

Report

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Review of End-Of-Life Management Options for Refinery Equipment and Lubricants/Greases Potentially Containing PFAS



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ABSTRACT

This report presents a review of end-of-life equipment and components containing PFAS, in particular fluoropolymers, used in refinery and fuel distribution facilities. The project involved a literature review of fluoropolymers types, their physical and chemical characteristics, where they are likely to be found in refineries' components and equipment and the main waste management options available when they become a waste. PTFE (polytetrafluoroethylene) is the main fluoropolymer in use. Together with other fluoropolymers such as FEP (fluorinated propylene), PFA (perfluoroalkoxy alkanes) ETFE (ethylene tetrafluoro ethylene) and other tetrafluoroethylene-copolymers, they account for around 75% of fluoropolymers in the market. Fluoropolymers (FP) are plastics which are virtually chemically inert, non-wetting, non-stick, and highly resistant to temperature, fire and weather and they have become critical components in numerous technologies, industrial processes and everyday applications. Compared to other plastics, fluoropolymers are usually used as part of other applications and represent around 0.1% of the total plastics processing demand of the EU countries. They include a wide range of applications, such as pipe liners, lining of valves, lining of distillation units, containers for storage and transportation, hoses, seals, gaskets, filters, membranes, coatings, etc., and they are also found as additives in lubricants oils and greases. In 2020, most fluoropolymers waste was (co-) incinerated in Municipal Solid Waste Incineration (MSWI) plants or in dedicated hazardous waste incineration plants (83.5%) typically with energy recovery. Landfilling corresponded to about 13.1%, while some fractions of pre-sorted fluoropolymer waste was sent to recycling (3.4%). Currently, the recycling of post-consumer fluoropolymer waste from commingled (mixed) waste streams from commercial and industrial end-users is almost non-existent and will not be a promising option for circularity of in the coming years. Only if all stakeholders along the fluoropolymer value chain work more closely together, progress can be made in increasing their recycling.

KEYWORDS

Waste, European refinery waste, PFAS, Fluoropolymers, waste framework directive, waste production, waste management options, circularity, sustainability.

INTERNET

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SUMMARY

This study aims at developing a better understanding of PFAS containing equipment and components in refineries and fuel distribution equipment and available waste management options when they become waste at the end of their operational life. Given the little information available on end-of-life management options specific for refineries, this report explores overall end-of-life management practices from industry as a whole. The report focuses on fluoropolymer plastics which are dominated by PTFE (polytetrafluoroethylene), FEP (fluorinated propylene), PFA (perfluoroalkoxy alkanes), ETFE (ethylene tetrafluoro ethylene) and others, and accounting for around 75% of fluoropolymers in the market. They are high molecular weight plastics with unique properties due to the strong C-F bonds, making them highly stable, with high thermal, chemical, photochemical, oxidative, hydrolytic and biological stability, making them ideal materials in industrial processes.

Fluoropolymers (FP) in refineries and fuel distribution sites are found primarily in solid form in industrial equipment and components. They are also found as additives in lubricants and greases and as coatings. They are present in plant safety equipment, compressors and agitators, gaskets and sealings, pumps, valves, tubing lining and many other components, making their use vital and widespread across all essential equipment in most refineries. In 2020, approximately 49 kt of fluoropolymers were produced in the EU to be used in a variety of industry and commercial sectors (Conversio 2023). The largest share accounted for PTFE materials (-56%) followed by PVDF (polyvinylidene difluoride, -12%), FKM (fluorine kautschuk material, -8%) and FEP (fluorinated ethylene propylene, -8%).

Considering a typical industrial facility, after the dismantling of end-of-life equipment and components containing fluoropolymers (such as pipes, valves, pumps, tanks, liners, tubes, etc), these are collected as waste and mainly separated on site for further waste treatment. According to 2020 data, most FP were (co-)incinerated in Municipal Solid Waste Incineration (MSWI) plants or dedicated hazardous waste incineration plants (83.5%) typically with energy recovery of which 11.5% included metal components that are recycled in smelters. Landfilling of FP waste corresponded to about 13.1%, while some fractions of pre-sorted FP waste were sent to recycling (3.4%). Currently, the most relevant disposal routes for waste lubricant oils (WLO) and greases containing fluoropolymers available in Europe are regeneration and reprocessing and incineration with or without energy recovery. This report also discusses the potential gaseous, solid and liquid emissions related to the main management options identified including the formation of fluoropolymers microplastics that may be suspended in landfills' leachate (Lohman et al. 2020).

In 2020, only 3.4% of all fluoropolymers, including those in industrial equipment, were recycled in the EU, of which less than 0.1 kt involved some form of thermal recycling (Conversio, 2023). Primary and secondary recycling are common processes in the manufacturing of PTFE products and includes the recycling of waste/fragments generated during the production of the final products. However, these processes change the properties of the fluoropolymer and cannot therefore be used in their typical applications. Tertiary recycling, also known as "Up-Cycling" or chemical recycling allows the reprocessing of fluoropolymers into monomers (primarily tetrafluoroethylene (TFE), and hexafluoropropene (HFP)) which can then be fed into the production of fluoropolymers.

To date, above half of the refineries surveyed for this project indicated they were in the process of developing such plans and that their focus was on the management of waste water relating primarily to PFAS-containing firefighting foams and refrigerants. This report also identifies several challenges to the development of PFAS management plans in refineries. In recent years, guidance on the management of PFAS-containing waste have been developed by some countries, but they typically focus on long-chain PFAS given their widespread distribution in the environment and human health concerns. Fluoropolymers are rarely mentioned, with a few exceptions and none provide plans for the identification, decommissioning and collection of fluoropolymer-containing equipment in industrial facilities.

This report argues that the waste management of fluoropolymer plastics is more closely related to the management of waste plastics in general. In this context, effective waste collection is a vital first stage for efficient recycling, and this is true of plastics. Improved waste collection significantly impacts the waste streams and their suitability for downstream pre-treatment, sorting and recovery. The report found that the recycling of post-consumer fluoropolymer waste from commercial and industrial end-users is almost non-existent at present and is likely to remain as such in the coming years. Higher recycling rates will only occur if stakeholders along fluoropolymers value chains work together more closely to increase circularity.

1. INTRODUCTION

This report describes a review of End-of-Life waste management processes for refinery components containing, or potentially containing, per- and polyfluorinated alkyl substances (PFAS), in particular fluoropolymer plastics, and fluoropolymers in lubricant oils and greases.

A Universal PFAS restriction proposal has been introduced by ECHA¹. While exemptions for refinery operations and refineries' products distribution were not originally included in the restriction proposal, Concawe has requested an exception for continued use of all PFAS in refinery operations. PFAS used in refineries are primarily fluoropolymers while other gases and liquids containing PFAS are also used. While some work has been done to understand the places in equipment where PFAS might be applied/included, no actual inventories exist for refineries and this project aims at generating a clearer understanding of PFAS containing equipment and components, the types of PFAS used and the fate of equipment, greases and lubricants that may contain fluoropolymers and other PFAS. Fluorinated fire-fighting foams are subject to a separate proposed restriction and thus are not part of this report. Similarly, fluorinated gases, which may also contain PFAS, are not part of the scope since they are: normally inside closed systems; being addressed in another specific legislation, and; usually disposed via incineration.

The identification of waste management options for PFAS-containing equipment was based on a literature review of technical papers, online technical websites, contractors' information and previous Concawe commissioned work on the matter, together with information provided by Concawe member companies related to the identification of PFAS-containing equipment in their refineries. Where possible, information was also obtained from specialist plastic recycling companies and waste management companies. A study by Accenture on behalf of Concawe showed that, as of 2023, whilst none of the companies that participated in the survey had a dedicated PFAS emissions management plan in place at that time more than half of the companies were working towards developing PFAS emission control plans. However, the majority of these are around wastewater management and only limited PFAS categories are included such as refrigerant and fluorinated firefighting foams. Consequently, while the search included waste management plans for the industry, no such plans were found. Therefore, the search was widened to other industries that may be handling PFAS in waste components and government agencies providing guidance, advice or requirements regarding the waste management of PFAS-containing components/equipment/ liquids. The literature search included.

- Government agencies waste management plans for PFAS-containing components.
- Government agencies advice/guidelines on the disposal and treatment of industrial wastes containing PFAS compounds.
- Industry associations producing similar industrial wastes that may also contain PFAS and, in particular, fluoropolymers (for example cable insulation waste in the electronic industry containing PTFE).
- Research papers/technical publications describing the current state of managing techniques specifically for the recycling, recovery and destruction of PFAS components.

¹ <https://echa.europa.eu/registry-of-restriction-intentions/-/dislist/details/0b0236e18663449b>

- Research papers/technical publications describing emerging technologies for the management of PFAS-containing waste equipment.

Focus was given to wastes similar to those found in refineries and fuel distribution activities, the nature of any pre-treatment/segregation of PFAS from industrial components and focus on fluoropolymers and the main process units and fuel distribution components identified in the Accenture report and in other sources.

Section 2 of this report provides an introduction and general descriptions of PFAS and of fluoropolymers in particular, their overall production volumes in Europe, fluoropolymer types and the types of refinery equipment where fluoropolymers are present.

Section 3 discusses current waste management options for refinery equipment containing fluoropolymers, in particular incineration, landfilling and recycling, and the reported volumes of fluoropolymers managed by these options in Europe, including observations regarding the fate fluoropolymers attached to metal components that undergo recycling. This section also contains a general description of the regeneration and general management options of lubricant oils and greases containing fluoropolymers. Finally, this section presents a brief description of innovative techniques options for the management of fluoropolymers waste.

Section 4 discusses European and international regulations that are relevant for the management of fluoropolymers waste and provides short descriptions of government and industry guidance related to their end-of-life management.

Finally, **Section 5** provides a summary of the previous sections and some final observations and conclusions resulting from the review of the available information.

2. BACKGROUND TO PFAS INCLUDING FLUOROPOLYMERS

2.1. PER- AND POLYFLUOROALKYL SUBSTANCES²

The group of per- and polyfluoroalkyl substances (PFAS) consists of polymers and non-polymers (Lohmann et al, 2020). They comprise a large group of fluorinated synthetic substances with diverse properties that have been used in a wide variety of industrial and consumer applications. Polymeric PFAS include fluoropolymers, side - chain fluorinated polymers and poly-perfluoropolyethers (Table 1). Fluoropolymers represent a distinct subset of fluorinated polymers which have a carbon-only polymer backbone with F atoms directly attached to it (Henry et al, 2018).

Most regulatory and academic attention so far has focused on the non-polymeric PFAS, either perfluorinated or polyfluorinated alkyl substances. Some PFAS have been regulated in the European Union, United Kingdom, United States, Canada and other countries. This is the case for PFOA, PFOS and chemicals that can degrade to them (part of the group of “long chain PFAS”). They are PBTs (persistent, bio accumulative and toxic) or vPvBs (very persistent and very bio accumulative) and they are found in the environment, in humans and in animals, sometimes far from contamination sources. For these reasons, PFOA and PFOS have been listed under the Stockholm Convention on Persistent Organic Pollutants (POPs) and as a consequence, are now restricted under the EU POPs Regulation. Another long-chain PFAS (PFHxS), less widely used than PFOA and PFOS but often found in the environment and in human biomonitoring, is currently being assessed for a restriction under REACH and is also considered for listing under the Stockholm Convention (EU Commission Staff Working Document on PFAS).

The group of fluoropolymers is dominated by PTFE (polytetrafluoroethylene). Together with other fluoropolymers such as FEP (fluorinated propylene), PFA (perfluoroalkoxy alkanes) ETFE (ethylene tetrafluoro ethylene) and other tetrafluoroethylene-copolymers, they account for around 75% of fluoropolymers in the market (Lohmann et al 2020). The main fluoropolymer discussed, PTFE, accounted for 58% (by weight) of 2015 worldwide fluoropolymer consumption (IHS 2016). Other important fluoropolymers include PVDF (polyvinylidene fluoride), PVF (polyvinyl fluoride) and fluoroelastomers³.

Polymers can be defined based of how many repeat units they should contain, such as the repeat unit $(CF_2-CF_2)_n$ for PTFE. In polymer science a polymer is typically defined as a chain consisting of at least 50 monomers. Chain-lengths from two to 50 monomers are called oligomers (EU, 2011). A polymer can also be defined based on its material properties, since having high molecular weight shows polymer-like properties such as film and fibre forming and the addition or removal of one or a few of the units has a negligible effect on its properties. On the other hand, a material with regular repeating structure but too low average molecular weight to achieve these properties is usually called an oligomer (Naka, 2014).

²The OECD defines PFAS 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 (-CF₃) or a perfluorinated methylene group (-CF₂-) is a PFAS. All PFAS contain a chain of carbon atoms bonded to fluorine atoms. In perfluoroalkyl substances, all the carbons except the last one in the carbon chain, are attached to fluorine atoms. In polyfluoroalkyl substances, at least one, but not all, the carbons in the carbon chain are attached to fluorine atoms.

³ A fluoroelastomer is a fluorocarbon based synthetic rubber. Several compositions of fluoroelastomers exist including FKM, perfluoro-elastomers (FFKM); and tetrafluoro ethylene/propylene rubbers (FEPM).

The manufacturing of per- and polyfluoroalkyl substances (PFAS) follows a systematic process that transitions from monomer synthesis to the final product via different polymerisation and/or extrusion processes which are relevant for later discussions on recycling options. Electrochemical fluorination (ECF) and telomerization are the main methods for producing fluoropolymers. Telomerization, is currently the main technique in use, favoured for its specificity in developing PFAS chains. It achieves this by initiating a reaction between short-chain hydrocarbons and fluorinated monomers that subsequently undergo polymerization to form PFAS polymers. Fine powder forms of PFAS are typically achieved through solution or emulsion polymerization, a process characterized by the creation of polymer chains within a liquid medium. The alternative resin form of PFAS is produced through gamma-irradiation, which involves using high-energy radiation to initiate the polymerization reaction. For paste forms, PFAS polymers are subjected to extreme extrusion pressure, which aligns the polymer chains and imparts the necessary viscosity and texture. Granular forms of PFAS are created by sintering polymer powders with fillers, a process that involves heating the powder below its melting point to create solid particles.

Fluoropolymers are high molecular weight plastics with unique properties due to the strong C-F bonds, the strongest between C and another atom, making them highly stable, with high thermal, chemical, photochemical, oxidative, hydrolytic and biological stability (Henry, et al, 2018). They also have low flammability, neutral electrical charge and resistance to degradation. Another important aspect of fluoropolymers is the negligible presence of residual monomers and low molecular weight oligomer content. Therefore, they have limited low molecular weight leachable compounds. This is important because monomers or oligomers⁴ resulting from incomplete polymerisation processes, may be able to migrate out of the polymer and cause potential environmental and human health concerns.

Based on an assessment of the above fluoropolymers properties, some technical literature (Henry et al, 2018) suggests that fluoropolymers should be considered as polymers of low concern (PLC), according to the OECD definition: “polymers of low concern are those deemed to have insignificant environmental and human health impacts” (OECD 2007). Fluoropolymers are persistent in the environment but are not toxic or available for bioaccumulation in organisms. This has been contested by some indicating that more research is necessary (Lohmann, 2020). Furthermore, in recognition of the potential risks posed by PFAS-related polymers, the US Environmental Protection Agency (USEPA) has denied PLC exemptions for side-chain fluorinated polymers but has not implemented restrictions for fluoropolymers per se.

⁴ Monomer is a molecule that can react together with other monomers to form a polymer chain in a process called polymerisation. An oligomer is a molecule that consists of a few repeating units that could be derived from smaller molecules (monomers).

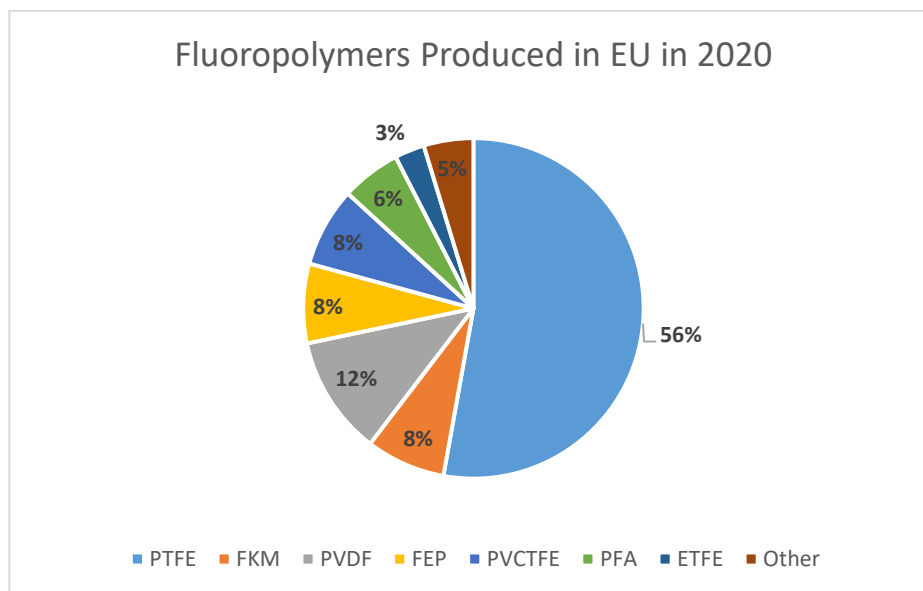
Table 1. Per- and Polyfluoroalkyl Substances (adapted from Henry et al, 2018)

Per- and Poly-fluoroalkyl Substances (PFAS)	
Non-Polymers	Polymers
Perfluoroalkyl Substances Compounds for which all hydrogens on all carbons have been replaced by fluorines. Examples: PFOA, PFOS, PFHxS	Fluoropolymers Carbon-only polymer backbone with fluorines directly attached. Examples of fluoropolymers: PTFE, FKM, FEP, PVDF, ETFE, etc.
	Perfluoropolyethers Carbon and oxygen polymer backbone with fluorines directly attached to carbon. Includes four main families of PFPEs identified based on their respective typical synthesis methods
Polyfluoroalkyl Substances Compounds for which all hydrogens on at least one carbon have been replaced by fluorine atoms, but not all C atoms are fully fluorinated. Examples: fluorotelomer substances, Perfluoroalkane Sulfonamido substances.	Side-chain Fluorinated Polymers Variable composition non-fluorinated polymer backbone with fluorinated side chains. Examples: fluorotelomers, perfluoroalkanesulfonyl fluoride (PASf) derivatives, perfluoroalkanoyl fluoride.

Fluoropolymers are used in various applications and different industry sectors, e.g. transportation, petrochemical industry, electronics, pharmaceutical industry, etc. Since the discovery of PTFE in 1938, fluoropolymers have become critical components in numerous technologies, industrial processes and everyday applications. Compared to other plastics, fluoropolymers are usually used as part of other applications and represent around 0.1% of the total plastics processing demand of the EU countries.

In 2020, approximately 49 kt of fluoropolymers were produced and 40 kt were sold in the EU. In the same year 24 kt were exported and 15 kt imported into the EU (Conversio, 2020). The largest share accounted for PTFE materials (~56%) followed by PVDF (~12%), FKM (~8%) and FEP (~8%) (Figure 1). The distribution of FP types shown in Figure 1 is unique for the EU market and differs with regard to individual FP shares in other regions. For example, the share of FEP in North America, used for house applications, is significantly higher compared to the EU market. In terms of FP products produced, tubes & pipes (~15%), followed by liners (~13%), coatings (~12%) and seals (~11%), were the most relevant FP applications. Given that the net production of FP raw materials in 2020 was 49 kt, the EU is a net exporter of FP raw materials.

Figure 1. Fluoropolymers produced in Europe, 2020 (adapted from Conversio’s FP Waste in Europe Report 2020).



2.2. PER- AND POLYFLUOROALKYL SUBSTANCES IN REFINERY AND FUEL DISTRIBUTION EQUIPMENT

A market study produced in 2022 (Wood Group, 2022) presented quantities of FP sold per sector, with the chemical industry positioned second with 11 kt, and the transport sector in first place with 15.5 kt. In a second breakdown category looking at the quantities of FP that found applications in industrial sectors (Conversio 2023), the application of FP in the petroleum industry in 2020 was approximately 11.5 kt, behind transportation (16 kt), and followed by construction (4.5 kt) and electronics (4.5 kt). The study did not provide information as to what activities formed part of the petroleum sector mentioned in the report.

In 2023, Concawe commissioned a study (ECHA, 2023⁵) to understand the use of PFAS in industrial equipment of refineries and fuel distribution networks. PFAS in refineries and fuel distribution sites are found primarily in solid form (mainly fluoropolymers) in industrial equipment and components. Their unique combination of resistance to the high temperatures, pressures and corrosive environments found in refineries, as well as resistance to combustion and leakage required in fuel distribution, ensure the safety of operations.

PFAS are used as plastics and elastomers, lubricants and coatings, and are present in plant safety equipment, compressors and agitators, gaskets and sealings, pumps, valves and many other components, making their use vital and widespread across all essential equipment in most refineries. **Figure 2** provides an overview of the main types of PFAS identified in EU refineries equipment based on the review of technical literature and interviews with equipment suppliers (ECHA, 2023).

⁵ https://echa.europa.eu/documents/10162/17233/rest_pfas_rcom_part105_en.docx/58f41dbf-184c-cb1c-661f-fb6ffd2c2553?t=1698664558751&download=true

Figure 3 shows typical equipment containing fluoropolymers and other PFAS-containing materials for both, refinery operations and fuel distribution activities. They include a wide range of applications, such as pipe liners, lining of valves, lining of distillation units, containers for storage and transportation, hoses, seals, gaskets, filters, membranes, etc.

Figure 2. PFAS types in EU Refineries Equipment and Materials and Reasons for their Use (ECHA, 2023)

Refinery Equipment	PFAS Name	Use
Filters	PTFE, PVDF, PFOA, ETFE, PFOS	PFAS are used in electret filters to improve oil mist resistance and collection efficiency by lowering the surface tension of the fibrous material and increasing oil repellency
Tanks	ETFE, PVDF, PTFE	PFAS are used as anti-corrosion protection at high temperatures
Fuel cells	PVDF	PVDF is composited into electrolyte material to improve electrochemical performance and enhance mechanical strength for a low-temperature solid oxide fuel cell
Seals & O-Rings	FFKM	FFKM provides exceptional high temperature and high-pressure performance to equipment parts like O-Rings and seals. FFKM can also be used to increase the mean time between failure (MTBF) of a screw spindle pump in a petrochemical plant
Membranes	PTFE	PTFE is used in TPV membrane module. PTFE is used as a backbone to suppress the swelling of Nafion component in composite membranes for high temperature PEM fuel cell application
Cooling Towers	PVDF	PVDF is used to reduce microbiological activity in cooling tower systems. It helps with sunlight resistance and is used in the construction of sodium hypochlorite feed systems to inhibit the growth of algae and bacterial species in cooling towers
Heat Exchangers	PTFE, FEP, PVDF	PTFE, FEP and PVDF materials can be included in the oleophilic surface of the heat exchanger
Piping	PTFE	PTFE is used to form hydrophobic pigs in a method of minimizing mixing of aqueous-based materials in pipes
Coating	PTFE	PTFE coating for antifouling purposes in gas-absorption desulfurization
Pumps	ETFE	ETFE is used for a wide range of corrosives and solvents
Diaphragm Pumps	PTFE	PTFE is used in metering diaphragm pumps because of its chemical resistance
Refrigerant gas	R410	R410 offers high thermal conductivity and high stability
Valves	PTFE	PTFE stem sealing system (V-Pack) is mentioned as a new advanced sealing system for valve stems that removes the need for an elastomer O-ring, making the valve suitable for use with a wide range of chemicals

Figure 3. Typical equipment containing fluoropolymers and other PFAS-containing materials in refining and fuel distribution operations (ECHA, 2023).

Process Unit Equipment			Fuel Distribution	
 Agitators	 Distillation Towers	 Instruments	 Fuel Dispensers	 Hoses
 Fans	 Heat Exchangers	 Reactors	Safety and Protection	
 Conveyors	 Evaporators	 Refrigeration Systems	 PPE	 Firefighting Foams
 Cooling Towers	 Fired Heaters	 Piping	Power and Utilities	
 Couplings (Motors)	 Gaskets & Sealings	 Valves	 Power Supply	 Cables & Wiring
 Pumps	 Steam injectors		Other Products	
			 Grease	 Lubricants
			 Catalysts	 Refrigerants

Complete inventories of PFAS types within equipment in refineries are difficult to find. This is due to several reasons:

The limited information provided by suppliers who have limited awareness of the existence of PFAS in products especially if they are distributors of equipment;

The use of old equipment (up to 20-30 years old) for which information cannot be obtained;

The use of assembled and packaged equipment with limited information of each internal component; and

The need for refineries to focus on performance of the equipment rather than its composition.

Concawe members were asked in a survey to identify the main PFAS substances used in refineries and fuel distribution facilities. Their answers are summarised in **Table 2**, listing the main PFAS identified in both solid state and in lubricants and greases, and showing general **agreement** with the information provided by suppliers and found in the technical literature.

Table 2. Main Types of PFAS Reported by EU Refineries

PFAS in Solid State	PFAS in liquid State
Fluoropolymers	Lubricants and Greases
FKM (Viton, Tecnoflon, Dyneon)	PFAE
FFKM (Kalrez, Tecnoflon)	PFPE
PTFE	PFPAE
FEP	PTFE (Interflon, Oraflon, Nevastane)
PVDF (Kynar, Hylar, Solef)	PCTFE (Vultalef)
PFA	
ETFE	
PCTFE	
ECTFE	
Other PFAS	
PFSA*	
PFCA*	

* These PFAS are not fluoropolymers

A popular use of PFAS in tribological applications is the utilization of PTFE and other fluoropolymers in coatings, lubricant oils and lubricant greases, due to their lubricity, resilience at high temperatures, and resistance to chemical attack. Utilizing PFAS in lubricant additives, exemplified by nano- and micro-sized PTFE and PVDF particles, helps enhance their friction and wear performance, representing a key advancement in lubrication technology. The structure of fluoropolymers such as PTFE molecules generates hydrophobicity, resulting in a non-adhesive behaviour that effectively reduces friction. In addition, the presence of strong C-F bonds enhances its efficacy in countering frictional stresses. Moreover, the material's inherent smoothness lessens direct asperity contact, minimizing surface wear and ensuring the longevity of contact surfaces (Dias et al, 2024).

PFAS materials such as PTFE and PVDF also exhibit several unique properties making them the two primary PFAS coatings in common use. PTFE finds applications in lubrication systems, including bearings and gears. Another popularly used PFAS coating is PVDF which has been widely used in small scale lubrication systems. With excellent thermal stability, resistance to deformation under stress, and high crystallinity, PVDF is commonly used as a coating material in demanding environments. Its low permeability to gases and liquids, alongside robust resistance to mechanical and corrosive damage, makes it ideal for protective applications in the chemical and petrochemical sectors.

3. END-OF-LIFE MANAGEMENT OF FLUOROPOLYMERS COMPONENTS

3.1. CURRENT MANAGEMENT OPTIONS FOR FLUOROPOLYMERS

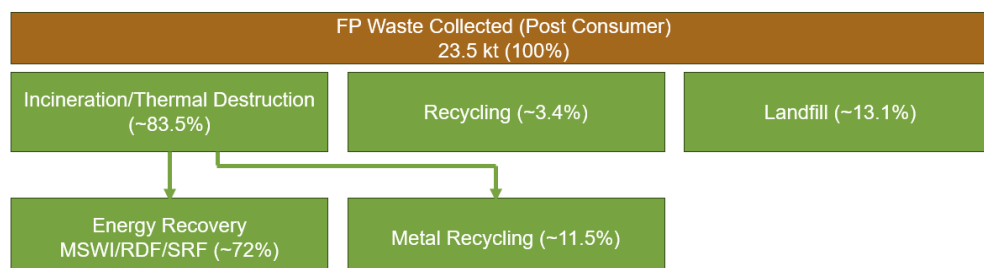
As indicated in the previous Section, approximately 40 kt of fluoropolymer materials were sold to EU fluoropolymer product manufacturers in 2020. In the same year, 23.5 kt of fluoropolymer waste were collected in the EU, either in commingled waste streams or as separated waste fractions. This represents less than 0.01% by weight of all waste collected, while plastics in total, accounted for about 4.8% of the total waste collection volume in 2020 (Conversio, 2023). The differences between FP manufactured products & applications and FP waste collected in different waste streams in the same year is the result of several causes such as:

- Export-import balance of manufactured products;
- The average lifetimes of different FP associated products and applications;
- Maintenance measures of FP associated products and applications in use; and
- Differences in official waste statistics among others, in particular due to the fact that not all fluoropolymer waste would be identified as such when it becomes a waste.

On a sector-by-sector basis, the Chemical sector generated the largest amount of fluoropolymers waste with 9.5 kt, followed by the automotive sector with 3.5 kt, and electronics with 2.7 kt (Conversio, 2023). A category identified as “other” generated some 5.3 kt and included a mixed category waste generated from a variety of sources, from cookware to food and drink FP waste, textiles and metals applications and other applications not listed in other industry sectors. The chemical sector category includes also the wider petrochemical sector. The most relevant waste streams for the collection of end-of-life FP applications are commercial and industrial waste streams, and this was the case for the chemical sector. This waste stream is usually collected by private waste management or industrial service companies. Only a small proportion of FP waste is collected in residential or private waste streams, such as mixed residential waste, which is often collected on behalf of municipal waste collection services.

In 2020, most FP were (co-) incinerated in Municipal Solid Waste Incineration (MSWI) plants or dedicated hazardous waste incineration plants (83.5%) typically with energy recovery (**Figure 4**). This includes FP waste from commercial and industrial waste producers that is either pre-sorted or results directly from dismantling operations of which 11.5% included metal components which are recycled in smelters. Landfilling of FP waste corresponded to about 13.1%, while some fractions of pre-sorted FP waste were sent to recycling, either to domestic recyclers or exported for recycling in intra- and extra-EU countries (<0.5%). Recycling included for example re-grinding and sintering as well as chemical recycling of FP materials, and to a lesser extend thermoplastic recycling. FP percentages sent to incineration and landfill vary from country to country. An assessment of FP management options for a group of sectors including chemicals, pharma, energy and food and drink found that Germany managed their FP waste almost exclusively via incineration (>99%), while for France, Italy and United Kingdom incineration accounted for 80 to 85% of the total FP with the remainder sent to landfill.

Figure 4. FP Waste per Management Options (adapted from Conversio's Fluoropolymer Waste in Europe 2020 Report)



A survey carried out by Concawe of some 36 refineries in the EU indicated that the main management options for refinery components and equipment containing FP was R3/4/5¹ (Recovery). R3 refers to the recycling or reclamation of organic substances and includes the reprocessing and recycling of plastics, while R4 refers to the recycling of metals. It is not clear if this refers to FP materials attached to metal equipment sent for metal recycling. The result of the survey seems to be at odds with EU-level data regarding the disposal and recovery of FP materials where incineration with energy recovery is the main management option followed by landfill and metal recycling. Incineration (disposal code D10) and incineration with energy recovery (R1) were reported as the main management options (together with recovery) for several components including personal protection equipment (PPE), gaskets and sealings and gas purification units. Lubricants and greases were mainly re-refined or recycle (both R9 and R3/4/5). Landfilling (D1/5) was associated with gaskets and sealings and compressors components. Finally, components in pipes, tanks, distillation units, heat exchangers and cable and wiring were mostly recycled (R3/4/5).

The lifetime of FP materials varies according to the type of FP and its application. FP materials in the refining and petrochemical industries can be exposed to high temperatures and high-pressure environments, often in the presence of corrosive substances. After a certain period of time FP components need replacing to avoid malfunction and keep downtimes as low as possible. Average lifetimes of liners and other associated FP products in the chemical industry can range between 10 and 20 years. Short lifetimes are typically associated for applications in very aggressive or demanding environments. Lifetimes can be much longer (up to 50 years) for thick tubes and pipes used for less aggressive substances in less demanding production environments. Table 3 lists typical refinery equipment with their estimated operational time as reported by European refineries in 2023.

¹ R and D are respectively Disposal and Recovery codes as per Eurostat Manual on Waste Statistics.

Table 3. Typical operational life of equipment at refineries. Values are reported in mean and Standard Error of the Mean (SEM).

	Operational life (years)
Valves and accessories	7 ± 1
Gasket and sealing	3 ± 1
Pumps	13 ± 2
Compressors	15 ± 2
Devices for process control, process analysis and instruments	6 ± 1
Refrigeration system and refrigerant	4 ± 1
Fans and turbines	10 ± 1
Heat exchangers	6 ± 1
Motors and couplings	11 ± 3
Piping	15 ± 2
Conveyors	No data
Cooling tower, storage tanks, distillation tower and adsorption tower	28 ± 2
Steam ejector	No data
Gas purification unit	No data
Plant Safety Equipment	7 ± 1
Personal Protection Equipment	3 ± 1
Cable and wiring	9 ± 2
Power supply equipment	35 ± 5
Grease	2 ± 1
Lubricants	1 ± 1
Catalyst	4 ± 1
Processing auxiliary aids	7 ± 1

The replacement of FP applications used in production and processing equipment can involve different practices and can be carried out by either internal maintenance service departments (often contracted third-party companies on site) or by external (and specialized) service companies providing services on request. A combination of both practices on one site is also possible. After dismantling end-of-life equipment and components containing fluoropolymers (such as pipes, valves, pumps, tanks, liners, tubes, etc), these are collected as waste and mainly separated on site for further waste treatment.

Steel pipes including FP liners are usually collected for metal recycling. Some companies extract the FP content for further processing or to simply increase the average recyclable metal content which is then sold to metal recycling companies. Most of the FP materials from chemical industry applications are usually collected (separately) by private waste management companies for waste incineration, either in MSWI or hazardous waste incineration plants. Smaller FP quantities are also collected in commingled (mixed) waste fractions which usually are also sent to waste incineration processes.

There are several routes for the treatment and disposal of waste lubricant oils (WLO), each subject to local regulations. Currently, the most relevant disposal routes available in Europe are regeneration and reprocessing and incineration with

or without energy recovery. According to GEIR - the European re-refining industry group, in 2016, 42% of the WLO was sent directly to regeneration within the EU countries where it was collected and 13% was regenerated after exporting to other EU countries. The second preferred pathway is reprocessing to produce fuel oil, which accounts for 31% of the collected WLO. The remaining WLO is incinerated with or without energy recovery. About 3% of WLO is sent to cement kilns.

Lubricating grease consists of three basic components: base oils, thickeners, and additives. The base oils of lubricating greases are categorized as mineral oils (naphthenic and paraffinic oils as per lubricant oils), synthetic hydrocarbons (polyalphaolefins (PAO) and alkylates), other synthetic compounds (esters and polyglycols), or any fluids with other lubricating attributes. Together, they make up 80-97 % of greases (Pinheiro, 2020). Thickeners are added to lubricating greases to modify the rheological properties and consistency of these greases. Thickeners greatly vary, with the most widely used being fatty acid soaps of lithium, aluminium or barium, calcium, and sodium. Synthetic polymers are increasingly used as additives (including FP). It is unclear what management options are commonly used for lubricating grease. However, a recent general meeting of the European Lubricating Greases stated that virtually no grease is recycled, suggesting that thermal treatment may be the main management option for these materials.

The following sections include a discussion of the main types of management options for FP currently being used in the EU (and other regions) such as incineration, landfilling, recycling and regeneration (of WLO).

3.2. INCINERATION OF FLUOROPOLYMERS AND OTHER PFAS

An incineration plant is a waste management facility that combusts waste while producing heat or heat and electricity. The combustion temperature varies in the range of 800 to 1400 °C depending on the incineration type. According to the EU framework directive for waste, waste incineration with efficient energy recovery is considered recovery and therefore, incineration plants are essential components in both waste recycling and energy production (IVL, 2021).

The knowledge on the fate of combusted PFAS is growing, however, at present, studies show different conclusions on the rate of combustion and at which temperatures this occur. PTFE is the most stable fluorine-containing polymer. Complete thermal decomposition of PTFE is achieved at a temperature of about 900 °C. It can therefore be assumed that other fluorine-containing polymers also thermally decompose completely at a temperature of 900 °C. Fluoropolymers are solids that do not evaporate with rising temperatures but rather start to decompose into volatile fluorinated compounds. At thermal decomposition, a variety of gaseous fluorine-containing products are therefore formed. If the combustion temperatures are not high enough to ensure the complete mineralisation of fluoropolymers to HF or degradation is incomplete, highly persistent TFA and HCF can be formed. The levels of volatiles formed in incineration depend on combustion/flue gas temperature, oxygen and residence time.

Municipal waste containing fluorinated polymers, such as end-of-life consumer products, is often incinerated in Europe and it is likely that waste containing fluorinated polymer is sent to municipal waste incineration plants. However, there is lack of reliable information on amounts of PFAS actually emitted in flue gases from municipal waste incineration plants.

Besides the flue gases that are emitted through the stack, solid residues are also formed such as fly and bottom ashes, and there are emissions of condensate water.

A study of 27 incinerators in Sweden (IVL, 2021) found the largest amount of PFAS emissions were expected from the bottom and fly ashes due to the large amounts generated each year. The bottom ash was dominated by PFCA precursors such as 6:2 diPAP, at concentrations of 0.22 to 12.76 µg/kg, while substances in the PFSA group dominated fly ash at concentrations of 0.18 to 37.71 µg/kg. The condensate water contained almost exclusively PFAS from the PFCA group at concentrations between 0.28 to 182.9 ng/l. No apparent relationship between high concentrations of analysed PFAS in the sampling matrices and the operational data, such as temperature, the composition of waste and furnace type, was found in the study.

The Industrial Emissions Directive (2024/1786) requires that waste incineration plants must be designed to ensure the flue gases reach a temperature of at least 850 °C for 2 seconds to ensure the complete breakdown of toxic organic substances. If hazardous waste with a content of more than 1% of halogenated organic substances is incinerated or co-incinerated, the temperature should be at least 1100 °C with a minimum residence time of 2 seconds in order to mineralise all organic compounds. EU incinerators are specifically designed and operated to meet these minimum conditions. By ensuring that the combustion gases are maintained at a minimum temperature for a minimum residence time (and at a minimum oxygen level), a good burnout of the combustion gases can be achieved. In addition, the Directive requires the installation of measurement systems to monitor the temperature and oxygen levels.

The fabrication of cement comprises the calcination and fusion of materials comprising calcareous materials, clays and iron and aluminium oxides in a furnace at high temperature (1450 °C). This furnace produces clinker. Co-processing is the use of alternative fuel and/or raw materials for the purpose of energy and/or resource recovery. The co-processing of waste in cement kilns provides energy and materials recovery while cement is being produced. Wastes can be processed in such furnaces because the specific conditions of the process, such as high temperatures, an alkaline environment, an oxidizing atmosphere, an optimal mixture of gases and products and a long residence time, are usually sufficient to destroy hazardous and non-hazardous waste.

There is not much available information on FP waste material sent to cement kilns. In countries where no waste incinerators are available, we have to assume that some FP waste may end up in cement kilns. Advantages of cement kilns in comparison to other incineration methods include the very large margins of temperature and residence time to complete the mineralisation of FP and the capacity to strip fluorine and its permanent capture as inert CaF₂ therefore reducing HF emissions. In addition, no special modifications of the kiln operation are needed, and there is no expected effect on the quality of the cement produced as fluorine has long been used to improve cement hardness. Finally, the Dutch Institute for Public Health and Environment (RIVM, 2021) concluded that although it can be assumed that fluoropolymers are destroyed with the gasification process, this does not provide enough information on the kind and degree of by-products formed or on the rate of mineralization.

Incineration of WLO without any pretreatment can be employed for energy recovery. As mentioned in **Section 3.1**, some WLO is also thermally destroyed in cement kilns. No information has been found as to the possible generation of volatile PFAS substances produced during the incineration of waste lubricant oil and greases. As per FP incineration is likely that the high temperatures commonly employed in hazardous waste or municipal waste incinerators, and in cement kilns, together with emissions control devices will minimise any releases of PFAS substances.

3.3. LANDFILLING OF FLUOROPOLYMERS AND OTHER PFAS

The goal of solid waste landfills is to contain waste, and thereby restrict the release of contaminants within the landfill from entering the environment. Landfills are commonly classified by the types of waste they accept. Main types of landfills include Municipal Solid Waste (MSW) landfills and Hazardous Waste (HW) landfills. Landfills control waste and corresponding pollutants through containment. Because of their many and varied uses, PFAS enter landfills as part of the general MSW stream, in industrial waste, or in other PFAS-containing wastes.

Some landfills are available disposal options for PFAS and PFAS-containing materials. MSW landfills commonly receive large quantities of wastes containing PFAS (e.g. biosolids, septage, soils excavated during remediation, and phytoremediation biomass). Permitted hazardous waste landfills employ the most extensive set of environmental controls (e.g. double liner systems with leachate collection/treatment and leak detection). They can contain commercial and industrial wastes containing PFAS and they are more effective at minimizing PFAS release into the environment than other landfill types.

Most modern MSW landfills, when constructed and operated with appropriate controls (e.g. a flexible membrane liner system and leachate and landfill gas collection and management systems), can also help contain PFAS. However, some research indicates that although MSW landfills contain PFAS for the most part, up to 5 % of the PFAS may be released in the landfill gas and 11 % may be released in the leachate annually (Tolaymat et al., 2023). Also, landfill leachates are often treated in wastewater treatment plants which are not designed to remove persistent chemicals such as PFAS substances.

Fluoropolymers such as PTFE are less likely to migrate within a landfill by partitioning to the gas or liquid (i.e., leachate). However, physical abrasion of the polymers can lead to the creation of fluorinated microplastics that may be suspended in landfill leachate. Although fluoropolymers are highly resistant to chemical and thermal degradation, they can still break down into microplastics due to weathering and physical strain, increasing their dispersion and bioavailability. Fluorinated microplastics have been measured in landfill leachate, but because degradation and abrasion processes of FP are relatively low in landfills, the bulk of stable fluoropolymers would be expected to be retained for a long duration.

3.4. RECYCLING OF FLUOROPOLYMERS

With a share of more than 50 %, PTFE is the most important representative of the fluoropolymers (Conversio, 2023). As indicated earlier, in 2020, a total of 23.5 kt of fluoropolymer waste were collected in the EU, either in commingled waste streams or as separated waste fractions (Conversio, 2023). According to different manufacturing processes PTFE can be classified as:

- Emulsion PTFE (E-PTFE);
- Suspension PTFE (S-PTFE);
- PTFE-Compounds;
- PTFE-Micropowder.

The polymerisation of TFE into PTFE can be differentiated into a suspension and an emulsion polymerisation process. While emulsion polymerisation occurs in an aqueous dispersion containing emulsifiers and dispersion aids, suspension

polymerisation is done in an aqueous suspension without emulsifiers. Emulsion PTFE (or E-PTFE) is built from very small primary particles (size of 200 nm), and a superficial secondary structure called coagulate, with a particle size distribution of 400 - 600 μm . In contrast, suspension PTFE (S-PTFE) consists of irregularly formed compact polymer particles of around 2 μm , which are milled in special mills to a particle size of around 10 μm or, optionally, are aggregated to free-flowing powders with a particle size between 100 and 700 μm .

PTFE-Compounds consist mostly of S-PTFE and inorganic or organic fillers. A separation of the single components is not possible. Finally, PTFE micro-powders are low molecular PTFE substances, which can be used as additive in different applications.

In 2020, only 3.4% of all fluoropolymers were recycled in the EU, of which less than 0.1 kt involved some form of thermal recycling (Conversio, 2023). Primary and secondary recycling are common processes in the manufacturing of PTFE products and includes the recycling of waste/fragments generated during the production of the final products. In primary recycling sintered PTFE waste is collected, sorted and ground to a powder. For pre-sintered PTFE, reprocessing can only occur if pressure and temperature are simultaneously applied as in the case of ram extrusion. In secondary recycling degradation of high molecular PTFE into PTFE micro-powder is achieved by either thermo-mechanical degradation or by using high energy irradiation (gamma or beta irradiation), and typically supplemented by a grinding step to achieve the desired particle size. This process changes the properties of the PTFE significantly and cannot therefore be used for typical PTFE applications. However, these micro-powders are suitable as additives in a variety of applications including non-PTFE plastics, lubricants, elastomers, printing inks, and coatings and paints among others. The recycling route described above only exists for unfilled, or virgin, PTFE. In contrast, there is a lack of large-scale recycling technologies for PTFE compounds.

Tertiary recycling, also known as “Up-Cycling” allows the reprocessing of FP waste into monomers (primarily tetrafluoroethylene (TFE), and hexafluoropropene (HFP)) which can then be fed into the production of FP. In effect, the process allows the collection of FP material and its transformation into new FP that can be incorporated into products again. The process was developed by 3M (Dyneon™) which opened the world’s first pilot plant for the recycling of fully fluorinated polymers in 2015, in Gendorf Chemical Park, Burgkirchen, Germany. In order to close the loop in fluoropolymer production, Dyneon™ uses a pyrolysis method in which perfluorinated polymers are decomposed creating gaseous monomers. Once cleaned, these monomers are fed back into production. The term “Up-Cycling” refers to the fact that the product quality is not impacted in any way. The plant accepts a variety of FPs including PTFE, PFA, TFM, FEP, etc, in various forms such as liners, blocks, pellets, chips and semi-finished goods. The plant is open to third party producers and manufacturers, and it is unclear if they received any type of waste (i.e., end of life components). Waste that is declared hazardous cannot be accepted and cannot be recycled in the Up-Cycling plant. The Up-Cycling process is considered an R3 recycling process (EU Waste Code) for turning waste flows into basic raw materials.

The chemical recycling of fluoropolymer waste offers the opportunity to produce virgin-like fluoropolymer raw materials for the production of goods and products without quality limitations. However, current capacity is low and increasing this capacity will require the building of robust supply chains for large-scale and economical feasible recycling processes. In the meantime, recycling activities are, however, mainly concentrated on scrap from production and manufacturing, which

generate large amounts of fluorinated polymer wastes. This is especially the case for the manufacturing of semi-finished parts and end-use articles made of PTFE. The processing steps, such as moulding, sintering, machining and cutting, usually produce 10-30% waste, and in some cases more than 50%.

The barriers for recycling of fluorinated polymers in products are mostly technical: a major part of the end-use of fluorinated polymers is scattered over a variety of uses in often complex products where the amount of fluorinated polymers is often low compared to other materials. Dedicated recovery is therefore not put in place for a variety of products. The recycling of post-consumer FP waste is more or less limited to the recovery and separation of 'clean' fractions, e.g. from commercial and industrial production and processing equipment. Some products are also difficult to collect for subsequent recycling, such as wire and cable insulation, printed circuit boards, seals and hoses, coatings of metal surfaces, coated fabrics, additives in lubricants, and tubing and valves. Given that the global recycling rate of all plastics is approximately 9%, it can safely be assumed that the recycling rate of end-of-life fluorinated polymers is substantially lower.

The specialised literature reviewed identifies several fluoropolymer recycling facilities in Switzerland, Italy, Netherlands, Germany, and Belgium. Most are producers of fluoropolymers and some can recycle waste scrap from their own production process or from external sources. Most work primarily with PTFE although a few also accept other FPs. The author contacted a producer of specialised plastics including PTFE located in The Netherlands. They accept only PTFE production residues, so called-by-products from manufacturing and processing processes, which is then recycled primarily by ram extrusion. While in principle they could accept end of life PTFE used in industrial components, they work primarily with established suppliers to guarantee the quality of the FP received. Still, the producer indicated that received materials do contain impurities and sometimes batches are rejected. While in theory, they are open to receiving industrial FP waste they prefer a continuous and known source to guarantee its quality. Analysis of received materials are carried out with the help of thermal analysers such as DSC (Differential Scanning Calorimetry) and TGA (Thermo Gravimetric Analysis). Their capacity to receive external materials is low, around 300 tonnes per year.

Another producer located in Switzerland, also receives scrap waste FP from production processes. They work mainly with PTFE but also PFA and FEP. They cannot receive mixtures of FPs and therefore the FP waste needs to be identified and sorted prior to being accepted. Also, the waste FP has to be devoid of any contamination. While they buy primarily in granular form or scrap size FP, they would also receive larger components. However, the volumes they can accept are quite small, in the hundreds of kilograms rather than in tonnes.

3.5. METAL RECYCLING

As discussed previously, fluorinated polymers are used in a wide range of applications, typically incorporated in products such as membranes, O-rings, coatings, electric insulators, etc., to provide them with specific properties. As a result, it is often difficult to separate thin layers containing fluorinated polymers. The Dutch National Institute for Public Health and the Environment along with the European Environment Agency's European Topic Center on Waste and Materials in a Green Economy have described the flow of PFAS during end-of-life metal recycling. While the focus has been on the transportation sector (i.e., vehicles waste arising from the automotive sector that typically ends up in metal shredding plants), it provides insights into the management of metal parts containing fluoropolymers. Prior to shredding a metal waste stream, reusable parts and recyclable plastics

(which may contain FP) are removed. Several technologies may be used to segregate the metal fraction from the non-metal fraction. The remaining non-recyclable fraction is referred to as Shredded Residue (SR) or Automobiles Shredded Residue (ASR) when referring to automobiles recycling facilities, which contains a mixture of plastics, rubber, textiles/fibers, wood, glass, and unrecovered ferrous and non-ferrous metals.

Metals that may be coated in FP or have FP-containing attachments that are difficult to remove are then sent to a high temperature smelter for metal recovery. Often, the remaining metal shredder residue is transported to a landfill, incinerated for energy recovery, or recycled. It has been reported (Conversio, 2023) that the majority of FP recovered from vehicle shredder facilities end up going into incineration and a smaller portion into landfill. It is unclear how much FP end up in metal recycling, however, steel pipes including FP liners from the chemical/petrochemical sector are usually collected for metal recycling (Conversio, 2023). The author contacted a large metal recycling facility in the UK to investigate further how the operation works. They receive primarily End-of-Life Vehicles (ELVs), waste from the electric industry sector and domestic appliances. While some industrial waste is sometimes received, this constitutes a small proportion. The majority of the waste they received is ferrous and non-ferrous metals and this is their preferred waste intake. When they do accept ELVs, these are dismantled on site and the non-metal components sent away for disposal or recycling. Plastics and polymers are sent to a recycling facility without any identification and separation of the materials.

European stormwater studies have shown that industrial runoff from metal recycling facilities can contribute to the environmental circulation of PFAS. Groundwater studies also suggest the potential for environmental cycling of PFAS derived from shredded residues. A statewide study conducted by the New Hampshire Department of Environmental Sciences (NHDES) in the US showed that 67% of the metal recycling sites sampled had PFAS concentrations greater than ambient groundwater quality standards (NHDES, 2020).

There are limited studies that evaluate environmental microplastics derived from the industrial process of recycling. However, a Swiss study on the environmental flows of microplastic from industrial sectors (Buser, a. et al, 2009) suggested that Automobile Shredded Residue was a primary source of microplastic outdoor air emissions. Given the identification of microplastics associated with metal recycling activities, the emission of FP microplastics from metal recycling activities cannot be discounted.

3.6. REGENERATION AND REPROCESSING OF WASTE LUBRICANT OIL AND GREASES

According to the WFD 2008/98/EC, regeneration “means any recycling operation whereby base oils can be produced by refining waste oils, in particular by removing the contaminants, the oxidation products and the additives contained in such oils.” The obtained base oil has the potential to produce lubricating oils with similar properties as virgin base oils.

Currently, the most relevant disposal routes available in Europe are regeneration, laundering, reclaiming, third party use as fuel, mild and severe reprocessing, and thermal cracking. Laundering and reclaiming are suitable for recovery of industrial lubricants. Laundering is a closed-loop treatment that involves the removal of solids by filtration, de-watering by vacuum distillation and the addition of fresh additives. In reclaiming, the WLO is centrifuged and/or filtered and then reused.

Mild reprocessing is a simple treatment process to remove water and sediments from heavy polluted WLO. After this treatment the oil can still contain metals, halogen, and sulfur but can be further used as replacement fuel oil for combustion in road stone plants, blended into fuel oil or in power stations. Severe reprocessing aims at separating the combustible portion of heavy polluted WLO from less desirable bottom fractions containing metals, non-combustible ash, and dirt. Chemical or thermal treatments are applied to produce a demetallized heavy fuel oil (HFO), also called heavy distillate, which can be used as marine diesel oil (MDO) for example.

Regeneration involves the production of base oil from WLO after the removal of contaminants, oxidation products, and additives, for further manufacture of lubricant products. The process is more complex than those described above and involves several treatment technologies to achieve a base oil with similar quality to those from crude oil refining. WLO contaminated with chlorine, PCB or with a chemical composition that hinders the treatment by regeneration are typically managed using other treatment or disposal routes.

No information was found in the literature reviewed on the possible releases of PFAS substances from the regeneration or reprocessing of WLO and waste greases containing FP additives.

3.7. EMERGING MANAGEMENT OPTIONS FOR FLUOROPOLYMERS

Beside incineration and landfilling, and a small component going to thermal destruction associated with metal recycling, degradation of FPs can also be obtained through pyrolysis. **Pyrolysis** refers to the thermal decomposition of organic materials at high temperatures (400-600 °C) in an inert environment. The process turns organic materials into gaseous products and solid char. Pyrolysis commercial plants are increasingly being used for the treatment of biomass including waste wood, green waste, wood chips and sewage sludges. Other uses identified include the pyrolysis of waste paper, waste tyres and plastics. Plastic pyrolysis, at temperature below 600 °C has been promoted in recent years in the United States and Europe and small-scale plastic pyrolysis of mixed polymer inputs is carried out in such countries as India and Pakistan.

Depolymerisation by pyrolysis is effectively the only recycling method applicable to end-of-life fluoroplastic components, where fluoroplastics are decomposed into their monomers. This is the technology used in Germany, described earlier in **Section 3.4**. The plant has a capacity of treating 500 tonnes of fluorinated polymer waste per year including PTFE, PFA and FEP, producing the monomers TFE and HFP with a recovery rate of 90-95%. In addition, pyrolysis of mixed plastics to produce fuel has occurred in recent decades in the United States and Asian countries using carpets and auto-shredder residue as feedstocks which may contain fluorinated polymers. These pyrolysis plants are normally operated at temperatures below 650 °C, in which the thermal degradation of fluorinated polymers can result in toxic emissions including nano- and microparticles and long chain PFAS. The author could not find published studies that assess pilot and full-scale pyrolysis processes for PFAS and other toxic degradation products from fluorinated polymer degradation.

Life cycle analysis of incineration, landfilling and pyrolysis of oily sludges considering primarily the effects of air emissions impacts such as global warming, smog formation acidification potential, respiratory effect and also eutrophication impacts have shown pyrolysis performing better than incineration and slightly worse than landfilling. This is not surprising given the general impacts of air emissions considered and the consideration of the use of py-oil and py-gas in combustion in

the case of pyrolysis. When a wider sustainability assessment considering the three pillars of sustainability: environment, social and economics, and their position in the waste hierarchy was carried out, pyrolysis results in a more sustainable approach than both incineration and landfilling.

Emerging technologies for the treatment/destruction of PFAS relate primarily to PFAS in solution/wastewater streams, such as supercritical oxidation, and electrochemical oxidation. One technology that can be applied to solid matrices is **ball milling**, a technology that has been explored to treat PFAS contaminated solid media, such as contaminated soils or residuals from desolvation of concentrated waste streams. The milling process is conducted at modest temperatures and pressures in the presence of co-milling reagents (e.g. potassium hydroxide, calcium oxide, alumina, sodium persulfate, and zero-valent iron). The mechanochemical degradation of PFAS and the rapture of C–F and C–C bonds may be achieved either by amorphization of the crystal structure of PFAS and/or deforming valence bonds and angles under mechanical stress. Thus, the final milling powders would contain environmentally safe inorganic salts for disposal. The exact destruction pathway is still unclear. Some earlier studies have suggested that PFAS molecules would first undergo decarboxylation or desulfonylation, then a sequential chain-shortening by one CF₂ at each step, which is called the “flake-off” degradation mechanism. However, a recent study has revealed new evidence that does not support the previously assumed pathway and further investigations to elucidate the destruction mechanisms are required. It is unclear what the applicability of this technology to fluoroplastics is at this moment.

While no high temperatures or pressures are involved, ball milling requires significant energy to continuously drive the high impact collisions needed to achieve for treatment. It was reported that a milling batch process required an energy consumption of 400 kWh per tonne of contaminated soil.

4. FLUOROPOLYMERS WASTE MANAGEMENT GUIDANCE AND REGULATIONS

4.1. REGULATIONS RELATED TO THE MANAGEMENT OF PFAS WASTE

The EU waste classification system is primarily governed by the Waste Framework Directive (2008/98/EC), which sets out the general principles for managing waste in the EU. It establishes a harmonized waste classification system known as the European Waste Catalogue (EWC). The EWC provides codes and descriptions for different types of waste, allowing for standardized identification and classification of waste materials. PFAS substances do not have specific codes or classifications within the EWC. However, depending on the specific characteristics and properties of the waste containing PFAS, they may fall under existing waste codes that pertain to related substances or materials. For example: if the waste containing PFAS exhibits hazardous properties according to the EU's Hazardous Waste Directive (Commission regulation (EU) No 1357/2014; 2017/997/EU), it would be classified as hazardous waste.

Similarly, there are no specific categories for fluoropolymer plastics, but there more general are waste categories for plastic and rubber waste. Given the discussion of fluoropolymers end-of-life management options, FP are likely to be mixed with plastics and therefore may fall within the waste codes 070213 (plastic waste), 120105 (plastics and chips), 200213 (plastics) and others. These are generally non-hazardous wastes. These categories may include also FP associated with coatings and the treatment of metals. Lubricant oils are typically classified as hazardous whether they contain FP or not.

Several PFAS are regulated in Europe and internationally. This is currently the case for PFOA, PFOS and PFHxS and their salts, and chemicals that can degrade to them (part of the group of “long chain PFAS”), which were widely used in the past mostly as polymerisation aids, in fire-fighting foams, in textile treatment, and other applications. In addition, some 20 PFAS substances are listed in the EU Water Drinking Directive. PFAS are PBTs or vPvBs and are widely present in the environment. For these reasons, they have been listed under the Stockholm Convention on Persistent Organic Pollutants (POPs) which require parties to take measures to eliminate their production and use. Consequently, they are now also restricted under the EU POPs Regulation.

PFAS are present as contaminants in waste generated during their production and use, as well as in waste from waste management activities. They can be present in sludge from the treatment of industrial and urban wastewater, in landfill leachate and in emissions from incineration facilities. Wastes containing those PFAS identified as POPs in Annex IV and Annex V of the EU POPs Regulation have been provided with limits representing specific provisions. The limits in Annex V represent maximum concentration limits of substances listed in Annex IV allowed in specific waste streams to be dealt with in accordance with a method listed in the Annex V (i.e., permanent storage in hazardous waste landfills, or underground permanent storage (e.g. a maximum concentration limit of 50 mg/kg for PFOS wastes that can be permanently stored).

Some other long chain PFAS have a hazard classification under the Regulation on classification, labelling and packaging (CLP) of substances and mixtures. REACH regulation has included a PFAS group for restriction, C9-C14 PFCAS, their salts and related substances.

The recent restriction proposal under REACH from the national authorities of Denmark, Germany, the Netherlands, Norway and Sweden, to phase out all non-essential uses of PFAS and to accelerate the development of safe and non-persistent alternatives to all uses of PFAS, considers all PFAS according to the OECD 2021 definition. This is in contrast to the approach followed until now for PFAS in REACH that considers restriction or elimination of individual substances or groups of closely related substances. The proposal further includes a combination of limits which can be detected in a solid matrix using different analytical approaches (for some of which such polymeric PFAS are excluded). The proposal is relevant for, and can impact, circular economy aspirations. From an End of Waste (EoW) perspective, a waste containing PFAS that achieves EoW status must meet any relevant requirements under REACH, since as stated in the proposal, *“the proposed restrictions will apply to articles regardless of whether they are made from virgin or recycled materials”*.

4.2. AVAILABLE GUIDANCE ON THE MANAGEMENT OF FLUOROPOLYMER WASTE

A survey commissioned by Concawe in 2023 (ECHA, 2023) of EU refineries management plans in relation to the management of refinery wastes containing PFAS, revealed that no company in the survey had a dedicated PFAS emission management plan in place at the time of the survey. The survey indicated that more than half (55%) of the companies were working towards the development of PFAS emission control plans. However, the majority of these plans relate to the management of wastewater and relate primarily to PFAS-containing firefighting foams and refrigerants. The plans include actions such as routine analysis at upstream and downstream locations, the identification of products containing PFAS and suspected releases of PFAS-containing substances triggering the collection of samples for analysis. When PFAS are identified, refineries then define action plans to identify and mitigate the source.

There are several challenges to the development of PFAS management plans in refineries. Such plans would require the identification of PFAS in components requiring specialised laboratories to conduct FP analysis. Companies typically rely on contractors to collect and select the most applicable techniques to manage waste, including PFAS in end-of-life components. There are also limited options for the management of end-of-life components, while recycling requires significant logistical effort to collect sufficient volumes, and concerns remain about the presence of hazardous products. Consideration of additional installations onsite to manage FP waste is limited by limited available footprint, diverse legislation and potential impact to the license to operate.

In recent years, guidance on the management of PFAS-containing waste have been developed by some countries. They typically contain guidance on the monitoring of PFAS in the environment, the storage of waste and the best/accepted techniques for the management of wastes containing PFAS substances. Given their widespread distribution in the environment, and their toxicity to human health and ecosystems, the guidance reviewed typically focus on long-chain PFAS. Fluoropolymers are rarely mentioned, with a few exceptions. Most guidance refers to disposal into landfills or incineration as the main waste management options available. Recycling is not typically their focus. None provide plans for the identification, decommissioning and collection of FP-containing equipment in industrial facilities.

One of the most recent and comprehensive guidance on PFAS waste management options is USEPA's Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances, issued in April 2024 (still under public

consultation). This guidance provides a distinction between solid, liquid and gas phase waste containing PFAS and presents dedicated subsections to aqueous film-forming foams, soils and biosolids, textiles and spent water treatment materials. It discusses the main three types of available management options in the US: thermal treatment, landfill, and underground injection wells, as possible options depending on the type of PFAS (e.g. solid, soluble, or volatile PFAS), the type of waste in which the PFAS is comingled (e.g. biodegradable or non-biodegradable), and their potential pathways for environmental release. There is a special mention of fluoropolymers where the guidance states that given their relative low degradation and reactivity rates, municipal and hazardous landfills may provide good disposal options. The report also states that while some data are available to support this assessment, more data are needed to resolve uncertainties, in alignment with existing technical literature.

Australia and New Zealand's Environmental Protection Agencies (HEPA) published their first *PFAS National Environmental Management Plan* (PFAS NEMP) in January 2018. The plan provides a consistent framework for the environmental regulation of PFAS-contaminated materials and sites and was intended to be a 'living document' reflecting the evolving knowledge surrounding PFAS. Since the release of the first version of the NEMP, the HEPA National Chemicals Working Group (NCWG) has been working to clarify and expand on the guidance in the NEMP. The NEMP 2.0 version was released in 2020 and the NEMP 3.0 version in October 2022 (for public consultation). The management plan focusses on perfluorooctane sulfonate (PFOS), perfluorooctanoic acid (PFOA) and perfluorohexane sulfonate (PFHxS), which are the most widely studied PFAS. It provides guidance about their environmental management with a focus on preventing and managing PFAS contamination.

The NEMP recognises that in addition to primary sources such as contaminated sites where PFAS has been used, secondary sources for PFAS contamination may include facilities that receive waste and wastewater containing PFAS from a range of diffuse sources, such as landfills and wastewater treatment plants. The NEMP is not strictly speaking a waste management plan since much of its content refers to PFAS environmental monitoring, storage, containment and transport of PFAS substances, and treatment and remediation of PFAS-contaminated sites. However, it has a section of PFAS disposed into landfills where it discusses the design, construction and monitoring of landfills required to received PFAS waste. The document does not provide any guidance regarding the incineration of PFAS-containing waste, probably due to the fact that there are few incinerators in the region. The only reference to fluoropolymers regards the fact that these types of PFAS are not within the typical analytical suite with others such as PFOA and PFOS.

In 2023, the United Kingdom Government (Health & Safety Executive / Environment Agency) published their "Analysis of the most appropriate regulatory management options (RMOA)". The report examines the nature of the risks posed by PFAS and the most appropriate options for the management of these risks. It is a non-binding technical document aimed at collecting, combining and analysing information on the intrinsic hazards, uses and routes of exposure to PFAS, as well as considering relevant domestic legislation and international approaches to the management of PFAS. The report helps gain a clearer view of the risks of PFAS to human health and the environment, and derivation of potential regulatory options to minimise the identified risks. Whilst the options suggested focus primarily on the UK REACH framework, others are suggested where appropriate. Fluoropolymers are not included.

The above guidelines are not waste management plans and they typically do not include fluoropolymer plastics. Other guidelines such as those associated with the management of POPs and including their waste are more useful. Using the United Kingdom as an example again, the UK POPs regulations provide general guidance as to the management of waste containing POPs (without mention to PFAS). However, the guidance would apply to those PFAS substances classified as POPs in EU and international regulations and it is not applicable to FP. The guidance require waste with POPs be sent to disposal, or recovery that can completely destroy the POP or irreversibly transform the POP and waste producers must use one of the following methods:

- D9 - physico-chemical treatment such as chemical destruction;
- D10 - incineration on land;
- R1 - using the waste as a fuel to generate energy;
- R4 - recycling or reclamation (for metals and metal compounds).

Other management plans/regulations deal with mobile, soluble PFAS through the adoption of POPs regulations. United Kingdom regulations for example do not allow the recycle or reuse of any waste that contains POPs and they must be destroyed. If the regulator approves the permanent storage of POPs-containing waste rather than destroying it, this can be done in the following suitable sites:

- Deep underground hard rock formations;
- Salt mines;
- Hazardous waste landfills.

FPS are not POPs and therefore are not regulated as mobile, soluble long-chain PFAS are. In fact, the waste management of FPS plastics is more closely related to the management of waste plastics in general. In a circular economy context, effective waste collection is a vital first stage for efficient recycling, and this is true of plastics. Improved waste collection significantly impacts the waste streams and their suitability for downstream pre-treatment, sorting and recovery.

A wide range of technologies are currently used for waste pre-treatment and sorting. These range from manual dismantling and picking to automated processes such as shredding, sieving, air or liquid density separation, magnetic separation, and highly sophisticated spectrophotometric sorting technologies such as UV/VIS (ultraviolet/visible), NIR (near infra-red), or laser/optical sorting and, more recently, digital watermark and bar-coding technologies. Modern sorting plants are complex facilities that apply several technologies adapted to specific waste streams to achieve optimum cost-effective output. Today's pre-treatment and sorting operations for commingled packaging and other dry recyclable materials can process more than 100,000 tonnes/year of plastics waste, producing sorted waste with a purity higher than 95% for some plastics. A pilot programme using artificial intelligence (Unilever and the Alibaba Group) aims to speed high-grade recyclable plastics back into the circular economy through the automatic identification and sorting of plastic packaging. The collection points automatically scan and sort the plastic enabling them to be fast-tracked for recycling.

Recycling of post-consumer FP waste from commingled (mixed) waste streams from commercial and industrial end-users is almost non-existent at present and will not be a promising option for circularity of FP in the coming years. The overall share of FP is too low to establish any sorting and recycling approach. The recycling of post-

consumer FP waste is more or less limited to the recovery and separation of 'clean' fractions, e.g. from commercial and industrial production and processing equipment. The accessible quantity of post-consumer FP waste suitable for recycling is significantly smaller. Only if all stakeholders along the FP value chain work more closely together, progress can be made on the circularity of FPs.

Sorting and separation are key to increase recycling. To be able to recycle different waste fractions, these must be carefully separated beforehand. Separate collection helps to pre-sort waste and to ensure that other types of waste are not hindering the process. However, if plastics waste fractions are collected via mixed waste streams, it would be necessary to add extra sorting steps in the recycling process. These cannot always be performed in the most efficient way, which means that not all plastics waste may be kept for recycling, e.g. if plastics become contaminated with organic waste or other types of waste. This is why post-consumer plastics waste collected via separate waste collection streams generally has 13 times higher recycling rate.

The situation is different for lubricant oils. According to GEIR, the European re-refining industry group, in 2016, 42% of the WLO was used directly in regeneration within the EU countries where it was collected and 13% was regenerated after exporting to other EU countries. The second preferred pathway was reprocessing to produce fuel oil, which accounts for 31% of the collected WLO. EU-28 reported 85% of recycling (including regeneration and reprocessing to fuel), which is comparable to GEIR values.

5. SUMMARY AND CONCLUSIONS

This report describes End-of-Life waste management processes for refinery components containing, or potentially containing fluoropolymer plastics, and fluoropolymers in lubricant oils and greases. Fluoropolymers represent a distinct subset of fluorinated polymers which have a carbon-only polymer backbone with F atoms directly attached to it and they can be defined based of how many repeat units they contain, such as the repeat unit $(CF_2-CF_2)_n$ for PTFE. Fluoropolymers can also be defined based on their polymer-like properties such as film and fibre forming.

The group of fluoropolymers is dominated by PTFE (polytetrafluoroethylene). Together with other fluoropolymers such as FEP (fluorinated propylene), PFA (perfluoroalkoxy alkanes) ETFE (ethylene tetrafluoro ethylene) and other tetrafluoroethylene-copolymers, they account for around 75% of fluoropolymers in the market. They are high molecular weight plastics with unique properties due to the strong C-F bonds, making them highly stable, with high thermal, chemical, photochemical, oxidative, hydrolytic and biological stability, making them ideal materials in industrial processes.

Fluoropolymers in refineries and fuel distribution sites are found primarily in solid form in industrial equipment and components. They are also found as additives in lubricants and greases and as coatings. They are present in plant safety equipment, compressors and agitators, gaskets and sealings, pumps, valves, tubing lining and many other components, making their use vital and widespread across all essential equipment in most refineries. In 2020, approximately 49 kt of fluoropolymers were produced in the EU. The largest share accounted for PTFE materials (~56%) followed by PVDF (~12%), FKM (~8%) and FEP (~8%).

The replacement of FP applications used in production and processing equipment can involve different practices and can be carried out by either internal maintenance service departments (often contracted third-party companies on site) or by external (and specialized) service companies providing services on request. A combination of both practices on one site is also possible. After dismantling end-of-life equipment and components containing fluoropolymers (such as pipes, valves, pumps, tanks, liners, tubes, etc), these are collected as waste and mainly separated on site for further waste treatment.

According to 2020 data, most FP were (co-) incinerated in Municipal Solid Waste Incineration (MSWI) plants or dedicated hazardous waste incineration plants (83.5%) typically with energy recovery. This includes FP waste from commercial and industrial waste producers that is either pre-sorted or results directly from dismantling operations of which 11.5% included metal components that are recycled in smelters. Landfilling of FP waste corresponded to about 13.1%, while some fractions of pre-sorted FP waste were sent to recycling, either to domestic recyclers or exported for recycling in intra- and extra-EU countries (<0.5%).

Currently, the most relevant disposal routes for waste lubricant oils (WLO) available in Europe are regeneration and reprocessing and incineration with or without energy recovery. According to GEIR, in 2016, 42% of the WLO was sent directly to regeneration within the EU countries where it was collected and 13% was regenerated after exporting to other EU countries. The second preferred pathway is reprocessing to produce fuel oil, which accounts for 31% of the collected WLO. The remaining WLO is incinerated with or without energy recovery. About 3% of

WLO is sent to cement kilns. Incineration of WLO without any pretreatment can be employed for energy recovery.

Fluorine-containing polymers are typically thermally decomposed completely at a temperature of 900 °C. Fluoropolymers are solids that do not evaporate with rising temperatures but rather start to decompose into volatile fluorinated compounds. At thermal decomposition, a variety of gaseous fluorine-containing products are therefore formed. If the combustion temperatures are not high enough to ensure the complete mineralisation of fluoropolymers to HF or degradation is incomplete, highly persistent TFA and HCF can be formed and mostly capture with emission control equipment. While end-of-life waste containing fluoropolymers are often incinerated European municipal waste incineration plants there is lack of reliable information on amounts of PFAS actually emitted in flue gases.

Besides the flue gases that are emitted through the stack, solid residues are also formed such as fly and bottom ashes, and there are emissions of condensate water. PFCA precursors and substances such as PFASs have been found in fly and bottom ashes and in condensate water. Incineration ashes are typically sent to landfills from where they can be released into the environment. While most PFAS releases from landfills relate to soluble long chain PFAS originating from a variety of domestic and industrial products, fluoropolymers such as PTFE are less likely to migrate within a landfill due to their stability. However, physical abrasion of the polymers can lead to the creation of fluorinated microplastics that may be suspended in landfill leachate. While fluorinated microplastics have been measured in landfill leachate, the bulk of stable fluoropolymers would be expected to be retained for a long time.

In 2020, only 3.4% of all fluoropolymers were recycled in the EU, of which less than 0.1 kt involved some form of thermal recycling (Conversio, 2023). Primary and secondary recycling are common processes in the manufacturing of PTFE products and includes the recycling of waste/fragments generated during the production of the final products. Primary recycling of PTFE waste involves grinding PPTFE waste into a powder reprocessing using ram extrusion. In secondary recycling degradation of high molecular PTFE into PTFE micro-powder is achieved by either thermo-mechanical degradation or by using high energy irradiation (gamma or beta irradiation), and typically supplemented by a grinding step to achieve the desired particle size. This process changes the properties of the PTFE significantly and cannot therefore be used for typical PTFE applications. Tertiary recycling, also known as “Up-Cycling” allows the reprocessing of FP waste into monomers (primarily tetrafluoroethylene (TFE), and hexafluoropropene (HFP)) which can then be fed into the production of FP. The process is based on pyrolysis and the quality of the product is not affected. Plastics’ pyrolysis, at temperature below 600 °C has been promoted in recent years in the United States and Europe and is being used in one plant in Germany for the recycling of fluoropolymers, primarily PTFE.

This report identified several challenges to the development of PFAS management plans in refineries. To date, above half of the refineries surveyed for this project indicated they were in the process of developing such plans and that their focus was on the management of waste water relating primarily to PFAS-containing firefighting foams and refrigerants.

In recent years, guidance on the management of PFAS-containing waste have been developed by some countries. They typically contain guidance on the monitoring of PFAS in the environment, the storage of waste and the best/accepted techniques for the management of wastes containing PFAS substances. Given their widespread distribution in the environment, and their toxicity to human health and ecosystems, the guidance reviewed typically focus on long-chain PFAS. Fluoropolymers are rarely

mentioned, with a few exceptions. Most guidance refers to disposal into landfills or incineration as the main waste management options available. Recycling is not typically their focus. None provide plans for the identification, decommissioning and collection of FP-containing equipment in industrial facilities.

In fact, the waste management of FPs plastics is more closely related to the management of waste plastics in general. In a circular economy context, effective waste collection is a vital first stage for efficient recycling, and this is true of plastics. Improved waste collection significantly impacts the waste streams and their suitability for downstream pre-treatment, sorting and recovery. The reality is that the recycling of post-consumer FP waste from commingled (mixed) waste streams from commercial and industrial end-users is almost non-existent at present and will not be a promising option for circularity of FP in the coming years. Only if all stakeholders along the FP value chain work more closely together, progress can be made on the circularity of fluoropolymers.

6. ACRONYMS

ASR	Automobile Shredded Residue
Cl	Chlorine
ECHA	European Chemical Agency
ECTFE	Ethylene-chlorotrifluoroethylene
EU	European Union
F	Fluorine
FEP	Fluorinated ethylene propylene
FEPM	Tetrafluoroethylene propylene
ETFE	Ethylene tetrafluoroethylene
FKM	Fluorine Kautschuk Material (Fluorine rubber)
FFKM	Perfluoroelastomer
FP	Fluoropolymer
FT	Fluorotelomer
FTOH	Fluorotelomer alcohols
HCF	Hydrofluorocarbon
HEPA	Heads of Environmental Protection Agencies (Australia and New Zealand)
HFP	Hexafluoropropylene
HFPO	Hexafluoropropylene oxide
MSW	Municipal Solid Waste
MSWI	Municipal Solid Waste Incinerator
NEMP	National Environmental Management Plan
REACH	Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals
O	Oxygen
OECD	Organisation of Economic Co-operation and Development
PASF	Perfluoroalkane sulfonyl fluoride
PCTFE	Polychlorotrifluoroethylene
PFA	Perfluoroalkoxy alkanes
PFAA	Perfluoroalkyl acid
PFAAs	Perfluoroalkyl acids
PFAS	Polyfluoroalkyl substances
PFAE	Perfluoroalkylether
PFBA`	Perfluorobutanoic Acid
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonate
PFPAE	Perfluoropolyalkylether

PFPE	Perfluoropolyether
PLC	Polymers of Low Concern
PMVE	Perfluoromethyl vinyl ether
POP	Persistent Organic Pollutant
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidene difluoride
RIVM	Dutch Institute for Public Health and the Environment
TFE	Tetrafluoroethylene
USEPA	United States Environmental Protection Agency
WLO	Waste Lubricant Oil

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