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Environmental Science for European Fuel Manufacturing

Study on PFAS applications, potential release, alternatives, and impact of the restriction proposal in refineries and its distribution segment

FPP4EU workshop– 11 December 2023

[redacted]

Data Sources

We have combined multiple sources of data to obtain a holistic view of the use of PFAS in industrial equipment in refineries and fuel distribution

Approach

Refineries → Questionnaire

Refineries, Suppliers, Associations → Interviews

Specialized Journals, Patents → Advanced Analytics

Objectives

- Conduct inventory of PFAS use in refining industrial equipment
- Identify existing management plans and substitution strategies
- Understand operational, social and environmental impact of potential PFAS ban

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- Increase understanding of PFAS use in current industrial equipment
- Identify potential alternatives for PFAS applications

- Define the trends of PFAS use in the global industry
- Identify PFAS molecules across brand names and equipment
- Understand alternatives for PFAS and their properties

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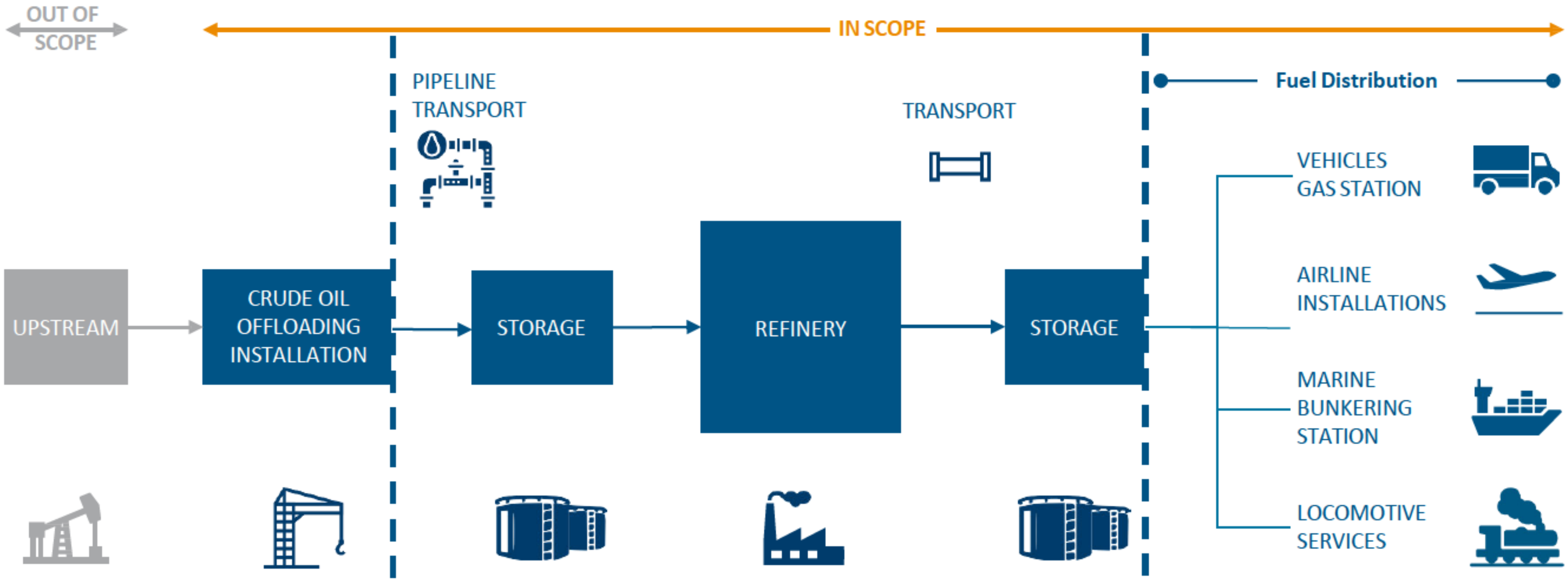
Scope of the Study

Our analysis covered a scope from crude offloading to refining activities and fuel distribution of refined products



Main PFAS Types

Companies have identified 10 main types of PFAS in plants, representing ~50 PFAS molecules

Identified PFAS substances*

Solid State

Fluoropolymers	PFAS compounds
FKM *(Viton, Tecnoflon, Dyneon,...)*	PFSA**
FFKM *(Kalrez, Tecnoflon,...)*	PFCA**
PTFE *(Teflon, Gylon)*	
FEP	
PFA	
PVDF *(Kynar, Hylar, Solef)*	
ETFE	
PCTFE	
ECTFE	

Liquid State

Fluoropolymers	PFAS compounds
PFAE	C6 Foams *(SFPM***)*
PFPE	PFBA
PFPAE	PFOA
PTFE *(Interflon, Oraflon, Nevastane HD2T)*	PFOS
PCTFE *(Voltalef)*	PFNA
	PFBS
	FK-5-1-12
	PFHA
	FTS

Gaseous State

CFC	HCFC	HFC
R11	R123	R134 a
R12		R143 a
		FM200

HFC/HFO - Blends	HFO
R448 a	R1233 zd
R449 a	R1234 yf
R452 a	R1336 mzz
R513 a	

HFC/HFO - Blends	HFO
R365 mfc	R410
R401 a	R417 a
R404 a	R422 d
R407 a,c,f	R427 a
R409 a	R507 a,c,f

**PFAS lists is potentially not exhaustive, the brand names identified are presented in italic font, **PFSA and PFCA are not fluoropolymers, ***Film-forming alcohol-resistant fluor synthetic emulsifier*

Sources: Accenture analysis of survey and interviews of Refining players and suppliers, text mining

Overview of PFAS by Equipment

	Equipment	Yes	Don't know	Possible presence	No	# of respondants
Process Units	**Valves and accessories**	**56%**	44%	100%	0%	18
	Gasket and sealing	**55%**	35%	90%	10%	20
	Pumps	**50%**	45%	95%	5%	20
	Compressors	45%	55%	100%	0%	20
	Agitators	42%	53%	95%	5%	19
	Devices for process control	42%	47%	89%	11%	19
	Refrigeration system	42%	58%	100%	0%	19
	Devices for process analysis	37%	53%	89%	11%	19
	Fans	37%	53%	89%	11%	19
	Heat exchangers	37%	58%	95%	5%	19
	Instruments	37%	58%	95%	5%	19
	Motors and couplings	37%	58%	95%	5%	19
	Turbines	37%	53%	89%	11%	19
	Wastewater treatment	37%	47%	84%	16%	19
	Piping	35%	50%	85%	15%	20
	Fired heaters	33%	56%	89%	11%	18
	Conveyors	32%	53%	84%	16%	19
	Cooling tower	32%	47%	79%	21%	19
	Storage tanks	32%	63%	95%	5%	19
	Transportation Pipeline	32%	53%	84%	16%	19

	Equipment	Yes	Don't know	Possible presence	No	# of respondants
Process Units	Vessels	32%	58%	89%	11%	19
	Distillation Tower	26%	58%	84%	16%	19
	Reactors	26%	63%	89%	11%	19
	Vacuum pumps	26%	53%	79%	21%	19
	Membranes	22%	67%	89%	11%	18
	Absorption tower	21%	58%	79%	21%	19
	Steam ejector	21%	68%	89%	11%	19
	Gas purification unit	11%	74%	84%	16%	19
	Evaporators	0%	74%	74%	26%	19
Safety And Protection	**Plant Safety Equipment**	**65%**	30%	95%	5%	20
	PPE	47%	42%	89%	11%	19
Power & Utilities	Cable & Wiring Equipment	37%	53%	89%	11%	19
	Power Supply Equipment	26%	68%	95%	5%	19
Other Products	Refrigerant	37%	53%	89%	11%	19
	Grease	21%	58%	79%	21%	19
	Other process unit equipment	17%	50%	67%	33%	18
	Lubricant	16%	68%	84%	16%	19
	Other equipment	16%	74%	89%	11%	19
	Processing/auxiliary aids	11%	68%	79%	21%	19
	Catalyst	0%	63%	63%	37%	19

4 equipment have over **50% of companies confirming PFAS presence*** when for **most equipment approx. 50% of companies don't know if PFAS are used**

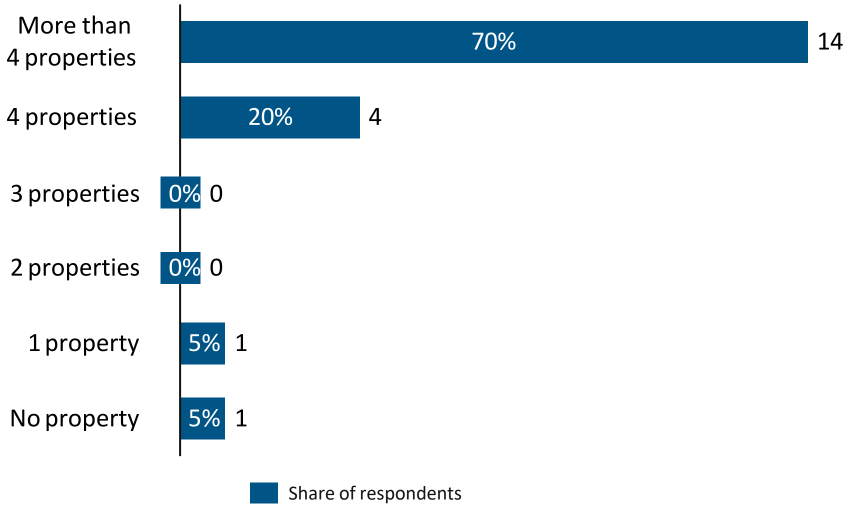
**Company having responded "Yes"*

PFAS Properties

Overall, PFAS are chosen for their unique combination of resistance to multiple factors required in refineries

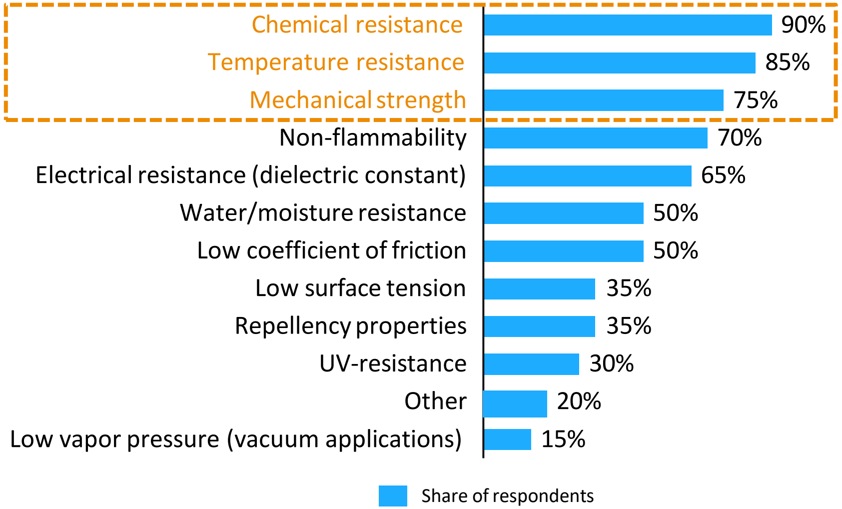
Distribution of companies by number of sought properties in PFAS

- Most companies seek a **combination of at least 4 properties** related to PFAS



Distribution of PFAS properties selected by companies

- Approx. **80% of companies** choose PFAS for their chemical, thermal and mechanical strength properties*



*The percentage was obtained by computing the ratio of the number of companies expressing interest in property X to the number of companies having responded to the survey

Refinery & Fuel Distribution Requirements

Fluoropolymers in particular show multiple resistance properties which make them the most used type of PFAS

Refinery Requirements

Chemical Properties

- **High resistance to corrosion:** Resistance to aggressive products (pH<1) such as nitric acid and chloride acid
- **Chemical inertia:** Material that degrades little over time, little product contamination (i.e., no impurities)
- **Resistance to permeation** and capacity to prevent migration of gases, liquids, and chemicals through material

Thermal Properties

- **Wide operating temperature range:** As example, PTFE has a permissible temperature range[1] of [-20 to +260] °C and can withstand high temperatures without degradation

Mechanical Properties

- **Resistance to pressure:** Some refining processes require high pressure
- **High tensile strength:** Can withstand mechanical stress and deformation
- **Low friction coefficient:** Non-stick and lubricants properties

Fuel Distribution Requirements

- **High resistance to corrosion:** Resistance to fuels with high percentage of aromatics, n-pentane etc.
- **High resistance to combustion:** Non-flammability and resistance to burning when exposed to a flame or ignition source
- **High resistance to ageing and drying** to avoid change in hardness, elongation at break and mass reduction from original values
- **Flexibility for various requirements:** In many cases, exact resistance requirements are not clearly defined (i.e., not all corrosive elements are known) and suppliers opt to use PFAS knowing of their resistance to a wide range of chemicals and conditions

 Sources: [1]Burkert's Chemical Resistance Chart, Accenture analysis of questionnaire and interviews of refining companies and suppliers, Desktop research, Accenture analysis

Exposure Risk During Operation

Risk of exposure to PFAS released during operation is low due to the containment of PFAS within equipment and the use of mitigation measures such as PPE and HSE management plans

PFAS State	Exposure to workers in refinery	Exposure to the general public	Exposure to the environment
Solid	• PFAS are confined within the equipment, there is a low exposure risk for workers	• No risk of PFAS exposure to the public if end-products (e.g., fuel) are contaminated with PFAS, as they are securely contained and transported using dedicated equipment (e.g., storage tanks, transportation facilities)	• No exposure to fluoropolymers in wastewater as they are insoluble in water
Liquid	• Personal Protective Equipment (PPE), such as coveralls, gloves and masks, is employed to safeguard the well-being of workers	• No exposure	• Risk of exposure to lubricant/grease mainly in contact with refining equipment if released accidently
Gaseous	• Industrial Hygiene best practices + specific measures guided by regional regulations substantially reduce the risk of exposure	• No exposure	• Industrial Hygiene best practices + specific measures guided by regional regulations substantially reduce the risk of exposure

 Sources: World Health Organization, Interviews of refining companies and suppliers, Desktop research, Accenture analysis

PFAS Disposal Phase

Refineries have in place measures for end-of-life management of solid, gases and liquids, fostered by local legislation

PFAS State	Disposal method in refineries	End of Life	Local legislation in place	Comments
Solid	1. Ordinary Industrial Waste (OIW) i. Metallic: Metal-specific waste bucket ii. Common: Ordinary waste bucket 2. Hazardous Industrial Waste (HIW) i. Equipment-Specific/PFAS-Specific	• Incineration • Recycling • Specific treatment	X	• Release of pollutants and ash residues into the atmosphere if incinerated
Liquid	1. Stored in special drums	For lubricants/grease: • Incineration • Recycling: regeneration to obtain a new lubricant	✓	• Regulation for the recycling of lubricants • Release of pollutants and ash residues into the atmosphere if incinerated
Gaseous	1. Gas capture with specific treatment	• Mandatory maintenance • Periodic recycling • Organized recovery	✓	• EU F-gas regulation in place • Gas treatment is subcontracted to specific companies

 Sources: World Health Organization, Interviews of refining companies and suppliers, Desktop research, Accenture analysis

Current PFAS Management Plans

- **More than half the companies in our study are adapting their environmental/emission management plans, mostly related to wastewater, to include PFAS"**

Environment/Emission Management Plan

Sources: [1]see footnote

More than half the companies are working towards **launching dedicated PFAS emission control:**

- Majority of plans are around **wastewater management**
- Plans are typically **driven by local or national regulations**
- **Limited PFAS categories are concerned**, such as refrigerant and firefighting foams

Example of Driving Regulations

European regulation on persistent organic pollutants (POPs):

- Defines **measure of around 20 PFAS types in waste**
- **When detected above limits**, companies are required to **dispose waste according to specific conditions**

Ministerial Order[2] to measure PFAS in wastewater in France:

- Companies have 3 months to submit **list of PFAS likely to be or to have been released**
- Mandates **3 consecutive monthly analysis** on all aqueous discharge points likely to present significant PFAS presence (e.g., industrial effluents, etc.)
- Defines measure of concentration of **20 types of PFAS**, fluoride levels (by Aqueous Organofluoride) and other substances

Recommendations[3] for nationwide assessment of **contamination** and **disposal** of PFAS-contaminated **water and soil**

- Defines measure of concentration of **13 types of PFAS**
- Measure and technique of **fluoride levels for aqueous & solid** samples and quantification of unknown PFAS

Sources: [1]Accenture analysis of questionnaire and Interviews of refining companies, [2]Ministerial decree of 20 June 2023 of French Ministry of Ecological Transition, [3]German BMUV Federal Ministry's Guidelines for PFAS assessment, Desktop research

Focus on Wastewater Plans

Refineries are developing wastewater management plans

Typical wastewater management actions

Routine Measurements
- Typically, monthly
- Samples collected from different areas (upstream & downstream)

Use of PFAS containing Products

Triggered by the use of products with PFAS compounds (e.g., firefighting foams)

Suspected Release
- Requires specific tests done by specialized companies

→

Reception of Samples
- Storing of samples in analytical parks to prepare them for chemical, physical and thermal analysis

→

Analysis of Samples
- Liquid chromatography (HPLC) coupled with a mass (MS) or mass-mass (MS-MS) detector

→

Reception of Response
- If PFAS are identified, refineries will define action plans to identify and mitigate PFAS source

Legend

Conducted by Refineries

Conducted by Certified organization or laboratory

PFAS typically measured

More measured PFAS

PFBA	**PFBS**
PFDA	**PFHpA**
PFHpS	**PFHxA**
PFHxS	**PFNA**
PFOA	**PFOS**
PFPeA	PFDoDA ; PFDoA
PFDS	PFHxDA
PFNS	PFODA
PFOSA	PFPeS
PFTrDA	PFTrDS
PFUnDA ; PFUnA	4:2 FTS
6 : 2 FTOH ;FHET	6:2 FTS
6:2 FTSA(H4PFOS)	8 : 2 FTOH ;FOET
8:2 FTS	C6O4
DONA ; ADONA	FHxSA
FTUCA	HFPO-DA (Gen X)
PFBSA	PFDoDS
PFDoS	PFTA
PFTeA ; PFTeDA	PFUdS
PFUnDS	PFBS
PFBA	PFHpA
PFDA	

Less measured PFAS

Sources: Accenture analysis of questionnaire and Interviews of refining companies, Ministerial decree of 20 June 2023 of French Ministry of Ecological Transition, German BMUV Federal Ministry's Guidelines for PFAS assessment, Interviews with refineries, Accenture analysis

Mature PFAS Treatment Methods

Across the mature treatments for PFAS today, incineration is the most usually adopted

Treatment category	Technology	Type of waste	Description
Separation	High-Pressure Membranes	Liquid	High-pressure membranes, such as reverse osmosis and nanofiltration, effectively remove PFAS by using pressure to force water through semipermeable membranes, selectively filtering out PFAS and other contaminants
Capture	Granular Activated Carbon (GAC)	Liquid	**High temperature technology (>700 °C)** GAC is a highly efficient adsorption technology that captures PFAS from water by attracting them to the surface of tiny carbon particles GAC has limitations but is widely used (~85% of capture installations). After use, GAC media can be reactivated and reused
	Anion Exchange Resin (AER)	Liquid	**High temperature technology (>700 °C)** AER is a treatment technology that effectively removes PFAS from water by using resin beads that exchange negatively charged PFAS ions with chloride ions in the resin, thereby capturing and removing PFAS contaminants from the water
Destruction	Incineration/Thermal oxidation*	Slurries and solid	**High temperature technology (>700 °C)** Thermal oxidation or incineration is a high-temperature treatment process that breaks down PFAS contaminants into non-hazardous byproducts through combustion, rendering them harmless and suitable for safe disposal The further application of thermal technologies will depend on the ongoing evaluation of the fate of PFAS residual waste in solids and gas phases

**most widely used treatment method, today*

 Sources: Addressing PFAS contamination (Suez, 2021), CDM Smith, EPA, Barr

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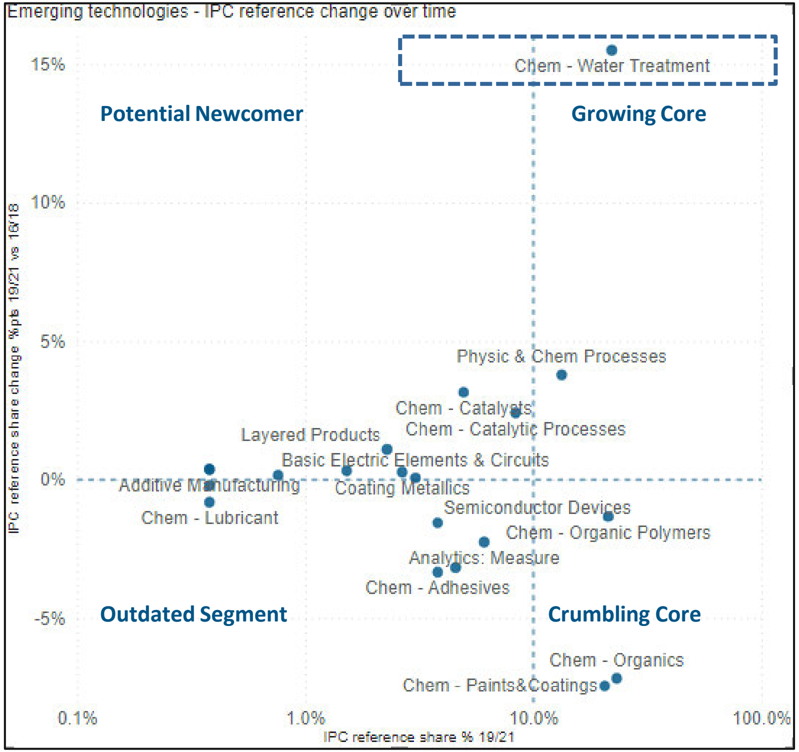
PFAS Removal – Wastewater Treatment

Water Treatment is a core focus of patents related to PFAS removal[1]



Innovation in water treatment included removing PFAS by…

- … heating concentrated stream in the presence of calcium oxide to **produce calcium fluoride**
- … **sorbing to colloidal gas aphrons**
- … using **metal organic framework (MOF)** material with improved adsorption efficiency and adsorption regeneration rate of more than 90%
- … adsorbing of PFOS by **modified hydrated iron oxide**
- … using **silicon-based mesoporous material** ass the adsorbing material
- … mixing water with **hydroxy radical quencher** and irradiating mixture with **UV light**
- … **electrochemical filtration** system that comprises filter body and carbon nanofiber membrane

[1]Patents related to PFAS removal include "PFAS" near / adjacent to keyword such as remove, recycling, replace, free of, destruct, destroy, substituting, alternative

Sources: Accenture Research based on DerwentInnovation™(Clarivate©,2023)

Key Challenges for PFAS Management Plans

However, the further adoption of PFAS management plans in refineries faces the following challenges

Current state	Unclear requirements due to legislative variety	Dependence on external capabilities	Other Drawbacks
• Companies' plans are compliant to **national and regional regulation** • Half the companies in our scope are **working towards adapting their wastewater management plans**	• Companies cannot invest in a technology and establish a process without confirmation that it will correspond to **requirements of license to operate** • Variety in legislation – including **existing local rules and wider regulatory requirements** – with potential varying requirements, create a heavier burden for companies to comply	• Refineries rely on **specialized laboratories to conduct detailed PFAS analysis** but there are **only a few able to measure concentration** of PFAS in water/soil • Companies also rely on waste contractors to **collect and select the most applicable technique** to manage PFAS waste • **Limited options for disposal** in **end-of-life management** including few incineration laboratories available	• **High GHG emissions** from high temperature elimination techniques • **Limited footprint in refineries** for installation of additional processes • Expenses would increase as **PFAS dismantling in equipment at end of life is complex and costly** • Difficulty to fulfill **the diversity of customer requests** regarding PFAS presence in products

 Sources: Accenture analysis of survey and interviews of Refining players

Potential Alternatives to PFAS

Some materials have been identified as potential technical alternatives to PFAS based on use-cases requirements

Focus on identified PFAS alternatives by categories

In refineries, most PFAS exist in solid state

Materials in Refinery Equipment

Solid State

Polymers

Plastics
- PVC
- PEEK
- PPS
- PSU

Elastomers
- NBR
- EPDM

Metals
- Stainless Steel
- Nickel Alloys
- Hastelloy
- Exotic material (Tantalum, Zirconium, Titanium)

Other Materials
- Glass
- Ceramics
- Graphite

Liquid State

Lubricants /Grease
- Powder Graphite
- Molybdenum

Foams
- Hydrocarbons
- Detergents
- Siloxanes
- Proteins

Gaseous State

Refrigerant
- Ammonia
- CO_2
- Hydrocarbons (e.g., Propane/Isobutane/Butane)

 Sources: Accenture analysis of survey and interviews of Refining players, Desktop research

Potential Substitutes by Equipment

The industry has identified some potential substitutes for the following PFAS equipment for certain use cases (1/2)

PFAS and alternatives identified in gaskets and piping equipment*

Equipment	Illustration	PFAS	Alternative	Alternatives' limits
Gaskets		PCTFE, PTFE	Metallic (e.g., nickel) gaskets	Not suitable for excessive tightening torque
		PTFE	Graphite or Mica (silicate) gaskets	Possible contamination issues
			EPDM, NBR**	Lower Chemical resistance (less safety in chemical plants, higher emissions)
			Organic, mineral fibre gaskets	Sealing level reduced by x(100-1000), shorter life span
Piping	 	PTFE, PFA, PVDF	TPM (Thermoplastics materials) (HD-PE, PP, U-PVC, C-PVC), SVR	Lower upper temperature limit and lower chemical resistance
			FRP (Fiber Reinforced Plastic)	Lower upper temperature limit and lower chemical resistance
			Hastelloy	Material heavy weight can induce changes in structural design of supports and civil construction
			Glass lining	Mechanical fragility
			Enamelled Steel, Nickel, Titanium	Mounting constraints, lower resistance to chemical reaction

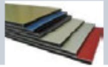
**The list of PFAS and alternatives identified is not exhaustive. **EPDM and NBR have insufficient chemical resistance for chlorine, sulfuric acid and nitric acid. In addition, NBR has insufficient chemical resistance for ammonia*

Sources: Unique Polymers (PTFE Sheet Division), SGL Carbon, Debrunner Acifer, Interviews of refining companies and suppliers, Desktop research, Accenture analysis

Potential Substitutes by Equipment

The industry has identified some potential substitutes for the following PFAS equipment for certain use cases (2/2)

PFAS and alternatives identified in valves, refrigerant gas and coating

Equipment	Illustration	PFAS	Alternative	Alternatives' limits
Valves Bodies (large components)		PCTFE	Vespel	No specific limits identified except high cost
		PTFE	Enamelled steel valves, Hastelloy, Noble metal grade	Higher friction coefficient and lower sealing capacities, low availability
Valves – Washers** (intermediate components)		PTFE	Polyethylene	Lower upper temperature limit
Valves - Gaskets		FKM, PTFE	EPDM	Lower chemical resistance, not suitable for all application
Refrigerant		Refrigerant	Ammonia	Higher risks due to toxicity, impact on refrigerant auxiliary system design and on energy consumption
			CO2	Much higher-pressure requirements for cooling, impact on refrigerant auxiliary system design and on energy consumption, narrower applicable temperature range, mainly applied in commercial refrigeration
			Hydrocarbons (e.g., Propane/Isobutane/Butane)	Highly flammable gas, impact on refrigerant auxiliary system design and on energy consumption, high GHG impact, mainly applied in commercial refrigeration, temperature of use must not go beyond certain levels***
Coating		PTFE, PVDF	PPV, Epoxy, Polyester, Melamine	Lower UV durability, corrosion resistance (e.g., for seaside applications) and resistance regarding high temperatures

*The list of PFAS and alternatives identified is not exhaustive. **Parts ensuring friction and sliding. ***The temperature difference between desired cooling temperature and outside temperature should not be too great, this is due to the specific properties of propane as a refrigerant.

Sources: Ferguson Industrial, Alundong, BuyBestAc, Interviews of chemical refining and suppliers, Desktop research, Accenture analysis

Drawbacks of PFAS Alternatives

Aside the material performance, alternative materials have other drawbacks that would make substitution challenging

Safety of the future installations

- As they are not widespread use material, need to **demonstrate performance** in the long term of existing alternatives. Some known reduced performances: sealing, emission
- International well established **design standards for PFAS-based equipment** in the industry will have to be updated, such as:
  - **ISO**
  - **API**
  - **ASTM**

Alternatives development

- **Long process of developing substitutes** potentially lasting many years, requiring:
  - R&D
  - Testing
  - Approval from certifying bodies and clients
- Long guarantee of new products required by clients (typically around 10 years)

Properties of alternative materials

- To satisfy the desired properties for equipment the alternative materials to PFAS will also be persistent materials, which will could bring **similar challenges to PFAS** long life

Production asset and supply chain adaptation

- Production asset debottlenecking:
  - **New sites to be built** from scratch for some materials and equipment (e.g., high nickel alloy or ceramic piping used in niche applications)
  - Important **brownfield modifications** on existing installations (e.g., gaskets)
- **Challenges in procuring** potential alternative material (e.g., tantalum)

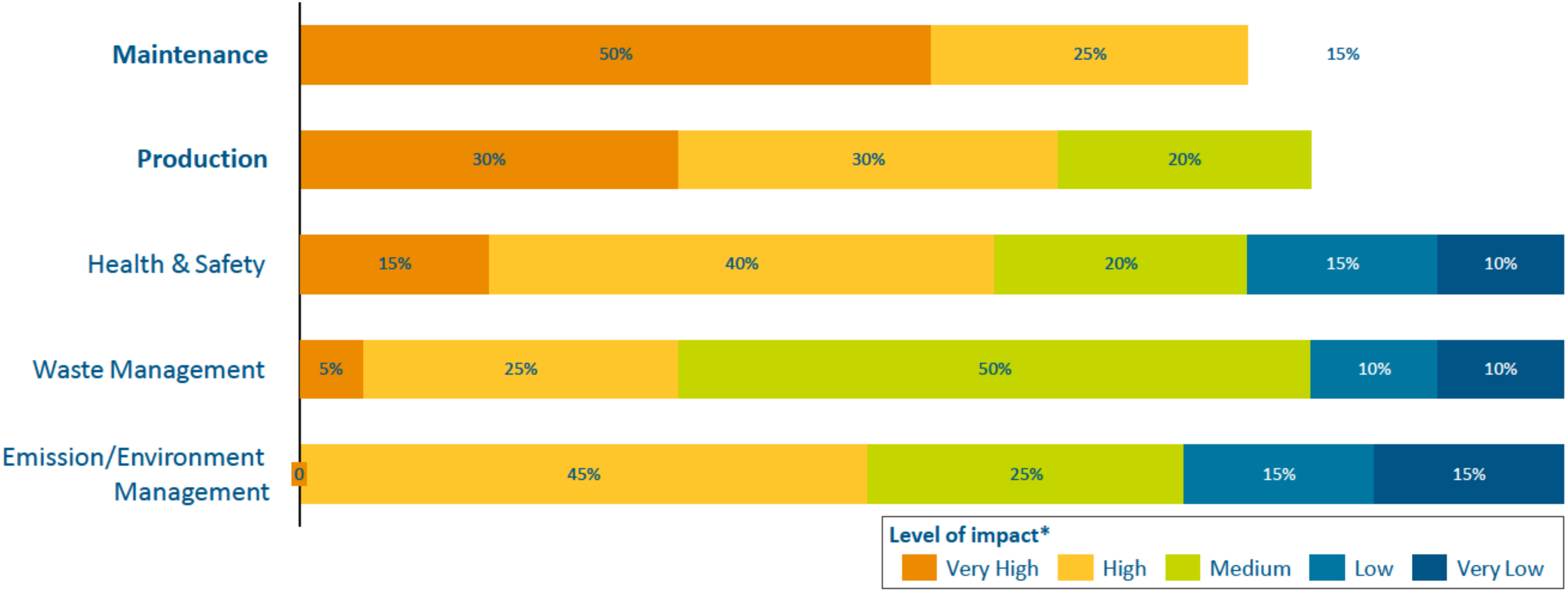
PFAS presence in alternative materials/equipment

- **PFAS potentially used** to improve performance of alternatives:
  - Some alternatives coated with thin layer of PFAS
  - PFAS surfactants used in the production of non-PFAS polymers identified as theoretical substitutes to PFAS polymers

 Sources: Interviews of Refining companies and suppliers, Accenture analysis

Impacts by Dimension

Refineries indicate higher impacts of the PFAS ban to be on maintenance, followed by production, health and safety



**The percentage was obtained by computing the ratio of the number of companies expressing interest in Level of impact X to the total number of respondents*

Sources: Accenture analysis of questionnaire

Impacts on the Value Chain

A ban on PFAS today would impact all the energy value chain, risking supply and access to fuels in Europe

Crude offloading	Refinery		Fuel Distribution
Risk of interruption of supply of crude oil to refineries	Risk of interruption of fuels and refined products supply in EU	Site closures leading to reduction of current production volume	Risk of supply interruption for fuel products up to end consumer
Reduction of reliability, availability and safety for each equipment	Increase in maintenance cycles resulting in higher costs	Loss of jobs or reduced job stability	Higher risk of end-user health & safety incidents (e.g., leakages)
Less performant equipment due to unmatching properties	Safety risk for personnel and equipment	Increase in CAPEX and OPEX affecting price of end-products	Unavailability of repair parts
	Hindered development of sustainable fuels	Higher risk of leakages and GHG emissions	

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Key Conclusions

The results of the industry survey, interviews, advanced analytics and patent analysis lead to the following conclusions for the use of PFAS in Refineries and Fuel Distribution

Despite **challenges in collecting information on the use of PFAS** from suppliers and equipment documentation, we have conducted a **detailed inventory of the use of PFAS in Refining and Fuel Distribution Equipment**

PFAS (mostly fluoropolymers) have been detected in a **large share of refineries' equipment**, especially in **ever-present components** such as joints, valves, pumps, etc.

There is a **growing effort** in the industry to develop **dedicated environmental management plans for PFAS**, especially related to managing **emissions of PFAS in wastewater**

For a significant share of industrial equipment, **alternatives to PFAS do no exist** to date. For most of the uses identified, potential substitutes **lack combined properties** needed for processes and safety requirements

The supply chain for potential alternatives does not have sufficient maturity today for all the refining and fuel distribution industry, with little to no capacity for the volumes required to update the complete value chain

A PFAS ban in refinery and Fuel Distribution equipment would have **severe impacts across the energy value chain, putting at risk fuel supply in Europe**

 Sources: Interviews of refining companies and suppliers, Industry survey. Desktop research, Accenture analysis