy of potential alternatives must carefully consider the distinction between 'critical' applications (where the use of PFASs is necessary, and alternatives are not available) and 'non-critical' applications (where use of PFASs is not necessarily needed).

6 Policy recommendations and areas for further work

List of recommendations

The policy recommendations made here are divided according to the intended audience in the sections below.

Recommendations for international organisations

Conduct further work to understand the potential health and environmental risks of PFASs and non-PFAS alternatives identified as having been used in hydraulic oils and lubricants throughout their lifecycle.

Consider systematic collection of market data on the use of PFASs and alternatives in hydraulic oils and lubricants.

Recommendations for national and regional governments and agencies

Develop and implement national-level or regional-level action plans and risk management measures to minimise the uses of PFASs in hydraulic oils and lubricants and limiting these uses to where the level of performance is established as being 'critical' and where alternatives are not currently viable. In addition, regulatory actions should look to prevent or minimise the environmental release of PFASs from remaining uses in lubricants and hydraulic oils at all stages of the product lifecycle.

Establish a regulatory approach at national level that includes requirements for users of hydraulic oils and lubricants to report the identity, specific application and volumes of PFASs used and conduct an assessment of the viability of alternatives in those uses. This could also include specific guidance to understand and identify what is considered a 'critical' application.

Provide and prioritise research funding to investigate development of alternatives, targeted at specific applications identified as being particularly challenging to achieve required performance and where knowledge gaps still exist.

Recommendations for individual companies

Take steps to phase out the use of PFASs in lubricant and hydraulic oil products and replace with available alternatives where this is viable. To facilitate this, it will be important to fully evaluate the performance requirements of the specific application and work closely with researchers (chemists, material scientists, engineers) and regulators to develop solutions that can eliminate PFASs and achieve required performance.

Conduct targeted comparative tests to fully evaluate the potential alternatives against established performance requirements.

Prevent or minimise the environmental release of PFASs from remaining uses in lubricants and hydraulic oils.

Recommendations for industry associations and specific industry sectors

Take action to better investigate and monitor the uses of PFASs across the full supply chain in different sectors of use for lubricants and hydraulic oils. This is an important pre-requisite to fully understanding where, why and which PFASs are being used, and what level of performance is 'critical' for different uses.

Support the sharing of knowledge and data regarding the use of PFASs and the identity and feasibility of alternatives between different users for different specific applications. This should include investigating ways to enable users to access test data for different alternatives for different uses.

Support the development and sharing of methods or approaches to help users determine if the use of PFASs in specific applications is 'critical' and to minimise PFAS use where their use is still needed.

Background to policy recommendations

The following sections provide background to the policy recommendations listed above.

Background to recommendations for international organisations

Although outside of the scope of the current study, as discussed in Chapter 1, clearly there is interest in understanding the potential human health and environmental risks that may be associated with both PFASs and their alternatives identified here, possibly through a complementary study to this report. This information is needed to avoid regrettable substitutions and will require further investigation. Whilst information is available concerning the potential health and environmental risks of certain specific PFASs and their alternatives, the coverage is often not comprehensive. It is recommended to consider further work to determine the level of understanding of the potential health and environmental risks of PFAS and non-PFAS alternatives used in hydraulic oils and lubricants.

One aspect that has hampered this study (see Chapter 7), is the absence of market information freely accessible in the public domain. Data are available from market research companies but at a prohibitive cost and of mixed reliability. The result of this absence of data has therefore been the reliance upon stakeholder contributions to better understand the overall marketplace and particular segments within it.

Background to recommendations for national and regional governments and agencies

This report has highlighted that the principal driver that will incentivise substitution of PFASs in lubricants and hydraulic oils is regulatory action, noting the challenges (technical and economic) and lack of other drivers (market, consumer demand) towards substitutions in this sector. Furthermore, while the scope of this study is focussed on the shift to alternatives for PFASs in this sector, the report has highlighted that, since it is indicated there are likely to be remaining uses in lubricants at least in the short term, the prevailing risks relating to remaining PFAS uses should be carefully managed. This includes ensuring that future releases to the environment at each stage of the products lifecycle (including manufacture, use and end-of-life) are effectively controlled.

Conversely, this report has also established that there are many uses of PFAS-based lubricants where substitution with alternatives is not currently viable, with manufacturers and users noting this the case for uses where performance requirements are heightened (e.g. due to safety/reliability requirements). One key challenge in developing appropriate regulatory controls is, therefore, to establish how to define suitable derogations. This report has noted the various terminology used to describe these uses (e.g. ‘essential’, ‘critical’, and ‘extreme’ or ‘harsh’ conditions) and how the precise definition is difficult to define and will vary between uses. Specific guidance to understand and identify what is considered a ‘critical’ application will therefore be an integral part of PFAS substitution in this sector. To address the issues highlighted in this report around the poor visibility of PFASs in the supply chain, it will also be important to encourage or stipulate better reporting requirements for manufacturers so different actors in the supply chain have better access to information on the identity and volumes of PFASs used.

While a number of specific alternatives are already well known, it has also been highlighted that many research gaps still exist, partly due to the wide array of different applications and use sectors PFAS-based lubricants are used in. Targeting specific research funding to address key knowledge gaps (e.g. where finding viable alternatives is particularly challenging) will be important in the longer-term.

Recommendations for individual companies

Inputs to this study from manufacturers and users of lubricants have suggested that currently, use of PFAS is limited to a relatively small proportion the total lubricant use worldwide and limited to only where the use is ‘critical’. However, there is also evidence to suggest the markets for PFAS-based lubricants could expand in the future, possibly into markets where this is less ‘critical’. It is important, therefore, to encourage the industry (both manufacturers and users) to ensure use of PFASs is phased out as much as possible and limited to only where truly needed.

This report reflects that minimising PFAS use in this sector will require the end users of lubricants to make a more detailed and objective assessment of which level of performance (and what technical functionality) is needed. The main virtue associated with using PFAS in this use is that they cover multiple functions at the same time. Establishing the level to which available alternatives can meet the precise performance needs (as opposed to the level of performance currently achieved with PFASs) will be important. This should inform how comparative assessments are conducted when evaluating alternatives.

Recommendations for industry associations and specific industry sectors

As discussed above, it is recommended that action should be taken to improve the visibility of PFASs through the full supply chain for lubricant and hydraulic oil products, to help end users fully understand for which specific applications PFASs are being used. Furthermore, the report highlights the importance of gaining an objective and well-informed understanding of when use of PFAS-based lubricants is ‘critical’ and what level of performance this constitutes. In both cases, users across all the relevant sectors could benefit from a collaborative and unified approach. For example, the cost and time for individual organisations to test and validate alternatives would be reduced if shared across the wider industry.

Industry associations can play an important role, for example in supporting companies share knowledge or best practice, in a way that does not hinder confidentiality or contravene competition rules. This would also provide support and guidance to SMEs that may not have the resources available to conduct the research or testing required to implement alternatives on their own.

7 Uncertainties and limitations

Key limitations of this study

There are a number of uncertainties and limitations associated with this report. These are mainly related to the lack of publicly available information that is free of charge to access, and the limitations of the additional stakeholder consultation conducted within the time and resource constraints of this study.

- Literature search:
  - Throughout this report, the (Danish Environmental Protection Agency, 2024[30]) and (ECHA(c), 2023[29]) studies have been widely referenced as these represent the most comprehensive reviews of available literature related to this topic to date.
  - It is acknowledged that a significant amount of information has been submitted to the ECHA public consultation related to the proposed REACH restriction for PFAS in Europe. It has not been feasible to conduct a comprehensive review of these submissions. A number of specific submissions were highlighted for inclusion and have been referenced in this report.
  - It has not been feasible to conduct a comprehensive review of patent data – it is also noted that the existence of a patent does not necessarily indicate the market availability of a commercial product.
  - Many market reports and analysis are available for the lubricant and/or hydraulic oil industry, but these were prohibitively expensive and previous reports have indicated can be of mixed reliability (OECD, 2022b[3]) so have not been used in the report.
- The stakeholder consultation:
  - While the Global PFAS group and additional stakeholders were consulted directly for this study (see Annex A), key trade associations were prioritised for additional consultation and therefore some use areas have more coverage than others.
  - It must also be acknowledged that there are a wide range of lubricant types and specific applications/functions associated with the use of PFASs and it cannot be considered that this report represents a comprehensive or exhaustive review of all applications.

As a result of the above aspects, reporting a comprehensive view of the marketplace hindered. The various limitations described here have influenced the overall assessment and the results and the level of confidence that can be attributed to the results presented in this report. This is particularly relevant for the results presented in Chapters 3 and 4.

Key data gaps/uncertainties

The following aspects are highlighted as representing continued uncertainty relating to the use of PFASs and alternatives in lubricants and hydraulic oils, where data gaps remain:

- Efficacy of alternatives:
    - Limited input from researchers or manufacturers involved in developing or marketing PFAS-free alternatives – lack of insight into the identity or efficacy of alternatives in different specific applications.
    - Limited number of studies carrying out comparative analysis of performance of non-fluorinated alternatives compared to PFASs. These exist for a number of specific applications in some downstream sectors (e.g. semiconductors, aerospace, automotive) but lacking for others.
    - Limited quantitative cost data on unit price differences between fluorinated and non-fluorinated lubricant products on the market for different uses/sectors.
    - Limited quantitative data for overall lifecycle costs (e.g. related to volumes of use, frequency of re-application, maintenance costs etc) between fluorinated and non-fluorinated lubricant products on the market for different uses/sectors.
- Market data:
    - Available market data (and cost data) is largely limited to Europe or European nations; data is more limited in other countries.
    - Limited information was obtained on the current market and trends related to alternatives to PFAS in lubricants and hydraulic oils. Insight is largely limited to specific industries (e.g. transport; energy) and there is lack of quantitative data.
- Drivers and barriers to substitution:
    - The list of standards/specifications highlighted in the report is not to be considered as exhaustive.
    - The insights into drivers and barriers to different downstream users is limited to a small number of sectors (e.g. aerospace, automotive); not all industries have been consulted so the situation is not fully clear in all uses.

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Annex A. Stakeholder consulted

In addition to the Global PFAS Group input and review, the following organisations were further consulted:

- Chemours
- European Automobile Manufacturers’ Association (ACEA)
- Kluber Lubricants
- Lockheed Martin
- RISE (Research Institutes of Sweden)
- Stockholm University
- Union of the European Lubricants Industry (UEIL)

Annex B. PFASs identified in lubricants and hydraulic oils – Part 1: Chemical identification

Table B.1. Overview of the PFASs used in hydraulic oils and lubricants

PFAS Name	Abbrev.	CAS No.	Lubricant component	Reference
Perfluoropolyethers Various including: Poly[oxy[trifluoro(trifluoromethyl)-1,2-ethanediyl]], α-(1-carboxy-1,2,2,2-tetrafluoroethyl)-ω-[tetrafluoro(trifluoromethyl)ethoxy]- (9CI, ACI)[24]	PFPEs	Various incl. 51798-33-5 60164-51-4	Base oil/grease	OECD (2024) ; Wang et al. (2020) ; Glüge, et al.(2021) ; ECHA, 2023a; Chemours (2015a) ZeroPM database + inputs of ATEIL, UEIL, ASD, ACEA,

[24] Used to make Krytox™ 157FSH (90-100% of total product) (Wang et al. 2020)

PFAS Name	Abbrev.	CAS No.	Lubricant component	Reference
Poly[oxy[trifluoro(trifluoromethyl)-1,2-ethanediyl]], α-(1,1,2,2,2-pentafluoroethyl)-ω-[tetrafluoro(trifluoromethyl)ethoxy]- (ACI)[25]				
Polychlorotrifluoroethylene	PCTFE	9002-83-9	Base oil/grease; Lubricant additive	Glüge, et al. (2021); ECHA (2023a); ZeroPM database
Polytetrafluoroethylene	PTFE	9002-84-0	Lubricant additive	Glüge, et al. (2021); ECHA (2023a); ZeroPM database + inputs of ATEIL, UEIL, ASD, ACEA,
Polyvinylideenfluoride	PVDF	24937-79-9	Lubricant Additive	ACC (stakeholder comment); Diaz et al. 2024
Cyclohexanesulfonic acid, decafluoro(pentafluoroethyl)-, potassium salt (1:1)		67584-42-3	Lubricant additive Hydraulic fluid	UNEP (2019)
Alkene-1-sulfonic acid, perfluoro-, potassium salt		12751-11-0	Lubricant additive Hydraulic fluid	Glüge, et al. (2021)
Cyclohexanesulfonic acid, 1,2,2,3,3,4,4,5,5,6,6-undecafluoro-, potassium salt (1:1)		3107-18-4	Hydraulic fluid	Glüge, et al. (2021)
Cyclohexanesulfonic acid, decafluoro (trifluoromethyl)-, potassium salt (1:1)		68156-07-0	Hydraulic fluid	Glüge, et al. (2021)
Cyclohexanesulfonic acid, 1,2,2,3,3,4,5,5,6,6-decafluoro-4-(1,1,2,2,2-pentafluoroethyl)-, potassium salt (1:1)		335-24-0	Hydraulic fluid	Glüge, et al. (2021)
Perfluorooctane sulfonic acid, its salts and perfluorooctane sulfonyl fluoride	PFOS	1763-23-1 2795-39-3	Base oil/grease Hydraulic fluid	KEMI (2015) UNEP (2019)
Ethene, 1,1,2,2-tetrafluoro-, oxidized	M & Z Fluid	69991-61-3	Base oil/grease	ECHA (2023a); ZeroPM database
Poly[oxy[trifluoro(trifluoromethyl)-1,2-ethanediyl]], α-(1,1,2,2,2-pentafluoroethyl)-ω	K-Fluid	60164-51-4	Base oil/grease	ECHA (2023a); ZeroPM database
Oxetane, 2,2,3,3-tetrafluoro-, homoPolymer, fluorinated		113114-19-5	Base oil/grease	ECHA (2023a); ZeroPM database

[25] Used to make Krytox® Sodium Nitrite Inhibited PFPE/PTFE Greases (71 - 80% of total product) and Krytox® PFPE High Performance Lubricant (60 – 100% of total product) (Wang et al. 2020)

PFAS Name	Abbrev.	CAS No.	Lubricant component	Reference
Siloxanes and Silicones, Me 3,3,3-trifluoropropyl		63148-56-1	Base oil/grease Lubricant additive	ECHA (2023a); ZeroPM database
Ethyl perfluoroisobutyl ether		163702-06-5	Carrier solvent	Norden (2020) ; ECHA (2023a); ZeroPM database
Methyl nonafluoroisobutyl ether		163702-07-6	Carrier solvent	ECHA (2023a); ZeroPM database
Ethyl nonafluorbutyl ether		163702-05-4	Carrier solvent	ECHA (2023a); ZeroPM database
1,1,1,2,2,3,4,5,5,5- Decafluoropentane		138495-42-8	Carrier solvent	ECHA (2023a); ZeroPM database
Cis-1,1,1,4,4,4-Hexafluoro-2-butene		692-49-9	Carrier solvent	ECHA (2023a); ZeroPM database
(Z)-1-Chloro-2,3,3,3-tetrafluoropropene		111512-60-8	Carrier solvent	ECHA (2023a); ZeroPM database
Trans-1-chloro-3,3,3-trifluoropropene		102687-65-0	Carrier solvent	ECHA (2023a); ZeroPM database
Methoxytridecafluoro-heptene isomers		Not stated	Carrier solvent	ECHA (2023a); ZeroPM database
Methyl perfluoropropyl ether		375-03-1	Carrier solvent	ECHA (2023a); ZeroPM database
Methyl nonafluorobutyl ether + Methyl nonafluoroisobutyl ether		163702-08-7; 163702-07-6	Carrier solvent	ECHA (2023a); ZeroPM database
1-Propene, 1,1,2,3,3,3-hexafluoro-, oxidized, Polymerized, reduced hydrolysed		161075-14-5	Lubricant additive	ECHA (2023a); ZeroPM database
1-Propene, 1,1,2,3,3,3-hexafluoro-, oxidized, polymd., reduced, hydrolysed reaction products with ammonia		370097-12-4	Lubricant additive	ECHA (2023a); ZeroPM database
Cyclohexanesulfonic acid, decafluoro(pentafluoroethyl)-, potassium salt (1:1)		67584-42-3	Lubricant additive	ECHA (2023a); ZeroPM database
Poly[oxy[trifluoro(trifluoromethyl)-1,2-ethane diyl]], α-(1- carboxy1,2,2,2-tetrafluoroethyl)-ω-[tetrafluoro (trifluoromethyl)ethoxy]-		51798-33-5	Lubricant additive	ECHA, 2023; ZeroPM database
6:2 Fluorotelomer alcohol	6:2 FTOH	647-42-7	Lubricant additive	ECHA (2023a); ZeroPM database
8:2 Fluorotelomer alcohol	8:2 FTOH	678-39-7	Lubricant additive	ECHA (2023a); ZeroPM database
10:2 Fluorotelomer alcohol	10:2 FTOH	865-86-1	Lubricant additive	ECHA (2023a); ZeroPM database
Poly(difluoromethylene), α-chloro-ω-(2,2-dichloro-1,1,2-trifluoroethyl)-		79070-11-4	Lubricant additive	ECHA (2023a); ZeroPM database

PFAS Name	Abbrev.	CAS No.	Lubricant component	Reference
Poly(difluoromethylene), α-(cyclohexylmethyl)-ω-hydro-		65530-85-0	Lubricant additive	ECHA (2023a); ZeroPM database
Poly[oxy[trifluoro(trifluoromethyl)-1,2-ethanediyl]], α-(1,1,2,2,3,3,3-heptafluoropropyl)-ω-(1,1,2,2,2-pentafluoroethoxy)-		52700-35-3	Lubricant additive	ECHA (2023a); ZeroPM database
Propylene tetrafluorethylene copolymer		27029-05-6	Lubricant additive	ECHA (2023a); ZeroPM database
Poly[oxy[trifluoro(trifluoromethyl)-1,2-ethanediyl]], α,α',α''-[phosphinidynetris[oxy[1-fluoro-1-(trifluoromethyl)-2,1-ethanediyl]]]tris[ω-(1,1,2,2,3,3,3-heptafluoropropoxy)-		2247153-51-9	Lubricant additive	ECHA (2023a); ZeroPM database
Ethanesulfonic acid, 1,1,2,2-tetrafluoro-2-(1,1,2,2,3,3,4,4,4-nonafluorobutoxy)-, potassium salt (1:1)		88707-88-4	Lubricant additive	ECHA (2023a); ZeroPM database
3,5,7,10,13-Pentaoxapentadecanedioic acid, 2,2,4,4,6,6,8,8, 9,9,11,11,12,12,14,14-hexadecafluoro-, sodium salt (1:2)		88707-87-3	Lubricant additive	ECHA (2023a); ZeroPM database
Phosphine, tris[4-[4,4,6,7,7,9,10,10,12,13,13,15,15,15-tetradecafluoro-6,9,12-tris(trifluoromethyl)-2,5,8,11,14-pentaoxapentade1-yl]phenyl]-		88750-33-8	Lubricant additive	ECHA (2023a); ZeroPM database
1-Propene, 1,1,2,3,3,3-hexafluoro-, oxidized		69991-67-9	Base oil/grease	ECHA (2023a); ZeroPM database

Annex C.
PFASs identified in lubricants and hydraulic oils – Part 2: Downstream sectors of use

Table C.1. *Overview of the PFASs used in hydraulic oils and lubricants and downstream sectors of use*

PFAS Name	Abbrev.	CAS No.	Automotive	Aviation and aerospace	Defence / Military	Chemical and Bulk Gas	Consumer products	Electronics / semi-conductors	Energy (incl. nuclear / renewables)	Food processing	Oil and gas industry	Other industry (e.g. paper, plastics)	Other commercial / professional
Perfluoropolyethers	PFPEs	Various	x	x	x	x	x	x	x	x	x	x	x
Polychlorotrifluoroethylene	PCTFE	9002-83-9			x	x		x	x		x	x	x
Polytetrafluoroethylene	PTFE	9002-84-0	x	x	x	x	x	x	x	x	x	x	x
Polyvinylideenfluoride	PVDF	24937-79-9					x						
Cyclohexanesulfonic acid, decafluoro(pentafluoroethyl)-, potassium salt (1:1)		67584-42-3	x	x		x	x	x	x	x	x	x	x

PFAS Name	Abbrev.	CAS No.	Automotive	Aviation and aerospace	Defence / Military	Chemical and Bulk Gas	Consumer products	Electronics / semi-conductors	Energy (incl. nuclear / renewables)	Food processing	Oil and gas industry	Other industry (e.g. paper, plastics)	Other commercial / professional
Alkene-1-sulfonic acid, perfluoro-, potassium salt		12751-11-0	x	x									
Cyclohexanesulfonic acid, 1,2,2,3,3,4,4,5,5,6,6-undecafluoro-, potassium salt (1:1)		3107-18-4	x	x				x					
Cyclohexanesulfonic acid, decafluoro (trifluoromethyl)-, potassium salt (1:1)		68156-07-0	x	x									
Cyclohexanesulfonic acid, 1,2,2,3,3,4,5,5,6,6-decafluoro-4-(1,1,2,2,2-pentafluoroethyl)-, potassium salt (1:1)		335-24-0	x	x									
Perfluorooctane sulfonic acid, its salts and perfluorooctane sulfonyl fluoride	PFOS	1763-23-1 2795-39-3	x										
Ethene, 1,1,2,2-tetrafluoro-, oxidized	M & Z Fluid	69991-61-3	x	x		x	x	x	x	x	x	x	x
Poly[oxy[trifluoro(trifluoromethyl)-1,2-ethanediyl]], α-(1,1,2,2,2-pentafluoroethyl)-ω	K-Fluid	60164-51-4	x	x			x	x	x	x	x	x	x
Oxetane, 2,2,3,3-tetrafluoro-, homoPolymer, fluorinated		113114-19-5	x	x			x	x	x	x	x	x	x
Siloxanes and Silicones, Me 3,3,3-trifluoropropyl		63148-56-1	x	x			x	x	x	x	x	x	x
Ethyl perfluoroisobutyl ether		163702-06-5	x	x		x							

PFAS Name	Abbrev.	CAS No.	Automotive	Aviation and aerospace	Defence / Military	Chemical and Bulk Gas	Consumer products	Electronics / semi-conductors	Energy (incl. nuclear / renewables)	Food processing	Oil and gas industry	Other industry (e.g. paper, plastics)	Other commercial / professional
Methyl nonafluoroisobutyl ether		163702-07-6											
Ethyl nonafluorbutyl ether		163702-05-4											
1,1,1,2,2,3,4,5,5,5-Decafluoropentane		138495-42-8											
Cis-1,1,1,4,4,4-Hexafluoro-2-butene		692-49-9											
(Z)-1-Chloro-2,3,3,3-tetrafluoropropene		111512-60-8											
Trans-1-chloro-3,3,3-trifluoropropene		102687-65-0											
Methoxytridecafluoro-heptene isomers		Not stated											
Methyl perfluoropropyl ether		375-03-1											
Methyl nonafluorobutyl ether + Methyl nonafluoroisobutyl ether		163702-08-7; 163702-07-6											
1-Propene, 1,1,2,3,3,3-hexafluoro-, oxidized, Polymerized, reduced hydrolyzed		161075-14-5	x	x		x	x	x	x	x	x	x	x
1-Propene, 1,1,2,3,3,3-hexafluoro-, oxidized, polymd., reduced, hydrolysed reaction products with ammonia		370097-12-4	x	x		x	x	x	x	x	x	x	x

PFAS Name	Abbrev.	CAS No.	Automotive	Aviation and aerospace	Defence / Military	Chemical and Bulk Gas	Consumer products	Electronics / semi-conductors	Energy (incl. nuclear / renewables)	Food processing	Oil and gas industry	Other industry (e.g. paper, plastics)	Other commercial / professional
Cyclohexanesulfonic acid, decafluoro(pentafluoroethyl)-, potassium salt (1:1)		67584-42-3	x	x		x	x	x	x	x	x	x	x
Poly[oxy[trifluoro(trifluoromethyl)-1,2-ethane diyl]], α-(1-carboxy1,2,2,2-tetrafluoroethyl)-ω-[tetrafluoro (trifluoromethyl)ethoxy]-		51798-33-5	x	x		x	x	x	x	x	x	x	x
6:2 Fluorotelomer alcohol		647-42-7	x	x		x	x	x	x	x	x	x	x
8:2 Fluorotelomer alcohol		678-39-7	x	x		x	x	x	x	x	x	x	x
10:2 Fluorotelomer alcohol		865-86-1	x	x		x	x	x	x	x	x	x	x
Poly(difluoromethylene), α-chloro-ω-(2,2-dichloro-1,1,2-trifluoroethyl)-		79070-11-4	x	x		x	x	x	x	x	x	x	x
Poly(difluoromethylene), α-(cyclohexylmethyl)-ω-hydro-		65530-85-0	x	x		x	x	x	x	x	x	x	x
Poly[oxy[trifluoro(trifluoromethyl)-1,2-ethanediyl]], α-(1,1,2,2,3,3,3-heptafluoropropyl)-ω-(1,1,2,2,2-pentafluoroethoxy)-		52700-35-3	x	x		x	x	x	x	x	x	x	x
Propylene tetrafluorethylene copolymer		27029-05-6	x	x		x	x	x	x	x	x	x	x
Poly[oxy[trifluoro(trifluoromethyl)-1,2-ethanediyl]], α,α',α''-[phosphinidynetris[oxy[1-		2247153-51-9	x	x		x	x	x	x	x	x	x	x

PFAS Name	Abbrev.	CAS No.	Automotive	Aviation and aerospace	Defence / Military	Chemical and Bulk Gas	Consumer products	Electronics / semi-conductors	Energy (incl. nuclear / renewables)	Food processing	Oil and gas industry	Other industry (e.g. paper, plastics)	Other commercial / professional
fluoro-1-(trifluoromethyl)-2,1-ethanediyl]]]tris[ω-(1,1,2,2,3,3,3-heptafluoropropoxy)-													
Ethanesulfonic acid, 1,1,2,2-tetrafluoro-2-(1,1,2,2,3,3,4,4,4-nonafluorobutoxy)-, potassium salt (1:1)		88707-88-4	x	x		x	x	x	x	x	x	x	x
3,5,7,10,13-Pentaoxapentadecanedioic acid, 2,2,4,4,6,6,8,8,9,9,11,11,12,12,14,14-hexadecafluoro-, sodium salt (1:2)		88707-87-3	x	x		x	x	x	x	x	x	x	x
Phosphine, tris[4-[4,4,6,7,7,9,10,10,12,13,13,15,15,15-tetradecafluoro-6,9,12-tris(trifluoromethyl)-2,5,8,11,14-pentaoxapentade1-yl]phenyl]-		88750-33-8	x	x		x	x	x	x	x	x	x	x
1-Propene, 1,1,2,3,3,3-hexafluoro-, oxidized		69991-67-9	x	x	x	x	x	x	x	x	x	x	x

Per- and Polyfluoroalkyl Substances (PFAS) and Alternatives in Hydraulic Oils and Lubricants

REPORT ON COMMERCIAL AVAILABILITY AND CURRENT USES

OECD Series on Risk Management of Chemicals

PFASs are used in lubricant components across a range of industrial sectors including transport, defence, energy and electronics, and in production industries such as oil and gas, iron and steel, chemical and others. PFASs in lubricants impart wide and unique combinations of properties that in turn enable a range of technical functions simultaneously. These are associated with key performance qualities often necessary to withstand 'harsh' or 'extreme' conditions and where the use is considered to be 'critical'. Use in hydraulic oils is specific to corrosion inhibition.

Progress in substituting PFASs in lubricants has been limited. Due to the technical and economic challenges involved in developing suitable alternatives—and in the absence of strong market drivers—the market for PFAS-based lubricants is expected to continue expanding. The report includes specific policy recommendations to address the barriers and challenges associated with the substitution of PFASs in lubricants and hydraulic oils.