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Per- and Polyfluoroalkyl Substances and Alternatives in Coatings, Paints and Varnishes (CPVs)

Report on the Commercial Availability and Current Uses

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Fax: (33-1) 44 30 61 80

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List of Abbreviations

C-F	Carbon-fluorine
ECTFE	Ethylene chlorotrifluoroethylene
ETFE	Ethylene tetrafluoroethylene
FEP	Fluorinated ethylene propylene
FEVE	Fluoroethylene vinyl ether
FP	Fluoropolymer
FSA	Fluorosurfactant
HDPE	High density polyethylene
LC	Long-chain
PCTFE	Polychlorotrifluoroethylene
PA	Polyamides
PET	Polyethylene terephthalate
PFA	Perfluoroalkoxy
PFAS	Polyfluoroalkyl substances
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulphonate
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidene fluoride
PS	Polyester
PU	Polyurethane
PBSF	Perfluoro-1-butanesulfonyl fluoride
PV	Photovoltaic
PVC	Polyvinyl chloride
SC	Short-chain
UV	Ultra-violet

Executive summary

This report examines the commercial availability and current uses of per- and polyfluoroalkyl substances (PFASs) and non-PFAS alternatives in coatings, paints and varnishes (CPVs) and was developed within the framework of the OECD/UNEP Global PFC Group.

The study considered publicly available information from worldwide sources, including those provided by members of the OECD/UNEP Global PFC Group. The information was supplemented by discussions with stakeholders and additional written contributions.

To assess the uses of PFAS and their alternatives in CPVs it has been necessary to go into sufficient detail to understand the function of PFAS in specific applications, rather than generalising at the sector or market segment level. From the wide range of applications that comprise the CPV sector, three applications have been examined more closely: coatings for cables and wiring, the front and backsheets of solar panels and household and architectural paints. The findings are as follows:

- The majority of PFAS identified in these three applications are fluoropolymers (FPs). An exception is that short-chain PFAS, which are fluorosurfactants, are used in household paints and function as levelling, wetting and anti-blocking agents[1].
- In coatings for cables and wiring, FPs are the choice of material if a high performance is required over a wide range of parameters, including fire safety. However, the majority of cable and wire applications do not require such high performance, hence alternative materials such as polyurethane (PU), polyethylene and polyvinylchloride are used instead. There is a significant cost differential between using FPs or alternatives, and FPs are chosen only as a last resort where performance requirements necessitate their use. FPs have a very small percentage of the overall market share, less than 10% and alternatives have more than 90% of the market share.
- Some FPs perform well in front and backsheet materials for solar panels and some continue doing so for 10 years plus. Other FPs perform well on key parameters such as UV light and corrosion resistance, are lightweight and flexible, but tend to fail over longer periods. Alternatives have been identified such as glass, polyester, polyamides and polyethylene terephthalate, but the available data indicate these perform less well than FPs. Publicly available market penetration data has not been identified.
- FP-based paints are available for use on bridges and from the evidence reviewed here, their weatherability and durability performance is superior to that of alternatives such as PU. FP-based paints are significantly more expensive at the outset, although after 30 years PU coatings are more expensive than PFAS coatings

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[1] Wetting is the ability of a paint to maintain contact with a solid surface i.e. not form beads; levelling is the ability of a paint to form a smooth surface, rather than cracking resulting in an orange peel effect; anti-blocking is prevention of sticking between painted surfaces.

because they require more frequent recoating, with associated labour, stoppage and material costs. In some cases, national specifications or legislative requirements regulate the use of both PFAS and alternatives for bridge protection paints. The overall market penetration for FPs in architectural protective coatings is very low, approximately 1% compared to alternatives at 99%.

Based upon this review, the report suggests a number of policy recommendations and areas that may be considered for further work. These have been divided into those aimed at international organisations/national governments and those aimed at industry.

1. Background

1.1. Aim of the study

PFASs are synthetic substances that are widely used in numerous technologies, industrial processes and everyday applications. Since the discovery of polytetrafluoroethylene (PTFE) in 1938, PFASs, both polymeric and non-polymeric, have been used extensively in various industries worldwide, due to factors such as dielectrical properties, resistance to heat and chemical agents, anti-weathering, anti-UV (ultraviolet) fading and surfactant properties. The highly stable carbon-fluorine bond and the unique physicochemical properties of PFASs make these substances valuable ingredients for products with high versatility, strength, resilience and durability.

Since 2002, there has been a trend amongst global manufacturers to replace so-called ‘long-chain’ (LC) PFASs, their salts and their potential precursors with chemicals containing shorter perfluoroalkyl chains or with non-perfluoroalkyl products. This trend is largely driven by concerns related to the properties of certain LC PFASs with respect to health and the environment.

The establishment of the OECD/UNEP Global PFC Group was noted by the Strategic Approach to International Chemicals Management Framework (SAICM) in 2012[2] and requested to facilitate the exchange of information on PFASs and to support a global transition towards safer alternatives. It brings together experts from OECD member and non-member countries in academia, governments, industry and NGOs as well as representatives from other international organisations.

The work of the PFC Group was established in response to the International Conference on Chemicals Management (ICCM 2) 2009 Resolution II/5[3], calling upon intergovernmental organisations, governments and other stakeholders to “consider the development, facilitation and promotion in an open, transparent and inclusive manner of national and international stewardship programmes and regulatory approaches to reduce emissions and the content of relevant perfluorinated chemicals of concern in products and to work toward global elimination, where appropriate and technically feasible”. One of the key work streams of the group is to gather information on alternatives to PFASs to understand what they are, what they are used for, their market penetration, feasibility, effectiveness and cost.

1.2. Scope of the study

For the purposes of this report, PFASs are defined as fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it), i.e. any chemical with at least a perfluorinated methyl group (–CF3) or a perfluorinated methylene group (–CF2–) is a PFAS. This definition comes from the OECD report “Reconciling Terminology of the Universe of Per- and Polyfluoroalkyl Substances: Recommendations and Practical Guidance” (OECD, 2021[1]). This is therefore a wider

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[2] SAICM Resolution III/3 (ICCM 3, September 2012)

[3] Resolution II/5 (ICCM2, May 2009)

definition than that which has been previously used for CPVs and includes fluoropolymers (FPs).

The terms LC and short-chain (SC) PFASs are set out in the OECD Synthesis Paper (OECD, 2013[2]) as follows: non-polymeric PFASs consist of a fully (per-) or partly (poly-) fluorinated carbon chain connected to different functional groups. Based on the length of the fluorinated carbon chain, SC and LC PFASs can be distinguished. LC refers to:

- Perfluorocarboxylic acids (PFCAs) with carbon chain lengths C8 and higher (i.e. with 7 or more perfluorinated carbon atoms), including perfluorooctanoic acid (PFOA);
- Perfluoroalkane sulfonic acids (PFSAs) with carbon chain lengths C6 and higher (i.e. with 6 or more perfluorinated carbons), including perfluorohexane sulfonic acid (PFHxS) and perfluorooctane sulfonate (PFOS); and
- Precursors of these substances that may be produced or present in products.

SC PFASs are PFCAs with carbon chain lengths of less than C8 and PFSAs with carbon chain lengths of less than C6.

As this study has progressed it has become clear that, with the exception of fluorosurfactants (FSAs) used in paints and varnishes, the majority of PFAS that are used in CPVs are FPs implying the split between LC and SC PFASs is less relevant in this sector and is more appropriate when considering telomeric[4] PFASs (USEPA, 2011[3]). The commercially available FSAs identified in this study are all SC PFASs.

For the purposes of this study an alternative refers to substances and mixtures that do not meet the definition of a PFAS, which in practice are non-fluorinated substances/mixtures. Information on non-chemical alternatives has not been identified during the course of this study and one of the recommendations in section 10 is that such data are further researched.

Geographically, this report focuses on data from countries and regions that are members of the OECD.

Distinguishing between CPVs in this report has proved to be challenging. At the same time this distinction has been important to assist in defining the scope of the report and to provide its structure. It was initially defined with reference to two aspects: 1) the paints and coatings product category described in Table 20 of the OECD document: ‘Internationally Harmonised Functional, Product and Article Use Categories’ (OECD, 2017[4]); and 2) the preliminary assessment of the scope of work prior to the initiation of the project. Some categories of coatings are excluded from the scope of this report e.g. coatings used in food and beverage packaging. Generic terms such as ‘industrial coatings’ have been avoided to allow a disaggregation of the applications covered.

As a result of the above, the CPV uses that are within the scope and structure of this report are shown in Table 2.1 and these broad uses are subdivided into applications and use examples. However, the limitations of this approach are acknowledged and have become

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[4] For example, the USEPA defines fluorotelomers as follows: fluorotelomers means the products of telomerization, which is the reaction of a telogen (such as pentafluoroethyl iodide) with an ethylenic compound(such as tetrafluoroethylene) to form low molecular weight polymeric compounds, which contain an array of saturated carbon atoms covalently bonded to each other (C-C bonds) and to fluorine atoms (C-F bonds). This array is predominantly a straight chain, and depending on the telogen used produces a compound having an even number of carbon atoms. However, the carbon chain length of the fluorotelomer varies widely. The perfluoroalkyl groups formed by this process are usually, but do not have to be, connected to the polymer through a functionalized ethylene group as indicated by the following structural diagram: (Rf-CH2CH2-Anything).

apparent as the preparation of the report has progressed. For example, the distinction between CPVs is obscured because in practice a coating is a generic term which refers to any type of paint, stain, lacquer, varnish, etc, whereas a paint is a pigmented coating material and a varnish is a clear coating material (OECD, 2014[5]). Nevertheless, the categorisation provided in (OECD, 2017[4]) has been retained to provide a structure to the report.

Compared with the previous report in this series, ‘PFASs and alternatives in food packaging (paper and paperboard): report on the commercial availability and current uses’ (OECD, 2020[6]), the current project is more complex, covering a wide range of industry sectors and applications. As a consequence, it has been necessary to adjust the structure of this report, seek an optimal way to present the diverse information and to focus on selected key areas. For example, it has not been possible to carry out an efficacy and market analysis for all of the CPV uses that have been identified here. Instead, specific uses have been chosen to go into further detail and case examples have been developed for these.

Specifically, the following uses have been focused on for further analysis. PFASs and their alternatives in:

- Coatings for cables and wiring;
- The front and backsheets of solar panels;
- Household and architectural paints.

The report is divided as follows: sections 2 and 3 are overviews of the uses and functions of PFASs and their alternatives in CPVs. These sections are not intended to provide a comparison of the performance of PFASs versus alternatives, although details of this have been provided where readily available.

Sections 4, 5 and 6 examine in more detail the uses and functions of PFASs and their alternatives for CPVs, respectively. Section 7 compares the efficacy of alternatives with that of PFASs and then the relative market penetration is described in section 8. The observed status of the shift to alternatives and its sustainability are covered in section 9 and policy recommendations and areas for further work in section 10.

As the title of the report indicates, generally only substances and mixtures that are commercially available are considered in this report. However, where information on developing materials that appear to be relevant have been identified it has been included. It is not claimed the coverage of this report is a comprehensive survey of what is commercially available in the OECD regions. Instead the report summarises the findings of the research carried out for this project and the subsequent analysis. There are known gaps in the material that is presented here, including the absence of: comprehensive market data, specific cost data and various other data, all of which has resulted in some deficiencies in the analyses that have been possible. This is described in section 11.

It is outside of the scope of this study to carry out a detailed regulatory analysis for the wide range of materials and uses covered by this study. Such an analysis is however recommended to check if there are particular regulatory barriers for the substitution from PFASs to alternatives.

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

1.3. Methodology

The study is based on a detailed literature review which provide one component of the information presented in this report. To supplement this, members of the Global PFC Group were invited to complete a template to provide information to support the development of the report. In addition, the study was complemented by a targeted stakeholder survey (STO, 2020 - 21) carried out by the drafting consultancy, which consisted of interviews and written exchanges with stakeholders on the basis of a questionnaire that was developed for this project.

2. Overview of the Commercial Availability and Market for PFASs and Alternatives in Coatings, Paints and Varnishes

Both FPs and SC PFAS are used in coatings, paints and varnishes but they carry out different functions. Typically FPs are added to CPVs to provide resistance to corrosion, weathering, abrasion and scratching, UV and overall provide durability. FPs used include polytetrafluoroethylene (PTFE), polyvinylidene difluoride (PVDF) and, to a lesser degree, fluoroethylene vinyl ether (FEVE). SC PFAS that are used generally act as levelling and wetting agents, have anti-blocking properties or confer oil and water repellence. SC PFASs used include perfluoroalkane sulphonic acids (PFSAs) with carbon chain lengths of 5 and lower, as well as pefluorocarboxylic acids (PFCAs) with carbon length chains of 7 and lower, C4-fluorinated polyethers, silicone polymers mixed with FPs and substances based on perfluorobutane sulphonic acid (PFBS).

A single identified use of perfluorooctanoic acid (PFOA), a LC PFAS was identified. To note, however, since 2002 there has been a trend amongst global manufacturers to replace LC PFASs, their salts and their potential precursors with chemicals containing shorter perfluoroalkyl chains or with non-perfluoroalkyl products. This trend is largely driven by concerns related to the properties of certain LC PFASs with respect to health and the environment, and consequent regulatory decision-making. For example, the Stockholm Convention aims at regulating persistent organic pollutants (POPs) globally (Stockholm Convention, 2021[7]).

Precursors to regulated POPs such as some fluorotelomer alcohols have been restricted in the EU as ‘related substances’ and in Canada as precursors[5]; however, other fluorotelomer alcohols are still being used, as described in further sections of this report. A summary of the PFASs and their alternatives used in CPVs is provided in Annex A.

PFASs identified in this study that are used in CPVs can be further divided into specific uses. These are summarised in Table 2.1.

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[5] For example, precursors of PFOA.

Table 2.1. Uses of PFASs in Coatings, Paints and Varnishes

	OECD Product Categories	Applications	Use examples	Fluoropolymers	Other PFASs (Non-polymeric PFAS)
Coatings	Powder coatings	Architectural	Exterior surfaces of bridges, buildings	PTFE, PVDF, ECTFE, FEVE, FEP	None identified
		Chemical industry	Lining of reaction vessels, metal surface coating		None identified
	Radiation curable coatings	Electronics	Phone and tablet screens	PTFE, PVDF	Perfluoropoly-ether and polyurethane blend
	Other coatings	Cable and wiring	Commercial indoor local area network (LAN) cables, cables in aircraft	PTFE, FEP, PFAECTFE and ETFE	None identified
		Anti-reflective coatings	Coating for semi-conductors	FP with a short fluoroalkyl side chain which is less than C4	PFOA, PFOS*
		Ant-graffiti coatings	Walls, public transport, bridges	PTFE has been used	None identified
		Renewable Energy	Solar panels, wind turbine blades	FEP, ETFE, FEVE, ECTFE	Formulations of fluoro- sulphonamides
Paints	Aerosol spray paints	Automotive paints	Car coatings	PTFE	None identified
		Architectural, Chemical industry	Architecture: bridges, construction Chemical: metal surface protection	PVDF, PTFE, FEVE	None identified
	Water-based paints	Architectural, Chemical industry, Domestic	Architecture: bridges, construction Chemical: lining of vessels, metal surface protection Domestic: doors, walls	PVDF, FEVE, ECTFE, PTFE, FEP	C4-PFBS and C4-fluorinated ethers**, C6-based PFAS
	Solvent-based paints				
Varnishes	Floor and surface finishes/ lacquers and stains	Domestic, Construction Printing	Protection for stone and tiles, work surfaces, floor polishes, table-top waxes, night-reflective road, pavement and traffic signs and reflective sheeting, printing inks, wood and cellulose shrinkage/swelling protectors	None identified	C4-based PFAS e.g. PBSF, fluorinated polyethers**, short-chain PFAS mixtures with silicone†. None identified for printing inks. Wood protectors: fluorinated hydrocarbons, fluorinated acrylic or methacrylic acid esters, fluoroalkane sulfonic acids and salts of fluorinated carboxylic acids

Key to table: *Still used in in semiconductor manufacturing and very limited derogations exist for PFOA in the Stockholm Convention (Stockholm Convention on POPs, 2017). PFOS is mainly no longer used in semiconductor manufacturing. ** For example, methyl nonafluorobutyl ether and methyl nonafluoroisobutyl ether and Polyfox. † For example Silres 38. C4 and C6 refer to the number of carbon atoms in the molecule, ECTFE = ethylene chlorotrifluoroethylene, ETFE = ethylene tetrafluoroethylene, FEP = fluorinated ethylene propylene, FEVE = fluoroethylene vinyl ether, FP = fluoropolymer, PFA = perfluoroalkoxy, PFOA = perfluorooctanoic acid, PFOS = perfluorooctane sulphonate, PTFE = polytetrafluoroethylene, PVDF = polyvinylidene fluoride, PS = polyester, PU = polyurethane, PBSF = perfluoro-1-butanesulfonyl fluoride, PVC – polyvinyl chloride.

2.1. The Market for PFASs and Alternatives in Coatings

2.1.1. PFASs used in Coatings

Coatings in which PFASs are used can be divided into five broad types: powder coatings, radiation curable coatings, anti-reflective coatings, cable and wiring coatings and coatings used in the energy sector such as solar panel coatings. Gas phase fluorination of coatings was also identified. This technique is used for fluorinating high density polyethylene (HDPE) to confer resistance from chemical attack when used in e.g. containers for pesticides (US EPA, 2021[8]) and liners for tanks in the chemical industry (Packaging Guruji, 2020[9]).

Powder coatings are FPs in powder form that can be applied either through spraying, or through dipping the object to be coated and then curing to form a hard coating for example by using radiation such as UV light, visible light or low energy electrons. These are used in the chemical industry including on chemical reactors and tanks, on metal surfaces such as aluminium and steel and powder coatings can also be used for architectural applications e.g. on bridges and buildings. These coatings usually consist of PVDF or ethylene chlorotrifluoroethylene (ECTFE).

Radiation curable coatings can consist of PVDF and can be used in electronics for example on the screens of phones, tablets and monitors, or in electronic circuit boards. PFAS coatings are used for cable and wiring for their corrosion prevention, these are mainly based on PTFE but can consist of other FPs as well, such as fluorinated ethylene propylene (FEP). These coatings can be powder based coatings.

PTFE powder is considered by industry as a low molecular weight material[6] that is chain scissioned[7] by gamma radiation to form a material that can be ground into powder. PFOA used to be used as a catalyst for this process, but in the last 10 years gamma radiation has been used. Gamma radiation has been found to result in the formation of eight carbon chain length (C8) telomers as a by-product. Therefore new scissioning processes are being examined e.g. thermal methods. In addition, there are alternative processing methods developed which reduce or eliminate the formation of PFOA during PTFE micro-powder manufacturing process through new technologies employing direct polymerisation and thermo-mechanical reduction (GLS, 2021[10]). PTFE is poorly water soluble and has a high melting point (327°C) making its processing difficult and expensive (Inofluon, 2021[11]). Even when molten, PTFE does not flow due to its exceedingly high melt-viscosity meaning processes such as extrusion are not as straightforward as with some other FPs.

Reports in the literature indicate LC-PFASs such as PFOA may still be used in manufacturing anti-reflective coatings for semi-conductors, which make up electronic devices[8]. Conversely, the semiconductor industry globally has announced (WSC, 2017[12]) it has successfully completed the phase-out of PFOS and in its 2018 review the Stockholm Convention concludes that PFOS has been mostly eliminated from this use already with the availability of alternative substances/techniques likely to lead to the remaining uses being phased out in the foreseeable future (Stockholm Convention, 2018[13])

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[6] Compared to other fluoropolymers because it is often used in a monomeric form that has been cut into smaller chain lengths.

[7] Chain scission is a term used in polymer chemistry describing the degradation of a polymer main chain.

[8] In the EU the use of PFOA is permitted for semiconductor manufacturing until 4 July 2025. To note that some members of US Semiconductor Industry Association (SIA) have already switched away from PFOA (US SIA, 2017[151]).

Alternatives are available such as ‘AZ Aquatar 8’ which is a FP with a short fluoroalkyl side chain, with less than four carbons (C4) (Microchemicals, 2007[14]). These semi-conductors, for example memory chips, are made up of layers created on a silicon wafer during a process called photolithography. During this process light can be reflected within these layers creating interference patterns. Anti-reflective coatings made of PFASs are usually top anti-reflective coatings and work by controlling the reflection of light by destructive interference, rather than changing the reflectivity of the silicon wafer (Brewer Science, 2020[15]).

Some coatings for cable and wiring are made from FPs. FPs are used for their thermal and flame resistance/retardancy properties, ability to repel moisture (hydrophobic), their outstanding dielectric (insulation) properties, high-end use temperature rating and resistance to corrosion for example from chemicals. Examples of FP used include PTFE, FEP (a copolymer of hexafluoropropylene and tetrafluoroethylene), ECTFE and perfluoroalkoxy (PFA).

FPs are used in solar panel coatings as frontsheets or backsheets, to increase the amount of sunlight reaching the solar panels or protect the photovoltaic cells that make up the solar panels, from dirt, moisture and UV rays. FPs such as FEP are used in the energy sector, for frontsheet solar panel coatings (Teflon, 2020[16]). Additionally ethylene tetrafluoroethylene (ETFE) and fluoroethylene vinyl ether (FEVE) have also been used (STO, 2020 - 21[17]).

PFASs have also been used in wind blade coatings, for protection from environmental damage. Their moisture resistant properties as well as corrosion resistance, makes them useful in this application. Specifically, fluorinated sulphonamides have been used in formulations for these coatings (STO, 2020 - 21[17]).

2.1.2. Non-fluorinated Alternatives Used in Coatings

A number of non-fluorinated alternatives to powder coatings are commercially available and some of these are marketed as PTFE-free (Micro Powders, 2021c[18]). These include HDPE-based products that contain nano ceramic (Micro Powders, 2021a[19]) and nano aluminium oxide (Micro Powders, 2021b[20]), polyurethane (PU), polyvinyl chloride (PVC), polyolefin[9] and epoxy powders. These PTFE-free alternatives have been described by sellers of these and PTFE to be cheaper and perform as well, or better than PTFE with regards to surface durability, scratch and abrasion resistance and lubricity[10] parameters (STO, 2020 - 21[17]). However, PTFE has a performance advantage at higher temperatures e.g. >200°C. These alternatives can be used in powder coatings for architectural applications such as on buildings, in the chemical industry to coat chemical vessels and in cable and wiring coatings.

Silica-based coatings such as silicone polymers can be used as alternatives to radiation curable coatings in electronics as they have similar properties and therefore can carry out the same function as PFASs used in this application. In electronics, however, FPs can be applied in a thinner layer compared to non-PFAS alternatives - FPs are typically applied in a coating thickness of 1-2 µm (nano coating), whereas alternatives such as acrylic, PU and silicone are applied at >25 µm. However, non-PFAS alternatives are seen as less effective as coatings in the electronics segment because they do not have the same water repellence

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[9] A polyolefin is a type of polymer produced from a simple olefin (also called an alkene with the general formula CnH2n) as a monomer. For example, polyethylene is the polyolefin produced by polymerizing the olefin ethylene. Polypropylene is another common polyolefin which is made from the olefin propylene.

[10] Lubricity is the measure of the reduction in friction and or wear by a lubricant and useful for example in applications where containers are required to not adhere to each other and for printing inks (STO, 2020 - 21[17]).

that FPs have, hence wetting occurs; components such as connectors and switches need masking from the non-PFAS insulating coating; the application process for alternatives is not as simple as for FPs; and the drying time can be longer (SCH India, 2020[21]).

In anti-reflective coatings used in the semi-conductor industry, it has been reported that non-FP-based alternatives are not yet available (Stockholm Convention on POPs, 2017[22]).

In solar panel frontsheet and backsheet coatings, alternatives such as PS, polyamides (PAs) and polyethylene terephthalate (PET) have been identified. However, it has been suggested that FP coatings in this application are more durable due to being less susceptible to degradation from UV and moisture and therefore most cost efficient in the long term (STO, 2020 - 21[17]).

For wind turbine blade coatings, epoxy and PU coatings have been identified as alternatives to PFAS formulated coatings. Two-component PU-based coatings, formulated with fluorinated sulphonamides have been identified that are used to protect wind turbine blades from environmental damage, such as from sand or rain erosion, from bird fouling, to provide a self-cleaning function and to prevent moisture in the air from affecting the curing process during application of the coating outdoors. Damage to wind turbine blades can reduce their efficiency by as much as 20% (STO, 2020 - 21[17]). An example of coatings used on wind turbine blades is 3M's Wind Blade Protection Coating W4600' (3M, 2014[23]).

2.2. The Market for PFASs and Alternatives in Paints

2.2.1. PFASs Used in Paints

In paints, FPs as well as SC PFASs are used.

The FPs that are used are additives that are binders in paints because they confer protective properties on the paints such as durability, weatherability and resistance to corrosion and dirt pick up as well as acting as a barrier to UV deterioration and providing a soft feel 'texturiser' for some applications. FPs commonly used in paints are primarily based on PVDF but can also be PTFE, FEP, ETFE and FEVE (ACA, 2021[24]). Typically, FP concentrations e.g. PTFE are < 3% of the wet (or formulated paint for powder coatings) (STO, 2020 - 21[17]).

FPs are used in aerosol spray paints, water-based paints or solvent-based paints primarily used for architectural purposes, in bridges, buildings and commercial steelwork. Steel and aluminium metal coils coated with FP are used in these applications and are formed into exterior building panels and roofs and can have an operational lifetime greater than 30 years (STO, 2020 - 21[17]) (see chapter 7).

FPs can additionally be used in roof coatings to lower the temperature of roofs and therefore, buildings, leading to energy savings (Arkema, 2020[25]). This is described as a 'cool roof' capability and works because PVDF for example is transparent and a white pigment under this reflects UV rays to the atmosphere. FPs such as PTFE are also used in automotive paints, usually as aerosol spray paints.

FP-based paints can be also used in the chemical industry, similar to powder coatings. Here they are used for primarily their corrosion resistance, as they are stable to a wide variety of chemicals they are well suited in applications where they might come into contact with harsh reagents or solvents. They are also used for their high temperature resistance and flame resistance. Their ability to withstand high temperatures is useful in the chemical industry where reaction tanks and vessels are likely to be subject to high temperatures. FPs also have good mechanical properties, in terms of being resistant to wear and tear, which is well suited for this application.

Figure 2.1. Fluoropolymer Paint Application in Bridges

Source: Tokyo Gate Bridge by Zengame is used royalty-free from CC BY 2.0.

SC PFASs are used in some paints as fluorosurfactants (FSAs) at low concentrations (<0.1%) (STO, 2020 - 21[17]). FSAs in paints and varnishes lower their surface tension and therefore improve wetting (the ability of a paint to maintain contact with a solid surface i.e. not form beads), levelling (the ability of a paint to form a smooth surface, rather than crack resulting in an orange peel effect), anti-blocking (i.e. reduce tackiness of painted surfaces) and oil repellence properties. SC PFASs used as FSAs include C4-fluorinated polyethers such as methyl nonafluorobutyl ether and methyl nonafluoroisobutyl ether, both of which confer levelling and wetting properties, as well as good adhesion, which refers to the ability of the paint to stick to the surface (STO, 2020 - 21[17]).

Substances based on PFBS can also be used as fluorosurfactants in paints which are polymeric anionic fluorinated surfactants, based on perfluorobutane sulfonates (Miljøprojekt, 2005[26]). Generally, these have been reported to be able to reduce surface tension to a much lower level than alternatives such as hydrocarbon and silicone surfactants (see non-fluorinated alternatives below) (3M, 2016[27]). Other fluorotelomer based products have been used for the same purposes in aqueous and solvent-based paints. For example, C6-based substances have been used as fluorosurfactants such as ‘Hexafor’ by Maflon (Maflon, 2020[28]). The main function of C-6 telomer based fluorosurfactants (they can be either polymer or small molecule based) are to provide anti-blocking properties, oil repellence and early dirt pick-up resistance. Due to these functions they are used in industrial maintenance and architectural latex-based paints.

Silicone polymers made of siloxane and silane have also been used in combination with FPs in solvent-based paint mixtures for their low surface tension.

2.2.2. Non-fluorinated Alternatives Used in Paints

Non-PFAS alternatives exist for fluorosurfactants such as silicone-based coatings (Miljøprojekt, 2005[26]) (Elkem, 2020[29]) without the use of FPs and hydrocarbons (3M, 2016[27]). Most non-fluorinated surfactants alone have to be used at higher rates than FSAs in paints for the similar functions (STO, 2020 - 21[17]). Some stakeholders have commented that they are also less effective in certain respects even at higher use rate e.g. oil repellence and dirt pickup resistance (STO, 2020 - 21[17]). Stakeholders have also reported that the use of non-fluorinated surfactants in paints and together with FSAs is for lowering the surface tension of the paint and emulsification purposes, rather than for preventing oil, grease and anti-blocking purposes. Propylated napthalenes and biphenyls are also used in marine paints for their hydrophobic properties (Stockholm Convention on POPs, 2017[22]).

Alternatives for binders in paints to confer the durability and other required performance characteristics include acrylic, a popular choice which is a water-based latex paint, PS-based formulations such as tetrashield PC-4000 (Eastman, 2021a[30]), PU, alkyds, phenolic or silicone alkyds, phenolic, vinyl and epoxy coatings (STO, 2020 - 21[17]) (USDA, 1998[31]). Another alternative is a low density polyester (LDPE)-based formulation that contains nano aluminium oxide (Micro Powders, 2021d[32]). This is claimed to confer unsurpassed scratch and scuff resistance.

2.3. The Market for PFASs and Alternatives in Varnishes

2.3.1. PFASs Used in Varnishes

In varnishes, PFASs are mainly used in terms of floor finishes and floor polish as well as varnishes for surfaces such as countertops. These are usually used on wood or PVC surfaces but can also be used on natural stone such as marble, travertine (a type of limestone) and granite. PFASs are generally used on these materials for their stain resistant properties. They can also be used to prevent graffiti or paint from sticking to these surfaces or sticking to building walls.

FPs and SC PFASs are used for their fluorosurfactant capabilities. FPs based on a C6 structure have also been used as fluorosurfactants, for example ‘Hexafor’ by Maflon (Maflon, 2020[28]) has been used in floor polishes and floor finishes. Similarly to their use in paints, C4-fluorinated polyethers such as methyl nonafluorobutyl ether and methyl nonafluoroisobutyl ether as well as substances based on PFBS are used in varnishes as fluorosurfactants.

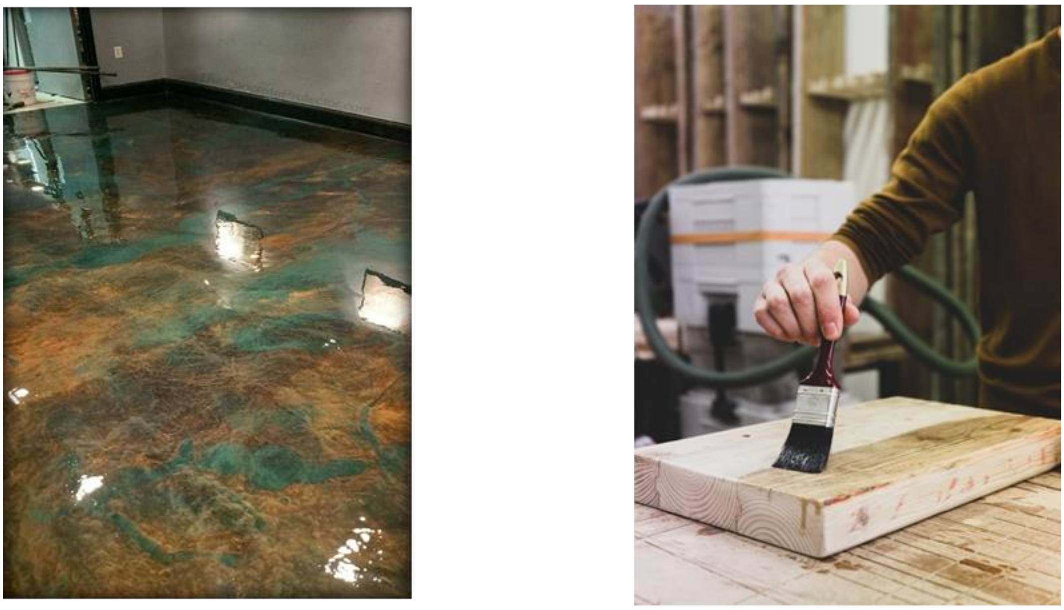
In addition, silicone polymers in combination with FPs have been used to prevent oil, grease and paint from sticking to surfaces.

2.3.2. Non-fluorinated Alternatives Used in Varnishes

Silica-based coatings such as silicone polymers made of silanes and siloxanes have been used in varnishes for their low surface tension as surfactants, without the use of FPs. Additionally, sulfosuccinates have been used in varnishes, specifically as wood primers, in water-based applications for their low surface tension. Both are used to confer wetting and levelling properties.

Alternatives for binders in varnishes to confer the durability and other required performance characteristics include acrylic, a popular choice which is a water-based latex paint, PS-based formulations such as tetrashield PC-4000 (Eastman, 2021a[30]), PU, alkyds, phenolic or silicone alkyds, phenolic, vinyl and epoxy coatings (STO, 2020 - 21[17]) (USDA, 1998[31]). Another alternative is a low-density polyester (LDPE)-based formulation that contains nano aluminium oxide (Micro Powders, 2021d[32]). This is claimed to confer unsurpassed scratch and scuff resistance.

Figure 2.2. Fluoropolymer Varnish Applications: Marble and Wood Surfaces



Source:
Left: Metallic Marble Floor – Camouflage Coloring by Decorative Concrete Kingdom is used royalty-free from CC BY 2.0.
Right: Picture by Beazy is used royalty-free from Unsplash.

3. Overview of the Function of PFASs and Alternatives in Coatings, Paints and Varnishes

The functions of PFASs that make them ideal for use in CPVs include: thermal stability, corrosion resistance, flame resistance, durability, weather resistance, UV fade-resistance, anti-soiling (stain resistant and prevent build-up of dust/dirt) conferred by water and oil repellence, levelling or wetting agent by acting as a surfactant (i.e. lower the surface tension at an interface such as between two liquids or between a liquid and a solid), dielectric properties, anti-blocking properties and smudge resistance.

The functions of PFASs are a result of their properties. PFASs have strong C-F bonds in which the fluorine atom is highly electronegative and forms a strong polar bond with carbon atoms. In addition, some PFASs are composed of two parts, a hydrophilic (water-seeking) head and a highly hydrophobic (water-repelling) fluorocarbon tail. The highly hydrophobic nature of the fluorocarbon tail makes PFASs uniquely oleophobic (lack of strong affinity for oils) and this dual hydrophilic/hydrophobic nature of PFASs molecules confers on them surfactant properties.

In powder coatings, radiation curable coatings and coatings for cable and wiring, only FPs have been identified as PFASs being used, however for other coating applications and in paints and varnishes, SC PFASs have also been used. FPs and SC PFASs share many of the properties listed above due to their common C-F bonds. Any differences between the properties of FPs and SC PFASs have been highlighted in the respective sections below. These functions are listed in Table 3.1 and explained in the following sections.

Table 3.1. PFAS Functions and their Non-Fluorinated Alternatives

	PFAS function	PFASs	Alternatives
Coatings	Thermal stability	PTFE, FEP	Epoxy, polyolefin, polymethylmethacrylate
	Flame resistance	PTFE, FEP, ETFE	PVC
	Corrosion resistance	PTFE, FEP, PVDF, ETFE, Formulations of fluoro sulphonamides	Epoxy, polyurethane, polyolefin, polymethylmethacrylate; galvanization and anodization are alternatives for some applications.
	Weather resistance	PTFE, ECTFE, PVDF, PCTFE, ETFE, Formulations of fluoro sulphonamides	Polyurethane, polyester, silicone modified polyester, polysiloxane, epoxy; galvanization and anodization are alternatives for some applications.
	Durability / abrasion resistance/ scratch resistance / UV resistance	PTFE, ECTFE, PVDF, FEVE, ETFE	Polyurethane, polyester, polysiloxane, polymethylmethacrylate
	Dielectric properties	PTFE, FEP, PFA	PVC, epoxy, polyurethane, polyolefin
	Smudge resistance	PVDF, Perfluoropoly-ether and polyurethane blend	Silica-based coatings
	Anti-graffiti coatings	PVDF, FEVE, PTFE and ECTFE	Polyurethane, polyester.
	Lubricity*	PTFE	HDPE-based products that contain nano ceramic and nano aluminium oxide
Paints	Corrosion resistance	PVDF, PTFE, FEVE, ECTFE, FEP	Epoxy, polyurethane, polyolefin, polysilozane, aliphatic diisocynates-based polyurethane
	Weather resistance	PVDF, PTFE, FEVE, ECTFE, FEP	Acrylic, polyurethane, polyester, polysiloxane, epoxy, ‘Hexafor’, silicone polymers, alkyds, phenolic or silicone alkyds, phenolic, polysilozane, aliphatic diisocynates-based polyurethane and vinyl
	Durability / abrasion resistance/ scratch resistance / UV resistance	PVDF, PTFE, FEVE	Polyurethane, polyester, polysiloxane, polysilozane, aliphatic diisocynates-based polyurethane
	Lubricity*	PTFE	HDPE-based products that contain nano ceramic and nano aluminium oxide
	UV ‘cool roof’ property	PVDF	None identified
	Levelling and wetting agent	C4-PFBS and C4-fluorinated ethers**, C6-based PFAS	Silica based and sulfosuccinates: e.g. Hydroplat
	Anti-blocking properties	C6 short-chain: ‘Hexafor’	None identified
	Oil repellence	C6 short-chain: ‘Hexafor’	None identified
Varnishes	Anti-soiling	C4-based PFAS e.g. PBSF, fluorinated polyethers**, short-chain PFAS mixtures with silicone†. Wood protectors: fluorinated hydrocarbons, fluorinated acrylic or methacrylic acid esters, fluoroalkane sulfonic acids and salts of fluorinated carboxylic acids	None identified
	Levelling and wetting agent	C4-based PFAS e.g. PBSF, fluorinated polyethers**, short-chain PFAS mixtures with silicone†.	Sulfosuccinates: ‘Hydropalat 875’and ‘EDAPLAN LA 451’
	Anti-blocking properties	C6 short-chain: ‘Hexafor’	None identified
	Lubricity*	PTFE	HDPE-based products that contain nano ceramic and nano aluminium oxide

Key to table: *Lubricity is the measure of the reduction in friction and or wear by a lubricant and useful for example in applications where containers are required to not adhere to each other and printing inks. **For example, methyl nonafluorobutyl ether and methyl nonafluoroisobutyl ether and Polyfox. † For example Silres 38.

C4, C6 and C8 refer to the number of carbon atoms in the molecule, ECTFE = ethylene chlorotrifluoroethylene, ETFE = ethylene tetrafluoroethylene, FEP = fluorinated ethylene propylene, FEVE = fluoroethylene vinyl ether, HDPE = high density polyethylene, PFA = perfluoroalkoxy, PTFE = polytetrafluoroethylene, PVDF = polyvinylidene fluoride, PCTFE = polychlorotrifluoroethylene.

3.1. Thermal Stability and Flame Resistance

3.1.1. Thermal Stability and Flame Resistance of PFASs

Powder coatings for industrial applications as well as coatings for cable and wiring need to be stable at high temperatures. High thermal resistance is a property of PFASs due to their strong C-F bonds. PFASs used for these purposes are additionally flame-resistant, this is because of their thermal resistance. FPs, rather than fluorotelomers have solely been identified for thermal stability and flame resistance uses in coatings. This is possibly due to the number of C-F bonds being much higher in fluoropolymeric substances than single chain substances. PTFE and PFA for example are particularly effective when melting points in the 260 – 327 °C range are required (STO, 2020 - 21[17]). At lower temperatures, non-fluorinated alternatives can compete with FP-based cables on thermal stability and flame resistance.

3.1.2. Thermal Stability and Flame Resistance of Non-fluorinated Alternatives

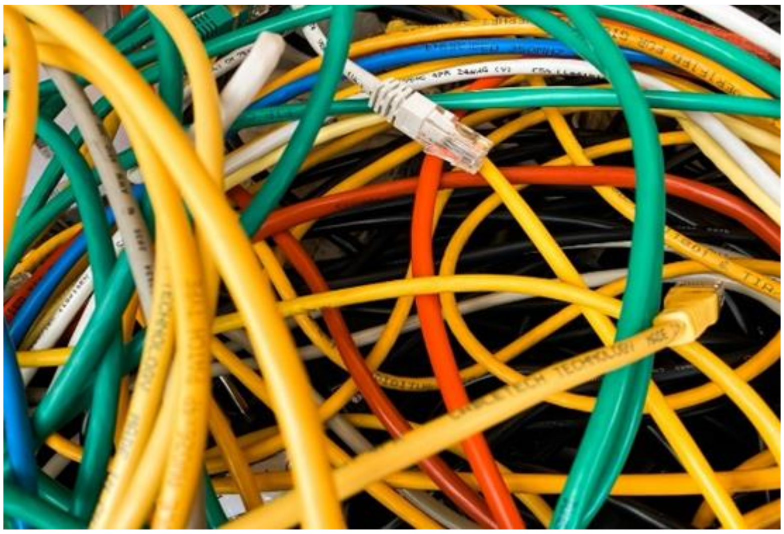
Non-PFAS alternatives used for thermal stability include epoxy-based coatings. These can resist temperatures up to 200 °C (Metal Coatings Corp., 2020[33]). This is still lower than FPs used in cable and wiring coatings, as well as powder coatings in the chemical industry, which can resist temperatures up to 230 °C.

Additives such as curing agents can be added to epoxy coatings to increase their temperature resistance, for example epoxy coatings that are formulated as rod structures can withstand higher temperatures than flexible structures (Chen, Su and Tseng, 2000[34]).

In cable and wiring, polyolefins can be crosslinked for example by irradiation to increase the number of bonds within their structure, increasing their thermal stability up to 150 (upper temperature) – 240 °C (short-term high temperature resistance) (IEWC, 2020[35]). In terms of flame resistance, PVC has been found to be flame resistant, as well as crosslinked polyolefins. Other coatings such as epoxy, PS and PU can become flame resistant in mixtures with halogen-free flame retardants (Habia Cable, 2020[36]).

Polyamide (PA) can be used for similar higher temperature applications but its electrical insulation properties are not significantly lower than PFA (STO, 2020 - 21[17]).

Figure 3.1. Cable and Wiring, PFASs and Alternatives Depending Upon the Required Thermal Stability and Flame Resistance



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3.2. Corrosion Resistance

3.2.1. Corrosion Resistance of PFASs

Powder coatings for industrial applications as well as cable and wiring coatings are likely to come into contact with harsh chemicals, therefore they require resistance properties to these chemicals. In FPs such as PTFE and PVDF there is a high number of C-F bonds in the polymer backbone which renders them highly unreactive, therefore stable to reactions with various chemicals and resistant to corrosion (O'Hagana, 2008[37]). Stakeholders have pointed out that this property is additionally important in coatings and paints used for external architectural purposes, where the paints are likely to be subject to harsh weather conditions such as moisture and salt (AFT Fluorotec, 2021[38]) (see section 7.2).

3.2.2. Corrosion resistance of non-PFAS alternatives

Epoxy coatings and PU coatings both provide suitable corrosion resistance due to their stability to various chemicals (Metal Coatings Corp., 2020[33]), (Habia Cable, 2020[36]). Crosslinked polyolefins also have this property, due to the increased number of bonds.

3.3. Durability, Weather and UV-fade Resistance

3.3.1. Durability, Weather and UV-fade Resistance of PFASs

Some PFASs are composed of two parts, a hydrophilic head and a highly hydrophobic fluorocarbon tail. The highly hydrophobic nature of the fluorocarbon tail makes PFASs uniquely oleophobic (Kovalchuk et al., 2014[39]).

Their water resistance and oil-repellent nature, as well as their chemical stability means that PFAS-coated surfaces are less affected by harsh weather conditions such as acid rain. This is a property of both FPs and SC PFASs and is important for paints and coatings used in the architectural industry.

PFAS coatings are additionally durable under harsh UV light. PFASs used in the architectural industry can resist UV rays and therefore the paints are able to retain their colour and gloss and not fade with UV damage. This as well as their hydrophobic nature, renders the paints resistant to chalking, where a chalk like surface appears on the paint surface due to their degradation with moisture and sunlight (AFCONA Additives, 2005[40]). PFAS paints such as PVDF have been described to be UV reflective, these paints can be used on roofs to reduce roof temperature and therefore, result in energy savings. These paints are said to have 'cool roof' capabilities. UV resistance and reflection have been described to be properties of FPs rather than SC PFASs. Other FPs identified to be used as weather-resistant coatings on glass include PTFE, FEVE and copolymers based upon a range of monomers such as tetrafluoroethylene (TFE) that includes polychlorotrifluoroethylene (PCTFE) (US Patent, 2019[41]).

Weather resistance and durability for coatings and paints in the renewable energy sector is particularly important. Here FPs such as FEP are used as coatings for example on the blades of wind turbines to repel dirt and water and therefore prevent the growth of mould, due to their hydrophobic and oleophobic properties.

3.3.2. Durability, Weather and UV-fade Resistance of Non-PFAS Alternatives

Non-PFAS alternatives are available that are used in the building and architectural industry (Green Science Policy Institute, 2021[42]) and these can be formulated both as powder coatings and as paints. For example, HDPE-based products that contain nano ceramic (Micro Powders, 2021a) and nano aluminium oxide (Micro Powders, 2021b), PU, PS, PS melamine and epoxy coatings all are used in this industry for weather resistance[11]. However, the efficacy and performance of these coatings compared to PFAS FPs can vary (see section 7. .2).

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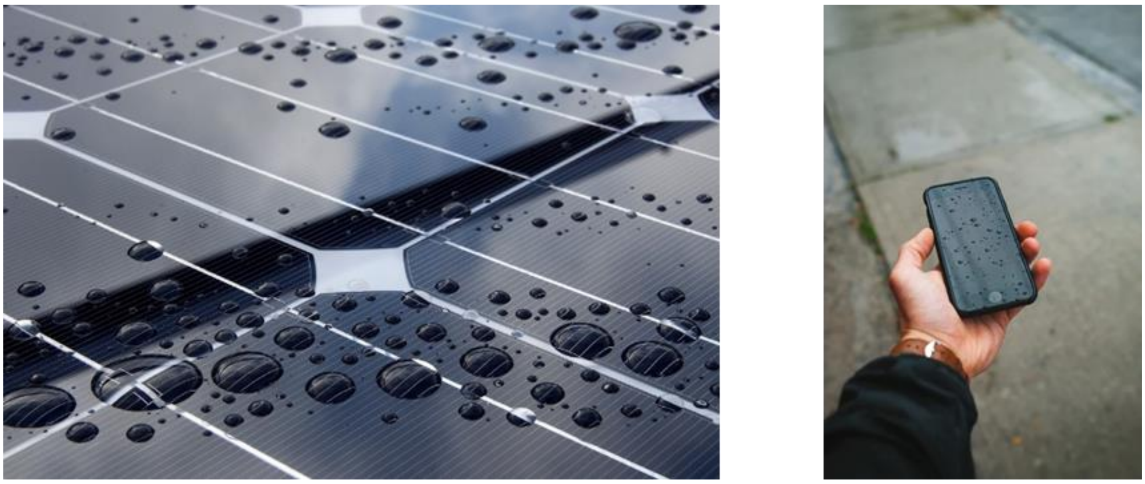
[11] Some stakeholders have commented PU & epoxy offered are not suitable for coil coatings. The next best alternative to PVDF is polyester melamine (PVDF coil durability 25-30 yrs.; PE melamine 15 yrs.).

Figure 3.2. Durability and Weather Resistant applications in Solar Panel Coatings and Radiation Curable Coatings Used on Screens



Source:
Left: Solar panel reflection by OregonDOT is used royalty-free from CC BY 2.0.
Right: Picture by Bannon Morrissy is used royalty-free from Unsplash.

3.4. Anti-soiling

3.4.1. Anti-soiling of PFASs

PFASs are useful in varnishes for anti-soiling purposes due to their hydrophobicity and oleophobic nature. Anti-soiling provided by PFASs mean coated surfaces are reported to be less affected by staining after spillages and are easier to clean due to less dust build up or may even be considered as self-cleaning (Hussain, Batra and Pachauri, 2017[43]). This is a property that may be conferred by both FPs and SC PFASs and SC PFASs used in paints confer anti-soiling properties – sometimes referred to as wipe-clean or easy-clean properties in household paints (3M, 2016[27]).

3.4.2. Anti-soiling of Non-PFAS Alternatives

No non-PFAS alternatives have yet been identified as anti-soiling agents.

3.5. Levelling and Wetting

3.5.1. Levelling and Wetting of PFASs

An important function of FPs and SC PFASs in paints and varnishes is as wetting and levelling agents. These refer to the ability of the paint to spread out efficiently and apply as an even surface. PFASs can act as wetting and levelling agents due to their low surface tension. Fluorine in the C-F bond has a low polarisability which means that the intermolecular interactions are weak, leading to an overall low energy (Kovalchuk et al., 2014[39]), nevertheless there is still a distribution of charge as shown in Figure 3.3. As a result, the low surface tension particles in paint arrange themselves to minimise their energy, in a process referred to as entropy. This leads to the particles maximising their surface area by spreading out as much as possible. This low surface tension of the paint will minimise defects that can otherwise be present, such as orange-peel texture (uneven texture which resembles an orange peel) (AFCONA Additives, 2005[40]).

Figure 3.3. Charge distribution in C-F bond

$$\mathrm{C}^{\delta+}\text{—}\mathrm{F}^{\delta-}$$

3.5.2. Levelling and wetting of non-PFAS alternatives

Silica-based coatings, such as silicone polymers made of silanes and siloxanes, have been used in paints and varnishes for their low surface tension (Poulsen, Jensen and Wallström, 2005[44]). Sulfosuccinates have also been used as wood primers in varnishes for their low surface tension (Poulsen, Jensen and Wallström, 2005[44]).

3.6. Dielectric Properties

3.6.1. Dielectric Properties of PFASs

Low dielectric properties mean that PFASs used in cable and wiring coatings can act as good insulators (Yoshimoto and Shimizu, 2018[45]). This property of PFASs also derives from the low polarisability of fluorine which results in the overall low energy of particles. Theoretically, this is a property of both FPs and SC PFASs; however, only FPs have been identified as PFASs used in cable and wiring coatings.

3.6.2. Dielectric Properties of non-PFAS Alternatives

PVC, epoxy, PU and polyolefins have low dielectric properties and therefore can be used as insulators in cable and wiring coatings (see Section 7.1).

3.7. Smudge (Anti-Fingerprint) Resistance

3.7.1. Smudge (Anti-Fingerprint) Resistance Properties of PFASs

Radiation curable coatings can consist of PVDF and can be used in electronics for example on the screens of phones, tablets and monitors, or in electronic circuit boards. Generally, in electronics FPs are used because they are hydrophobic and because they can be applied in a thinner layer compared to alternatives (SCH India, 2020[21]).

3.7.2. Smudge (Anti-Fingerprint) Resistance of Non-PFAS Alternatives

Silica based coatings have been used in the electronics industry and have similar properties to PFASs used here, they are oleophobic and hydrophobic, so easy to clean, scratch resistant and corrosion resistant (Ayold, 2020)[12].

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[12] A stakeholder has pointed out that silica based technology is only 20-25% as good as PFAS (C6) technology. More work is needed to find alternatives, or improve the silica based technology.

4. The Uses of PFASs and Alternatives in Coatings

4.1. Powder Coatings in the Chemical Industry and in Cable & Wiring

4.1.1. PFASs in Powder Coatings in the Chemical Industry and in Cable & Wiring

Powder coatings are used in the chemical industry on metal equipment likely to come into contact with harsh chemicals and be subject to high temperatures.

Powder coatings do not contain any solvent or water and therefore do not produce any organic waste during production and construction. They also usually only need to be applied in a single coat to achieve the desired properties and can be used, for example, on steel and stainless steel (in layers that are around 0.8 mm thick) (Oxyplast, 2020[46]) as well as on aluminium (KGE Jingaoli Group, 2020[47]). They can be applied in two different ways, either through spraying, or through dipping which is used for example in large objects such as pipeline valves in the oil and gas sector or on small objects such as circuit boards in the electronics industry.

Spray application of powder coatings is done electrostatically, where the powder is fed to a spray gun and the high voltage results in an electrostatic charge on each powder particle. These charged particles are attracted to the surface that is being coated. An advantage of powder coatings is that particles that are not deposited are instead recovered and reused. The coating is then cured with heat. In dipping, the surface that is being coated is pre-heated to around 70-2000 °C and immersed into the powder coating which is made into a fluid by bubbling air through it (BCF, 2020[48]).

Specifically formulated for use in the oil and gas industry 'Solef' by Solvay is a PVDF based coating, used for internal and external protection of pipelines, which is either applied in a two layer system for the external coating, or applied using spray methods to create several layers (Solvay, 2018[49]). ECTFE-based formulations, such as 'Halar' are coatings designed to be used as a powder on equipment such as vessels, reactors and chemical storage tanks (Impreglon, 2020[50]).

Cable and wiring coatings made of PTFE are formulated in four different ways for use; 1) as low density tapes, 2) skived tapes[13], 3) unsintered tapes[14] and 4) paste extrusion, depending on the application (Technetics, 2020[51]). Low density tape can be produced by a stretching process which enlarges the pore structure of the polymer. Usually fine-powder types of PTFE with the primary particle size around 0.1-0.4 µM, and secondary particle size as 300-600 µM, is applied with this application. This type of PTFE is used when excellent dielectrical properties are needed.

Skived tapes are manufactured as a more economical solution. Usually molding-powder types of PTFE with the particle size sub-millimeter is applied. They

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[13] Skim thin layers from a FP to create a thin sheet of film.

[14] For example unsintered tape is wrapped around a cable which is then sintered at a high temperature by means of infrared or a salt bath to create a protective harness to the cable.

have a lower tensile strength than low density tapes. Skived tapes are manufactured by a cold compression moulding and sintering process. Here, the PTFE resin is compressed in a mould and then sintered in an oven at around 370 °C to form a cylindrical shape. Then the surface of the columnar body is spirally stripped toward its center, so that sheet material is formed into film (Hinustan Nylons, 2020[52]).

Unsintered PTFE tapes and films are used as a medium density product, for example in the aerospace industry, for power feeder cables, power cables for seats and cockpits, as well as for in-flight entertainment wiring (Technetics, 2020[53]). These are produced from PTFE fine powders through a cold extrusion process, here, a volatile lubricant is added to the powder resulting in a paste, this paste is compressed into a cylindrical shape and placed through a die to get the desired shape. This is performed at around 20-100 °C. The resulting article is then dried to remove the lubricant (Inoflon, 2020[54]), (Plastomertech, 2010[55]). A diagram of this process can be found in (Daikin, 2020[56]).

Paste extrusion is a similar technique as the unsintered PTFE tape method stated above. PTFE fine powders with lubricant are charged into the extruder and discharged from small die into a tube shape. At the centre of hollow space of the extrudate, copper conductor moves forward with the same direction of PTFE and at the specific point both parts come together to form conductor-insulation shape. PTFE is dried out to remove lubricant and sintered afterwards.

In cable and wiring coatings these are mainly PTFE-based. Both FPs are corrosion resistant, however PTFE is more chemically inert compared to PVDF because it has a higher number of fluorine atoms in its carbon chain backbone.

Cable and wiring coatings additionally require excellent electrical insulation properties in the case of communication cable. Sometimes a dual layer of coating is used, the innermost layer providing the insulation and the outer layer providing chemical and mechanical resistance. FPs have a low dielectric constant which makes them good insulators. For example, a dual layer coating identified consists of polyolefin as the inner insulating layer, due to its excellent electrical properties and a FP outer layer due to its mechanical and chemical resistance (TE Connectivity, 2012[57]). The US National Electrical Code lists both PTFE and ETFE as acceptable materials for insulated wiring purposes whereas ECTFE, PFA, PTFE and ETFE are listed as suitable for building fixtures (NEC, 2017[58]).

4.1.2. Non-Fluorinated Powder Coatings Used in the Chemical Industry and in Cable & Wiring

In powder coatings and cable and wiring coatings, the ability of the coatings to resist high temperatures is important. Epoxy based coatings, used in both of these applications, have one of the highest thermal stabilities compared to other non-PFAS alternatives, they can resist temperatures up to 200 °C (Metal Coatings Corp., 2020[33]). This is still lower than FPs used here like FEP, which can resist temperatures up to 230 °C (Metal Coatings Corp., 2021[59]). One drawback of epoxy coating is the chemical leaching of bisphenol A at 50-200 °C (Katsuhiko, S et al, 2004[60]) whereas FPs do not show chemical deterioration at their service temperature.

Other coatings used in both applications such as coatings based on PS and PU can all generally only resist temperatures up to 100 °C. For cable and wiring, additional coatings can be used such as polyolefin which can be crosslinked to increase the number of bonds within its structure, which increases its thermal stability up to 200 °C (Champlain Cable, 2018[61]). PVC is another coating used in cable and wiring, however similar to PS and PU it can generally only withstand temperatures up to 100 °C and also leaching phenomena of additives in long-term use will lead to the significant deterioration of physical properties especially for outdoor use.

PU has been developed as a cable and wiring insulator due to its hydrophobic and corrosion resistant properties. Halogen-free PUs[15] have also been identified (Eland Cables, 2020[62]). An advantage of PU is its mechanical strength which makes it useful for cables and wiring that need to withstand wear and tear. However, PU does not have good dielectric properties (Habia Cable, 2020[36]) and therefore is only suitable for low voltage cables connection insulation (3M, 2020[63]). PVC, on the other hand, is flame resistant and relatively inexpensive. However, it only has limited resistance to acids and solvents.

Corrosion resistance is an equally important property of both coatings. Epoxy coatings and PU-based coatings both provide suitable corrosion resistance due to their stability to various chemicals. However, PS coatings only have some resistance to solvents and acids. This is similar to coatings used only in cable and wiring, such as PVC. Polyolefins on the other hand have good corrosion resistance when crosslinked.

PVC is flame resistant, however the other coatings mentioned above such as epoxy, PS, PU and polyolefins need flame retardants to be added to be flame resistant, of which possibilities are available that are marketed as halogen-free (Habia Cable, 2020[36]).

For cable and wiring coatings, good dielectrical properties are essential so they can be used as insulators. Almost all of the alternatives mentioned above can be used as insulators, except for PU, therefore it is only suitable as a jacket (outer layer coating) in cable and wiring not as an insulator (Habia Cable, 2020[36]). Late in the preparation of this report other alternatives identified for use in cable and wires included: silicone, chlorosulfonated polyethylene, PVC, polyethylene, cross-linked polyethylene, chlorinated polyethylene, thermoplastic elastomer, neoprene, ethylene-propylene rubber and nylon (Anixter, 2013[64]).

4.2. Powder Coatings in the Architectural Sector

4.2.1. PFASs Used in Powder Coatings in the Architectural Industry

The PFASs used in the architectural industry are similar to the PFASs used in the chemical industry in powder coatings. PFASs here are FPs which are used as resins in coating formulations to confer durability and weatherability properties. Two examples of commercially available PVDF powder coatings are 'Fluoplast' (Oxyplastuk, 2021[65]) and 'Kynar' (Arkema, 2021[66]). FPs in this industry are not intrinsically hard and impact resistant, which is why they are often mixed with hydrocarbon-based coatings. For example, 'Koflux' a PVDF powder coating, is 70 % PVDF/cyanide resin and 30 % acrylic resin (KGE Jingaoli Group, 2020[47]). The resulting formulation is described as a highly

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[15] I.e. without fluorine, chorine etc content.

durable product, giving the resulting coating with a long and sustainable lifespan (STO, 2020 - 21[17]). It is also noteworthy Kynar resins for coatings applications are produced without the use of PFAS surfactant polymerisation aids.

Other PFASs used here are FEVE and ECTFE. For aluminium window frames and the aluminium curtain walls of buildings[16], stakeholders have reported only the highest performance coatings can be used and this usually means FP-based coatings (STO, 2020 - 21[17]). FEVE is the most widely used coating in these applications (95-98%). PVDF is thermoplastic and cannot easily be used as a powder coating because it is complex to handle (STO, 2020 - 21[17]). PVDF, FEVE, FEP and ECTFE are usually applied by spraying electrostatically (Ifs Coatings, 2020[67]); for window frames and curtain walls these are first shaped and then powder coated.

4.2.2. Non-Fluorinated Powder Coatings in the Architectural Industry

Non-fluorinated alternatives to PFAS do exist for use in the building and architectural sector (Green Science Policy Institute, 2021[42]). PS, silicone modified PS and PU coatings have good weather resistance properties and resistance to UV light. This means that the colour of the coatings does not degrade under sunlight and that in general the coating is durable under harsh weather conditions (BCF, 2020[68]). PS and specifically PU coatings can also be used on buildings as an anti-graffiti powder coating, to prevent the graffiti from sticking to surfaces for example 'Alesta AG' by Axalta (Axalta, 2020a[69]), (Axalta, 2020b[70]). Galvanization and anodization are alternatives for some applications (STO, 2020 - 21[17]).

4.3. Radiation Curable Coatings

4.3.1. PFASs Used in Radiation Curable Coatings

PFAS radiation curable coatings are used in the electronics industry, specifically on glass, metal and plastics, for example on phones, tablets, monitors, screens, external windows and patios (Thin Film Partners, 2016[71]). In general, the coating is formed and solidified using UV light, visible light or low energy electrons. The formulation of the coating therefore needs to include photo initiators that react under light.

Radiation curable coatings in these uses need to be easy to clean, scratch resistant and corrosion resistant. PFASs found to be used in this application are FPs such as PVDF. Comparably to PFAS powder coatings, which are formulated along with hydrocarbons, PFAS radiation curable coatings can also be blended with other substances, for example, 'UVX' is a blend of a perfluoropolyether and PU (Thin Film Partners, 2016[71]).

Overall, radiation is just one method of curing coatings, coatings used in this industry can be dried in other ways for example evaporative curing, moisture curing and heat curing (Techspray, 2020[72]). Compared to coatings that cure under heat, radiation curable coatings are more effective in terms of the time it takes to cure the coatings (Coatings World, 2015[73]). Generally, in electronics

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[16] A curtain wall system is an outer covering of a building in which the outer walls are non-structural, utilized only to keep the weather out and the occupants in.

FPs are used because they are hydrophobic and because they can apply in a thinner layer compared to alternatives (SCH India, 2020[21]).

4.3.2. Non-Fluorinated Radiation Curable Coatings

Silica based coatings have been used in the electronics industry and have similar properties to PFASs used here, they are oleophobic and hydrophobic, so easy to clean, scratch resistant and corrosion resistant (Ayold, 2020[74]). They are also stable to a variety of chemicals and therefore corrosion resistant (Ayold, 2020[74]). Scratch resistance is generally a property of radiation curable coatings (Ruiz et al., 2018[75]).

'TEXTMATTE 6005' is another non-fluoro coating example which can be formulated as a radiation curable coating, made of a polymethylmethacrylate powder. It is used for its thermal stability, corrosion resistance, durability, matting and texture properties (Shamrock Technologies, 2021[76]).

4.4. Anti-Reflective Coatings in the Semi-Conductor Industry

4.4.1. PFASs Used in Anti-Reflective Coatings in the Semi-conductor Industry

The only type of coatings that have been found to possibly still use LC PFASs, such as PFOA, are anti-reflective coatings used in the manufacturing of semi-conductors, which make up electronic devices. However, other PFAS alternatives to these are available on the market such as 'AZ Aquatar 8' which is a FP with a short fluoroalkyl side chain which is less than C4 (Microchemicals, 2007[14]). These PFASs are commonly used as top anti-reflective coatings where they control the reflectivity problems through destructive interference[17].

These coatings are applied by a process called spin coating. The anti-reflective coating is dissolved in a solution and placed on the surface to be coated, in this case the silicon wafer. This is then rotated to spread the solution across the surface and evaporate the solvent. The thickness of the coating can be controlled by the spin speed as well as spin time (Khan et al., 2017[77]).

4.4.2. Non-Fluorinated Anti-Reflective Coatings in the Semi-conductor Industry

In anti-reflective coatings in the semi-conductor industry it was reported there are no non-FP-based alternatives as of yet (Stockholm Convention on POPs, 2017[22]).

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[17] It has been noted that FP coating is not present in the final chip and is spun out and goes to waste or destroyed in the etching process.

Figure 4.1. Anti-reflective Coatings Used in the Manufacture of Semi-conductors For Example Memory Chips

Source: Raspberry Pi 4 8GB Memory Chip by geerlingguy is used royalty-free from CC BY 2.0.

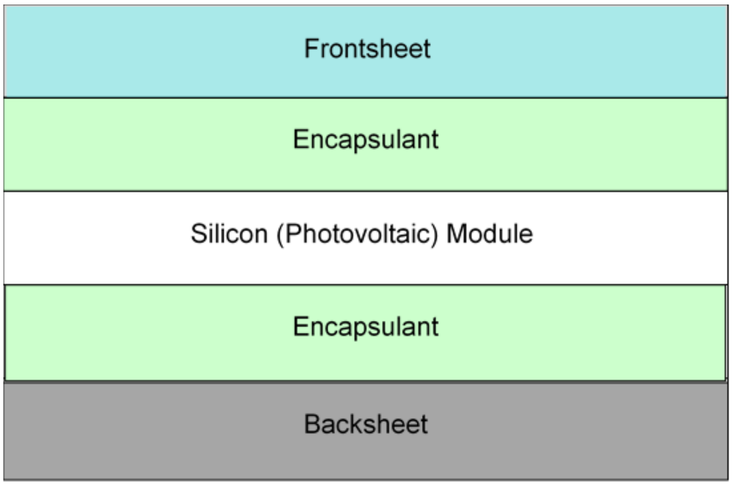
4.5. Coatings in the Renewable Energy Industry

4.5.1. PFAS Coatings Used in the Renewable Energy Industry

PFAS FPs are one choice of material in the renewable energy industry such as in solar panel (photovoltaic (PV) module) coatings. Solar panels work by converting light energy from sunlight into electricity, therefore this can be impacted by the amount of light reaching the photovoltaic cells in solar panels. This in turn is impacted by either internal factors, such as the reflectivity of the solar panels or by external factors such as temperature, wind, pollution, shading and cleanliness of the solar panel.

PV modules are made up of monocrystalline or polycrystalline silicon wafers which are embedded in encapsulants, placed between frontsheets, traditionally glass, or backsheets for additional protection. PFAS are used as both frontsheets, replacing glass and/or backsheet applications. In frontsheets, PFAS are used to increase the amount of light reaching the solar panel, whereas in backsheets they protect the PV modules from moisture, UV degradation and act as an electrical insulator, (STO, 2020 - 21[17]), (Dunmore, 2021[78]). A cross-section through a solar panel is shown in Figure 4.2.

Figure 4.2. Solar Panel Cross-Section



Currently, commercial solar panels only harness around 20% of the light energy due to energy loss through reflection or the build-up of dust (Mozumder et al., 2019[79]). The build-up of dust, dirt or air pollution impacts the ability of light to reach the photovoltaic cells, therefore reducing energy output. For example after several months without cleaning, air pollution can deteriorate the energy production of the solar panels up to 6.5% (Hussain, Batra and Pachauri, 2017[43]). In deserts, the accumulation of sand and dust can reduce the energy output much more, up to 40%, and therefore mechanisms to prevent this are employed (Hussain, Batra and Pachauri, 2017[43]). Overall, it is important for solar panel coatings to have high transparency, a low cleaning requirement or a self-cleaning ability.

So-called ‘self-cleaning’ coatings or films are used which improve the energy efficiency of solar panels by removing deposited dust, either by being hydrophilic, or through hydrophobic properties (Mozumder et al., 2019[79]). In hydrophilic coatings, water is attracted to the surface of the solar panels and spreads across it to form a ‘film’ on top. During the process of spreading (wetting), the contaminants on the surface are washed away. In hydrophobic coatings, such as PFAS coatings, water is repelled by the surface of the solar panels and washes away along with dust and dirt – the so-called ‘lotus effect’ (Mozumder et al., 2019[79]).

Coatings for solar panels are also aimed at being transparent coatings which work to reduce the reflectivity of solar panels, thereby capturing more of the incident solar energy. The frontsheets of solar panels are usually made of silicon and glass and therefore have high refractive indices meaning more than 30% of the light reaching the solar panels is reflected back. It is therefore important that these coatings are transparent to visible light to avoid any further losses (Mozumder et al., 2019[79]).

FP films in the front and backsheets of solar panels have been used to improve the performance of solar panels in these respects because of their hydrophobic properties. FEP and ETFE coatings are commercially available for frontsheet use that are supplied in a film form and can be directly applied to the solar panels, replacing glass (DuPont, 2020a[80]). These coatings can be used in a range of sizes of solar panels, from grid-connected systems to portable units. Additionally, ECTFE-based coatings for frontsheet applications have been identified, specifically for use on solar panels on boat decks, due to their ability to withstand harsh marine conditions (Amcor, 2021[81]).

In backsheet applications, a range of FP-based films have been identified that have been used such as FEVE, FEP and ETFE. Stakeholders in this project have noted that for backsheet applications it is important for the coating to be lightweight to be used on structures or roofs, easier to install and flexible so that they can be formed to the curvature of roofs (STO, 2020 - 21[17]). Other parameters such as durability, resistance to corrosion and UV light deterioration are also critical performance parameters that have been assessed (see Section 7.1.1).

4.5.2. Non-Fluorinated coatings used in the renewable energy sector

Many alternatives for hydrophobic PFAS coatings exist, for example silicones, carbon nanotubes, polystyrene, PU urea copolymer, polymethylmethacrylate, polycarbonate (PC) and PVC.

In relation to hydrophilic coatings, alternatives have been identified that are also photoactive. These react with ultraviolet light from the sun to decompose dirt and other impurities on the surface of the solar panels and are referred to as ‘super hydrophilic’ coatings. Most of these are reported to be made up of titanium dioxide nanoparticles (Mozumder et al., 2019[79]) and titanium dioxide is used due to its high physical and chemical stability, low toxicity and excellent photoactivity (Mozumder et al., 2019[79]).

PS has been identified as an alternative that is commercially available specifically for backsheets, for example, ‘Mylar UVHPET’ developed by DuPont Teijin Films (DuPont Teijin Films, 2021[82]), has been used not only as an alternative to FP based films, but also to traditional PS films. This film has been described to offer enhanced UV protection and moisture resistance. Comparison has also been made by DuPont between fluorinated backsheets and this PS film, with results suggesting that fluorinated backsheet materials may present environmental and health issues in relation to disposal, whereas the ‘Mylar UVHPET’ backsheet may not generate hazardous materials in high-temperature disposal processes (DuPont Teijin Films, 2021[82]).

In addition to PS, other alternatives include polyamides (PA) and polyethylene terephthalate (PET) which have been used for at least the last 10 years in the field (DuPont, 2020b[83]).

In wind turbine coatings, several alternatives exist. For example, ‘Hempadur 4774D’ is an epoxy-based paint used for its corrosion and abrasion resistance (Hempel, 2021[84]). Additionally, ‘Hempathane HS 5561 B’ is a PU-based coating, used specifically a topcoat in corrosive environments as it is suggested to have good gloss and colour retention. This coating is cured with aliphatic isocyanate and can be applied via spray method or a brush, however it has been suggested that more coats may need to be applied if using a brush, to attain the same result (Hempel, 2020[85]).

5. The Uses of PFASs and Alternatives in Paints

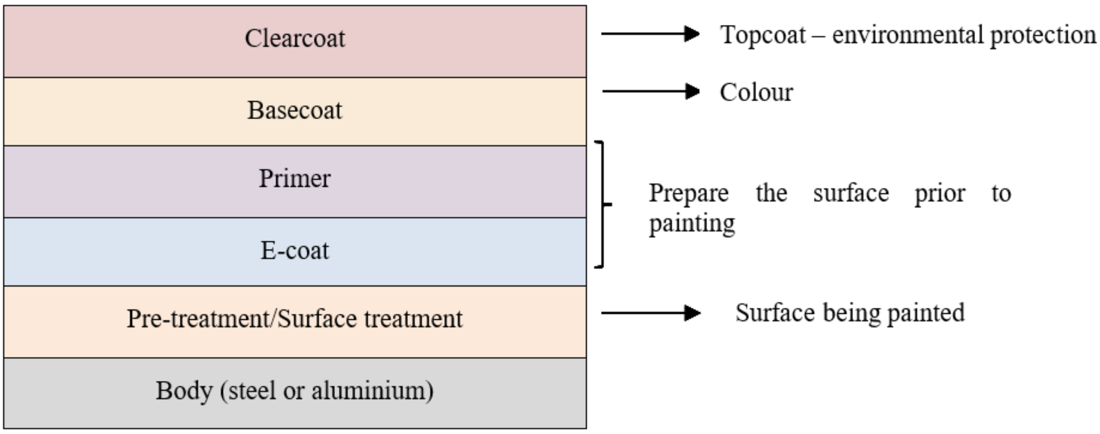
5.1. Automotive Paints

5.1.1. PFASs Used in Automotive Paints

Fluoropolymers can be used in automotive paints, to prevent environmental damage, such as from sunlight and roadside debris. These can be applied after the surface has already been painted. Fluoropolymers, such as PTFE, are used in this application for their corrosion resistance. Corrosion can occur on cars in the form of rust due to moisture or humidity from the environment, therefore because FPs are hydrophobic and can resist a wide variety of chemicals, such as fuel and oil, they can protect the surface of the car from corrosion (Coating Systems Inc, 2021[86]). PTFE in this application is also durable and can withstand chipping and flaking, to provide a smooth surface. An example of a PTFE-based coating is ‘Xylan’ which can be applied in a thin sheet, either in the basecoat or topcoat, or included in several layers (TOEFCO, 2021[87]).

Automotive paints are usually made up of different layers, each providing different functions. Firstly, a pre-treatment or surface treatment layer is often used to prepare the surface being treated which is usually a metal such as steel or aluminium. Then an E-coat or electrocoat is applied, which is used for corrosion prevention but can also provide durability. This is followed by a primer to prevent chipping of the paint layers to follow. These are the base coat used for colour and the desired effect, such as shine and then there is a clearcoat used for transparent protection. These layers in total make up about one tenth of a millimetre in thickness (BASF, 2021[88]), (Axalta, 2021[89]).

Figure 5.1. Typical Layers in Automotive Paints



Source: (STO, 2020 - 21[17])

5.1.2. Non-fluorinated Automotive Paints

Non-fluoro alternatives for use in automotive paints need to be dirt resistant, durable in terms of scratches or wear and tear, as well as resistant to environmental temperatures and corrosion.

For these functions, polysilazanes, silicon dioxide-based formulations have been described. For example, ‘Durazane’ is a product formulated by Merck (Merck, 2020[90]) and because of its properties can also be used for architectural and chemical industry applications. This product group has different formulations, for example Durazane 2000 series, made of inorganic polysilozane polymers, which work by adding a film to surfaces to form a glass-like layer and is used for its scratch resistance, thermal resistance and chemical stability. Durazane coatings have been described to be suitable for use on various metals such as steel and aluminium, plastics as well as surfaces that are already painted and can be applied using spray coating, wiping, or dipping (Merck, 2019[91]).

Figure 5.2. Applying Paint in the Automotive Industry

Source: Car Painting by WorldSkills UK is used royalty-free from CC BY 2.0.

Another type of alternative, also formulated by Merck, is ‘Xirallic’, a powder made up of aluminium oxide, coated with titanium dioxide, tin oxide and auxiliaries (Merck, 2017[92]), however here this substance is used for its high colour intensity, sparkle effect and depth.

Aliphatic diisocyanate-based polyurethane coatings have additionally been described for use in automotive coatings. They are marketed as providing excellent weather resistance and can resist yellowing or paint degradation due to sunlight, gloss retention, resistance to water, oil and chemicals such as salt which adds to vehicle corrosion and scratch resistance (American Chemistry Council, 2021[93]). These coatings can be applied by spray and are usually fast drying (American Chemistry Council, 2021[93]) and an example identified is CathoGuard® by BASF, that is based upon a two-component acrylic resin system with an isocyanate activator (Kwasny, 2021[94]).

Protection from the environment can also be conferred in the E-coats of automotive coatings such as the epoxy-based, such as ‘AquaEC series’ by Axalta, which has been described to have excellent mechanical properties, chemical stability and corrosion prevention (Axalta, 2021[95]).

5.2. Paints in the Architectural and Chemical Industry

5.2.1. PFASs Used in the Architectural and Chemical Industry

In paints both FPs and SC PFASs are used. FPs are used in a similar way to powder coatings as described in section 4.1 on Powder Coatings in the Chemical Industry and in Cable & Wiring. FPs such as PVDF, ECTFE and FEVE are used as binders in the paints in both industries for their corrosion resistance and weather resistance properties. Also, as with powder coatings, FPs are used as resins formulated in paints. An example of a commercially available PVDF paint is ‘Kynar’ (Arkema, 2021[66]) which is used as a ‘cool roof’ paint, i.e. allows UV rays to be reflected efficiently to decrease the temperature of roofs and lead to energy savings in hot weather.

Other examples of FP paints include, ‘ZEFFLE’ which is an FEVE-based paint formulated for use in buildings and construction, bridges, storage or reaction tanks, oil and gas and other applications (Daikin, 2020[56]). This product can be incorporated into solvent-based formulations as well as water-based formulations and can be cured with heat in a factory or air cured at ambient temperature. Furthermore, ‘Lumiflon’ is a FEVE based resin which can be incorporated into solvent and water-based paints, for uses in bridge coatings and coil coatings for architectural applications. It is marketed as being efficient for use in the field, for re-coating purposes, as well as to manufacture pre-coated panels. (Lumiflon USA, 2021[96]).

A FP with a two carbon (C2) PFAS unit has additionally been manufactured for similar purposes to Lumiflon and Zeffle, known as ‘Interfine 3399’. This has been described to be used for specifically anticorrosion purposes where a high standard of cosmetic appearance is essential, for example in bridges, sports stadia, offshore platforms, chemical plants and other applications (AkzoNobel, 2020[97]).

FP paints have also been manufactured to protect specific metal components from corrosion, which can happen due to environmental conditions such as moisture and salt, or in industrial environments where harsh chemicals can be present. These anti-corrosion paints can be PTFE based, for example AFT Fluorotec manufacture PTFE paints for this purpose (AFT Fluorotec, 2021[38]).

A SC PFAS based on a C6- structure, Hexafor, has additionally been used in architectural coatings due to its weather resistance properties (Maflon, 2020[28]). Primarily this is used as a fluorosurfactant; therefore, it is described in more detail in section 5.3.

Figure 5.3. Fluoropolymer Application in the Chemical Industry - Chemical Reactor Coating

Source: CMA reaches 45% destruction milestone by U.S. Army Material Command is used royalty-free from CC BY 2.0.

5.2.2. Non-Fluorinated paints in the architectural and chemical industry

Paints used in these industries are similar to the powder coatings used. Alternatives for binders in paints to confer the durability and other required performance characteristics include acrylic, a popular choice which is a water-based latex paint, PS-based formulations such as tetrashield PC-4000 (Eastman, 2021a[30]), PU, alkyds, phenolic or silicone alkyds, phenolic, vinyl and epoxy coatings (STO, 2020 - 21[17]) (USDA, 1998[31]). However, epoxy coatings,are more suited for use in indoor applications, because they tend to degrade in sunlight (Secoa, 2021[98]). An account of the comparative performance of FPs and non-fluoro paints is provided in section 7.2.

5.3. Paints for Household Applications

5.3.1. PFASs Used in Paints for Household Applications

Here, SC PFAS surfactants in paints are used for their levelling and wetting properties rather than for corrosion or weather resistance properties. Therefore, these paints are less likely to be used in industrial applications and more likely to be used for general household applications and indoors, where corrosion resistance and weather resistance are less important than overall aesthetics. Adhesion and anti-block properties are also important for household paints.

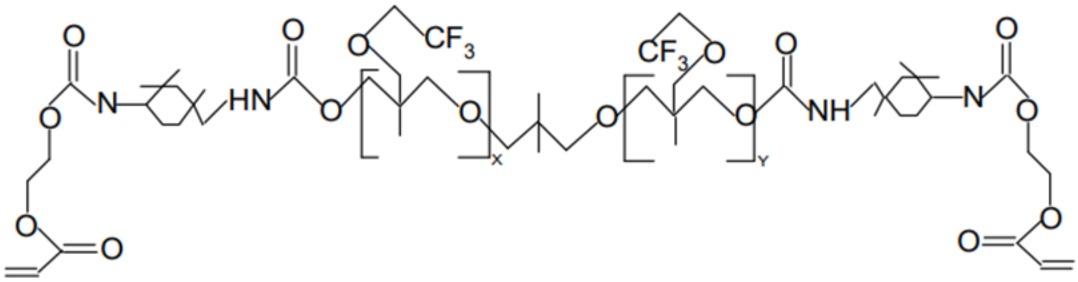
SC PFASs commercially available include PFASs based on a four carbon chain (C4-) PFBS such as FSAs which display a comparable low surface tension to FPs used in architectural paints (Poulsen, Jensen and Wallström, 2005[44]). Manufacturers claim that very little FSA is necessary to achieve a significant surface tension reduction, whereas by contrast hydrocarbons and silicone alternatives, require more product to significantly reduce surface tensions and achieve the required wetting and levelling effects (3M, 2016[27]). FSAs are also reported to perform well as second coats (3M, 2016[27]).

Adhesion refers to the ability of the paint to stick well to the surface being coated and not peel. Sometimes when a surface is being repainted with a different formulation, adhesion can be an issue, this is referred to ‘second coat adhesion’ and is mainly an issue in surfaces like metals and plastics being coated with water-based formulations. To prevent this, the surface tension of the new layer of paint needs to be similar of the previous coated layer, therefore if the previous layer has been coated with a fluorosurfactant, to ensure good adhesion, the new layer also needs to have the same low surface tension. Sometimes it is even necessary to remove the initial layer of paint for the new layer to stick well to the surface (Poulsen, Jensen and Wallström, 2005[44]).

Other SC PFASs are fluorinated polyethers which encompass SC C4 fluorinated ethers such as methyl nonafluorobutyl ether and methyl nonafluoroisobutyl ether. PolyFox is a fluorinated polyether line manufactured by OMNOVA Solutions Inc. (Omnova Solutions Inc., 2020[99]). These polymers are based on ether links within the polymer backbone and perfluoroalkyl side chains (C2- or C3-). The basic structure of a PolyFox formulation is illustrated in Figure 5.4. Again, these fluorosurfactants lower the surface tension, leading to a better spreading of the coating and an even application. PolyFox was manufactured primarily for use in floor polish and varnishes, however it has been used in paints as well, although the performance has not been described (Poulsen, Jensen and Wallström, 2005[44]).

Again, these fluorosurfactants lower the surface tension, leading to a better spreading of the coating and an even application. PolyFox was manufactured primarily for use in floor polish and varnishes, however it has been used in paints as well, although the performance has not been described (Poulsen, Jensen and Wallström, 2005[44]).

Figure 5.4. Structure of PolyFox Substance with C2- Side Chain



Source: (Poulsen, Jensen and Wallström, 2005[44])

PFASs based on a C6- structure have also been used as fluorosurfactants. Hexafor by Maflon is an example of this (Maflon, 2020[28]). The main function of C-6 telomer-based FSAs (they can be either polymer or small molecule based) are to provide anti-blocking properties (i.e. reduce tackiness of painted surfaces), oil repellence and early dirt pick-up resistance. This product includes the active substance of Hexanoic acid, 2,2,3,3,4,4,5,6,6-undecafluoro-, a SC PFAS, which gives it its general PFAS properties such as low surface tension and corrosion resistance. Hexafor products have been used in paints, as anti-blocking, levelling and wetting agents (Maflon, 2020[28]).

‘Capstone’ is a product line of FSAs made of partially fluorinated alcohol-substituted glycol substances (Chemours, 2017[100]), a fluorotelomer based product. These are used in aqueous or solvent-based paints for their anti-blocking, low surface tension and good wetting/levelling properties.

5.3.2. Non-Fluorinated Paints for Household Applications

Silica-based coatings such as silicone polymers made of silanes and siloxanes, have been used in paints as levelling and wetting agents (Elkem, 2020[29]). They can also be hydrophobic and resistant to high temperatures, i.e. show some of the characteristics of PFAS due to the dense structure of silicone resins. For example, two products made of silicone polymers have been identified in this project (Worlée-Chemie, 2020[101]). The first is made of non-ionic modified silicone polyethers and the second is a mixture of a silicone polyether and a diocylsulfosuccinate in ethanol and water (Poulsen, Jensen and Wallström, 2005[44]). However, to create a superior low surface tension, which is needed for good spreading of the paint and to apply as an even surface, silicones are often modified with fluorine (ShinEtsu, 2017[102]).

Sulfosuccinates such as Hydropalat 875 by Cognis (BASF, 2020[103]), a sulfosuccinate mixed with water and 2,2 dimethylpropane-1,3-diol, has been described to be used in water-based coatings for metal, wood and plastic, for example in furniture. These are additives that act as wetting agents.

6. The Use of PFASs and Alternatives in Varnishes

6.1. PFASs Used in Varnishes

In a similar way as with paints, PFASs used in varnishes are SC PFASs that act as FSAs. These include the same types of SC PFASs used in paints for household applications. Varnishes encompass floor finishes, floor polish, coatings for countertops, waxes and protective coatings.

PFASs based on C4 PFBS such as FSA products, fluorinated polyethers such as PolyFox (Omnova Solutions Inc., 2020[99]), fluorotelomers such as Capstone (Chemours, 2017[100]) and SC PFASs based on a C6 structure such as Hexafor (Maflon, 2020[28]) have all been identified as commercially available fluorosurfactants in paints but can additionally be used in varnishes.

PolyFox products were initially manufactured for use in floor polish and varnishes, similarly to Hexafor products. Capstone has been described for use in floor finishes, waxes and floor polish.

SC PFASs have also been manufactured in combination with silica-based substances. Silicone polymers themselves have similar properties to PFASs but used in combination with PFASs they are able to provide very low surface tensions. ‘SILRES 38’ (AICIS, 2020[104]) is a solvent-based mixture made up of silane, siloxane and a PFAS (1-butanesulfonic acid, 1,1,2,2,3,3,4,4,4-nonafluoro-), with a carbon chain length of less than C8 (AICIS, 2020[104]). It has been marketed for use in floor finishing, coating for countertops and invisible protective coatings. It has also been marketed for use on building walls to make the removal of oil, grease and paint, from surfaces that have been coated, easier (Wacker, 2020[105]).

A varnish that protects the dimensional stability (i.e. against shrinkage and swelling) of wood and other cellulosic materials has been identified that consists of PFAS and non-PFAS components. PFAS such as fluorinated hydrocarbons, fluorinated acrylic or methacrylic acid esters, fluoroalkane sulfonic acids and salts of fluorinated carboxylic acids confers water repellence properties. The non-PFAS, polymeric component can be PU, PS, PA, epoxy, acrylic polymers, vinyl polymers including polymers made from ethylene unsaturated monomers such as polybutene, oligomers of above chemistries and natural polymers (Gao et al, 2006[106]).

Furthermore, PFAS have been developed to be used in road and pavement markings and traffic signs. For example, 3M use a PBSF (perfluoro-1-butanesulfonyl fluoride) based surfactant in a variety of different pavement marking and reflective sheeting products to retroreflect light from vehicles at night. PBSF-enabled surfactant is used also in inks used to image the reflective sheeting used for traffic signs.

6.2. Non-Fluorinated Varnishes

In relation to FSAs used in paints, the problem of second coat adhesion has been mentioned above. For floor polishes an alternative is to use soft waxes instead of hard waxes. Soft waxes are a mixture of cleaning agents and polish and instead of fluorosurfactants these are formulated with non-ionic or anionic surfactants. Hard waxes refer to older waxes which were previously formulated with PFAS-related compounds and had to be removed before applying a new layer. Soft waxes have the advantage of being able to be applied directly on the previously coated surface, without adhesion related issues (Poulsen, Jensen and Wallström, 2005[44]).

Similarly, sulfosuccinates have been used in varnishes, specifically as wood primers. These can be used as wetting agents for water-based applications and have been suggested to be able to replace fluorine-based wetting agents. An example of these products ‘EDAPLAN LA 451’ (Munzing, 2021[107]), which is based on a sulfosuccinate derivative in ethanol (19%) and water (12.5%) (Poulsen, Jensen and Wallström, 2005[44]).

Another product which has been identified is Hydropalat 875 by Cognis, a sulfosuccinate mixed with water and 2,2 dimethylpropane-1,3-diol, has been used as an overprint varnish (Stockholm Convention on POPs, 2016[108]; Cognis, 2020[109]).

7. Efficacy of Alternatives

7.1. The Efficacy of PFASs and their Alternatives in Coatings

7.1.1. The Performance of PFASs and their Alternatives

Cable and Wiring Applications

In order to compare the performance of PFAS cable and wiring compared to cable and wiring using alternatives, the specific properties of the PFASs used in specific cable and wiring applications as well as their functionalities need to be considered (see sections 2.1 and 4.1).

Stakeholders contributing to this report have indicated that PFAS FPs are used for their specific combination of properties in specific applications. In particular, FPs are used for their thermal and flame resistance/retardancy properties, ability to repel moisture (hydrophobic), their outstanding dielectric (insulation) properties, high-end use temperature rating and resistance to corrosion for example from chemicals. Examples of FP used include PTFE, FEP, ECTFE and PFA. Stakeholders have also pointed out that FP cables and wires are out competed by other materials in applications where physical strength is needed.

Specific examples where FPs are used include in aerospace which requires low smoke emissions, low flame spread, chemical resistance as well as a 200 °C rating e.g. wiring in wings where exposed to high temperature and kerosene; in cars close to the catalytic convertor which is a high temp area; use in the chemical, oil and gas industry (STO, 2020 - 21[17]); and LAN cables for buildings which have low smoke emissions, low flame spread and good electrical insulation performance (Cable World, 2021[110]). It is also important to note that the required performance of cables and wires may vary according to the end use application, for example cable and wiring used in residential applications might not need as high performance levels for these parameters compared to cable and wiring used in industrial applications.

Considering cables used in commercial buildings, riser cables (cables rising vertically in the building walls) compared to cables in the plenum space (the space that is used for air circulation in heating and air conditioning systems, typically between the structural ceiling and the suspended ceiling or under a raised floor), significantly stricter fire resistance performance are required for plenum cables (Nicab, 2021[111]). LAN ethernet cables are also required to meet strict fire performance standards (TrueCable, 2021[112]). Consequently, the polypropylene, polyethylene (PE), or polyvinylchloride (PVC)-based jackets that may be used for riser cables cannot be used for plenum or LAN cables. Instead plenum cables are typically FP-based but may also use other materials if they have been treated with fire retardants separately (STO, 2020 - 21[17]).

Table 7.1. shows a detailed performance comparison of electrical insulation properties of different materials used for cable and wiring coatings for applications where electrical insulation, temperature and water-resistant properties are very important. Comparing the values for dielectric breakdown voltage, melting point and water absorption, FEP and PFA have significantly higher electrical insulation, temperature resistance and water resistance

performance than PE or PVC-based materials, making them ideal coating for the applications requiring these properties. PTFE and PFA are particularly effective when melting points in the 260 – 327 °C range are required (STO, 2020 - 21[17]). Polyamide (PA) can be used for similar higher temperature applications but its electrical insulation properties are not significantly lower than PFA. In general, FP-based materials performed better across the range of parameters shown here.

Table 7.1. Comparison of Electrical, Temperature and Water Resistance Performance of Cable and Wiring Coatings

Parameter	Unit	PTFE	FEP	PFA	LDPE	HDPE	PVC	PA
Dielectric constant	[-]	2.05-2.10	2.10	2.06	-	-	-	-
	[-]	2.05-2.10	2.10	2.06	2.3	2.32	-	3.5
Dielectric Breakdown Voltage	[kV/mm]	23.6	80	79	33-36	22	30-50	30-40
		(at 0.2mm)	(at 2.25mm)	(at 2.25mm)				
DC resistance	[Ohm*cm]	>10^18	>10^17	>10^18	>10^14	>10^15	>10^12->10^14	>10^12->10^14
Arc resistance	s (seconds)	>300	>300	>300	-	-	-	120-180
Melting point	Deg C	327	266-270	302-310	105-111	130	-	220-300
Continuous service temp.	Max deg C	260	200	260	100	120	80	120-150
Water absorption	%	<0.01	<0.01	<0.03	<0.02	<0.01	>1.0	>2.0

Note: PTFE= polytetrafluoroethylene, FEP= fluorinated ethylene propylene, PFA= perfluoroalkoxy alkane, LDPE= low density polyethylene, HDPE= high density polyethylene, PVC= polyvinyl chloride and PA= polyamide.
Source: (Yoshimoto and Shimizu, 2018[45]) & (CPTH, 2018[113])

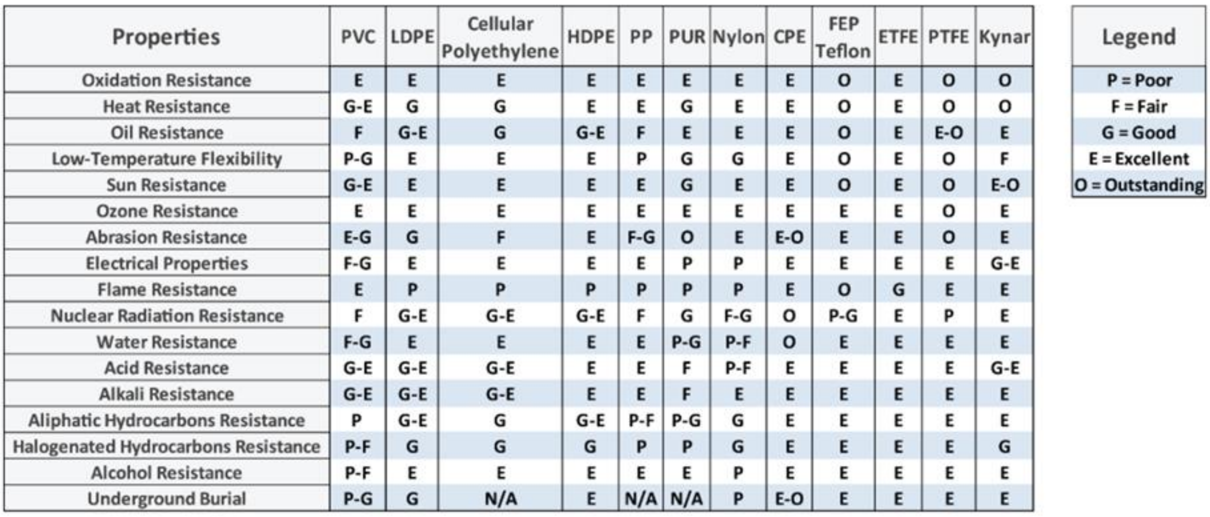
Across an even broader range of parameters, FPs are reported to perform consistently well in comparison to non-fluoro alternatives as is shown Figure 7.1 (Sycor, 2021[114]). The performance of FPs: FEP, ETFE, PTFE and PVDF-based Kynar are compared across a range of 17 parameters that may be required in various cable and wiring applications. It can be seen the FPs, with only few exceptions, perform between excellent and outstanding. The performance of the alternative materials such as polyolefins such as PE, PVC or PU are more mixed. Nevertheless, alternatives may have sufficiently high performance for many applications.

Epoxy-based coatings, used in both of these applications, have one of the highest thermal stabilities compared to other non-PFAS alternatives, as they can resist temperatures up to 200 °C (Metal Coatings Corp., 2020[33]). This is still lower than FPs used like FEP, which can resist temperatures up to 230 °C (Metal Coatings Corp., 2021[59]). Other coatings used in both applications such as coatings based on PS and polyurethane can all generally only resist temperatures up to 100 °C. For cable and wiring, additional coatings can be used such as polyolefin which can be crosslinked to increase the number of bonds within its structure, which increases its thermal stability up to 200 °C (Champlain Cable, 2018[61]). PVC is another coating used in cable and wiring, however similarly to PS and PU it can generally only withstand temperatures up to 100 °C.

PU has been developed as a cable and wiring insulator due to its hydrophobic and corrosion resistant properties. Halogen-free polyurethanes have been identified (Eland Cables, 2020[62]). An advantage of PU is its mechanical strength which makes it useful for cables and wiring that need to withstand wear and tear. However, PU does not have good dielectric properties (Habia Cable, 2020[36]) and therefore is only suitable for low voltage cables connection insulation (3M, 2020[63]). PVC, on the other hand, is flame resistant and relatively inexpensive. However, it only has limited resistance to acids and solvents.

Corrosion resistance is an equally important property of both coatings. Epoxy coatings and polyurethane based coatings both provide suitable corrosion resistance due to their stability to various chemicals. However, PS coatings only have some resistance to solvents and acids. This is similar to coatings used only in cable and wiring, such as PVC. Polyolefins on the other hand have good corrosion resistance when crosslinked.

Figure 7.1. Comparison of the Performance of Materials Used in Cable and Wiring Coatings



Properties	PVC	LDPE	Cellular Polyethylene	HDPE	PP	PUR	Nylon	CPE	FEP Teflon	ETFE	PTFE	Kynar
Oxidation Resistance	E	E	E	E	E	E	E	E	O	E	O	O
Heat Resistance	G-E	G	G	E	E	G	E	E	O	E	O	O
Oil Resistance	F	G-E	G	G-E	F	E	E	E	O	E	E-O	E
Low-Temperature Flexibility	P-G	E	E	E	P	G	G	E	O	E	O	F
Sun Resistance	G-E	E	E	E	E	G	E	E	O	E	O	E-O
Ozone Resistance	E	E	E	E	E	E	E	E	E	E	O	E
Abrasion Resistance	E-G	G	F	E	F-G	O	E	E-O	E	E	O	E
Electrical Properties	F-G	E	E	E	E	P	P	E	E	E	E	G-E
Flame Resistance	E	P	P	P	P	P	P	E	O	G	E	E
Nuclear Radiation Resistance	F	G-E	G-E	G-E	F	G	F-G	O	P-G	E	P	E
Water Resistance	F-G	E	E	E	E	P-G	P-F	O	E	E	E	E
Acid Resistance	G-E	G-E	G-E	E	E	F	P-F	E	E	E	E	G-E
Alkali Resistance	G-E	G-E	G-E	E	E	F	E	E	E	E	E	E
Aliphatic Hydrocarbons Resistance	P	G-E	G	G-E	P-F	P-G	G	E	E	E	E	E
Halogenated Hydrocarbons Resistance	P-F	G	G	G	P	P	G	E	E	E	E	G
Alcohol Resistance	P-F	E	E	E	E	E	P	E	E	E	E	E
Underground Burial	P-G	G	N/A	E	N/A	N/A	P	E-O	E	E	E	E

Legend
P = Poor
F = Fair
G = Good
E = Excellent
O = Outstanding

Note: PVC= polyvinyl chloride, LDPE= low density polyethylene, HDPE= high density polyethylene, PP = polypropylene, PUR= polyurethane, CPE = chlorinated polyethylene, FEP= fluorinated ethylene propylene, ETFE = ethylene tetrafluoroethylene, PTFE = polytetrafluoroethylene, Kynar is based on polyvinylidene fluoride PVDF (Arkema, 2021[66]).
Source: Based on (Sycor, 2021[114])

PVC is flame resistant (Sycor, 2021[114])[18], however the other coatings mentioned above such as epoxy, PS, polyurethane and polyolefins need flame retardants to be added to be flame resistant, of which possibilities are available that are marketed as halogen-free (Habia Cable, 2020[36]).

For cable and wiring coatings, good dielectrical properties are essential so they can be used as insulators. Almost all of the alternatives mentioned above can be used as insulators, except for polyurethane, therefore it is only suitable as a

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[18] To note, (Sycor, 2021[114]) reports the use of PVC for insulation and jacketing having ‘excellent’ flame resistance. However, other sources (Black Box, 2021[152]) indicate otherwise, possibly reflecting the use of flame retardants together with PVC for these applications.

jacket (outer layer coating) in cable and wiring not as an insulator (Habia Cable, 2020[36]).

From the above, if high performance is required over the full range of parameters depicted in Figure 7.1. it can be assumed FPs would be the consistent choice for use in cable and wire coating materials. However, because the majority of cable and wire applications do not require such a wide range of high performance (STO, 2020 - 21[17]), alternative materials are sufficient.

Solar Panels

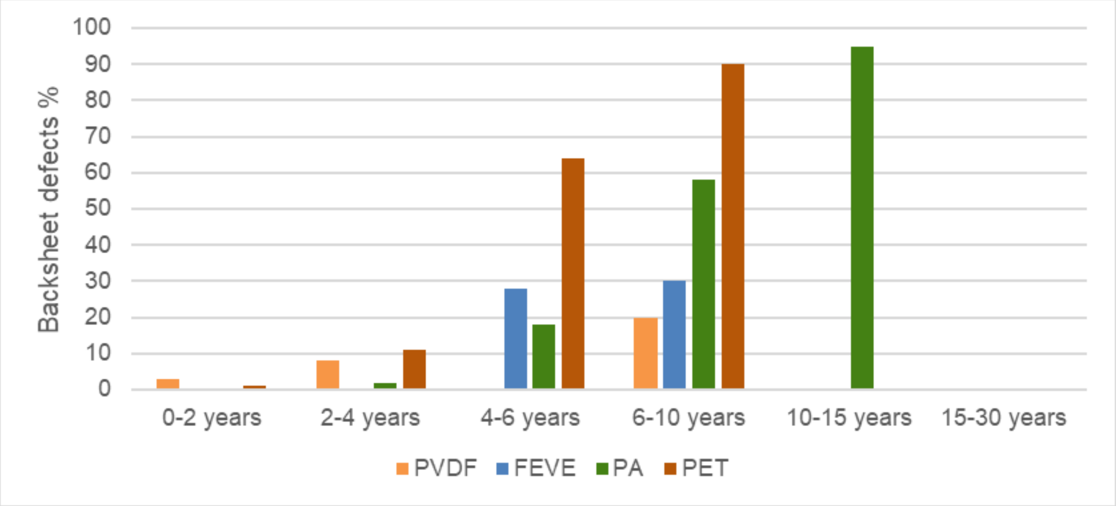
This section compares the performance of FPs used in PV modules with their alternatives; specifically when used in frontsheet and backsheet applications (see section 4.5). In frontsheet applications, FPs such as ETFE, FEP, FEVE and ECTFE are used commercially where their function is to reduce the loss of light reaching the solar panel by preventing the build-up of dust, dirt and air pollutants on the surface of the solar panels, the so-called 'lotus effect' (Mozumder et al., 2019[79]), as well as conferring weather and corrosion resistance. The latter is particularly important for coming in contact with saltwater environments. Additionally, these coatings need to be durable, to increase lifetime of the solar panels.

In backsheet applications, similar properties are needed, the coatings are intended to protect the PV modules so are required to be resistant to moisture, heat, humidity and to reflect UV light, to protect the PV modules from UV degradation. PVDF and FEVE have been used as well as non-fluoro alternatives such as PAs and PET. Again, these coatings need to be durable. Since the properties of FPs in frontsheets and backsheets is similar, available backsheet studies have been used in this project as representative of FP performance in PV modules.

It is important to note stakeholders contributing to this study have reported they are continually seeking to improve the performance of solar panel front and backsheet formulations (STO, 2020 - 21[17]). In part this is because a small improvement in sunlight conversion efficiency, such as 1% can result in a 5% reduction in the overall cost of the solar power generation system (DuPont, 2021c[115]).

A 2020 study investigated the global reliability of PV modules in the field, looking specifically at backsheet degradation (DuPont, 2020b[83]). The percentage defects in backsheets were investigated such as outer-layer (air side) and inner-layer (cell side) cracking, delamination and yellowing using a range of materials: FPs such as PVDF and FEVE compared with non-fluoro alternatives such as PAs and PET. The results in Figure 7.2 show that after 0-2 years, PVDF had the highest percentage of backsheet defects at around <5%, compared to other FPs and non-fluorinated alternatives. After 2-4 years, PET had the highest percentage of backsheet defects at just above 10% and this continued to rise up to the 6-10 year interval. PA defects steadily rose from the 2-4 year interval up to over 90% by the 10-15 year interval and nearly a four-fold cumulative increase in PVDF outer-layer cracking defect rates between year four and year nine after installation in China, Europe, India and North America. The 2020 study points out deeper backsheet cracks have led to backsheet delamination, exposing the core layer to elements and leading in some instances to inverter tripping and ground faults.

Figure 7.2. Backsheet Defect Rates



Note: PVDF = polyvinylidene fluoride PVDF, FEVE = fluoroethylene vinyl ether, PA = polyamide, PET = polyethylene terephthalate.
Source: Based on (DuPont, 2020b[83])

The results from (DuPont, 2020b[83]) also indicate inner layer cracking has been frequently encountered in fluoroethylene vinyl ether (FEVE) and polyethylene terephthalate (PET) backsheets. This can directly impact power through delayed inverter starts, ground faults and fires. Based upon the defects measured in this study, all of the materials surveyed showed performance limitations. Materials such as the FPs PVDF and FEVE generally outperformed their non-fluoro counterparts, PET and PA in terms of the defect rates with the effects becoming more marked from the 6-10 year time interval onwards. New silicon-based sealants and adhesives entering the market may address some of these issues (DuPont, 2021d[116])

A shorter-term study was conducted by Daikin (Daikin America Inc., 2012[117]), comparing the performance of fluorinated and non-fluorinated backsheets. The study was principally focused on an FEVE-based FP, Zeffle and its performance compared to PET and other FPs in a series of experiments intended to simulate performance following weathering and aging. Parameters measured included gloss retention, tensile strength and colour. In these tests study showed PET exhibited significantly decreased gloss after 5000-7000 hours, where gloss retention fell to 1.6-10.1%, compared to FPs which were above 63.4% gloss retention. To note 7000 hours is equivalent to approximately 1.6 years aging, hence this study was short relative to the expected lifetime of solar panels which is around 20-30 years. The colour retention study used method ASTM E313[19] (ASTM International, 2021[118]), to calculate yellowness (a measure of colour degradation due to UV exposure). It was demonstrated that PET showed visible yellowness, and therefore degradation, after 500 hours under UV light, compared to FPs which showed little to no change after 7000 hours.

The performance of alternatives other than PET and PC has been reported. Metallization pastes, such as Solamet® are commercially available and it is

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[19] Standard practice for calculating yellowness and whiteness indices from instrumentally measured colour coordinates.

claimed they have the ability to enhance performance of the PVs to the order of 0.1% (DuPont, 2021c[115]). These metallic pastes are based upon a silver and/or aluminium base and enhanced performance is observed when measuring the conductance and firing of the PV cells. However, data on the defect rates over time of these metallic pastes has not been identified.

PS has been identified as another alternative base material which is available for use in solar panel backsheets, for example in ‘Mylar UVHPET’ developed by DuPont Teijin Films (DuPont Teijin Films, 2021[82]). This material has been used not only as an alternative to FP-based films, but also to traditional PS films. This film has been described to offer enhanced UV protection and moisture resistance. Comparison has also been made by DuPont between fluorinated backsheets and this PS film, with results suggesting that fluorinated backsheet materials may present environmental and health issues in relation to disposal, whereas the ‘Mylar UVHPET’ backsheet may not generate hazardous materials in high-temperature disposal processes (DuPont Teijin Films, 2021[82]).

A summary of the commercially available materials and their properties are available in Table 7.2., based on data collected in the stakeholder consultation (STO, 2020 - 21[17]). All the materials are assumed to have a high transparency to incident light. From the available data it can be seen that some FPs such as FEVE, FEP, ETFE perform well compared to their non-fluoro competitors such as PET on key parameters such as light and corrosion resistance, self/easy clean properties and are lightweight and flexible (important if the solar panel is being placed on roofs for example). However, the backsheet failure rate for FPs such as FEVE and PVDF were only considered fair. Alternative materials are commercially available although data on the key performance parameters was largely absent.

Table 7.2. Summary of Materials Identified in this Study Used in Solar Panel Front and Backsheets and their Properties

	Frontsheet	Backsheet	Failure Rate (10 yrs.+)	UV resist	Salt Spray Resist	Self/ Easy Clean	Fire Safety	Flexibility	Light Weight
ETFE	Y	Y	No data	Y	Y	Y	Y	Y	Y
FEP	Y	Y	No data	Y	Y	Y	Y	Y	Y
ECTFE	Y	N	No data	Y	Y	Y	No data	No data	No data
FEVE	Y	Y	F	Y	Y	Y	Y	Y	Y
PVDF	No data	Y	F	No data	No data	No data	No data	No data	No data
PET	No data	Y	P	N	No data	N	No data	Y	Y
PC	No data	No data	No data	Y	No data	No data	Y	No data	Y
Glass	Y	Y	No data	Y	Y	No data	Y	N	N
PS	No data	Y	No data	Y	No data	No data	No data	Y	Y
PA	No data	Y	F	No data	No data	No data	No data	No data	No data
MP	Y	Y	No data	No data	No data	No data	No data	No data	No data

Note: ETFE = ethylene tetrafluoroethylene, FEP= fluorinated ethylene propylene, ECTFE = ethylene chlorotrifluoroethylene, FEVE = fluoroethylene vinyl ether, PVDF = polyvinylidene fluoride, PET = polyethylene terephthalate, PC= polycarbonate, PS= polyester, PA = polyamide, MP = Metallization pastes, Y= yes, N = no, F= fair, P=poor.
Source: (STO, 2020 - 21[17])

7.1.2. Comparison of the Costs of PFASs Versus Alternatives

Cable and Wiring Applications

The relative costs of cable and wire coating have been compared with reference to the specific example of cable costs for a commercial property. This is based on information obtained during the stakeholder consultation carried out for this study (STO, 2020 - 21[17]) and from suppliers of supply chain management services such as Graybar (Graybar, 2021[119]).

The example in Table 7.3. illustrates the estimated cost differential between using FP or non-FP cables in a commercial office space of approximately 3716m2. As can be seen there is a significant cost differential between using fluoro- and non-fluoro cables and this is a possible reason for not choosing FP-based cables unless it is necessary to do so for performance reasons e.g. fire safety. This is illustrated in the case example in Figure 7.3.

Table 7.3. Estimated Cost of Cables in a Commercial Property (40,000 ft2 (3716m2))– Fluoropolymer Versus Non-Fluoropolymer Coated Cable

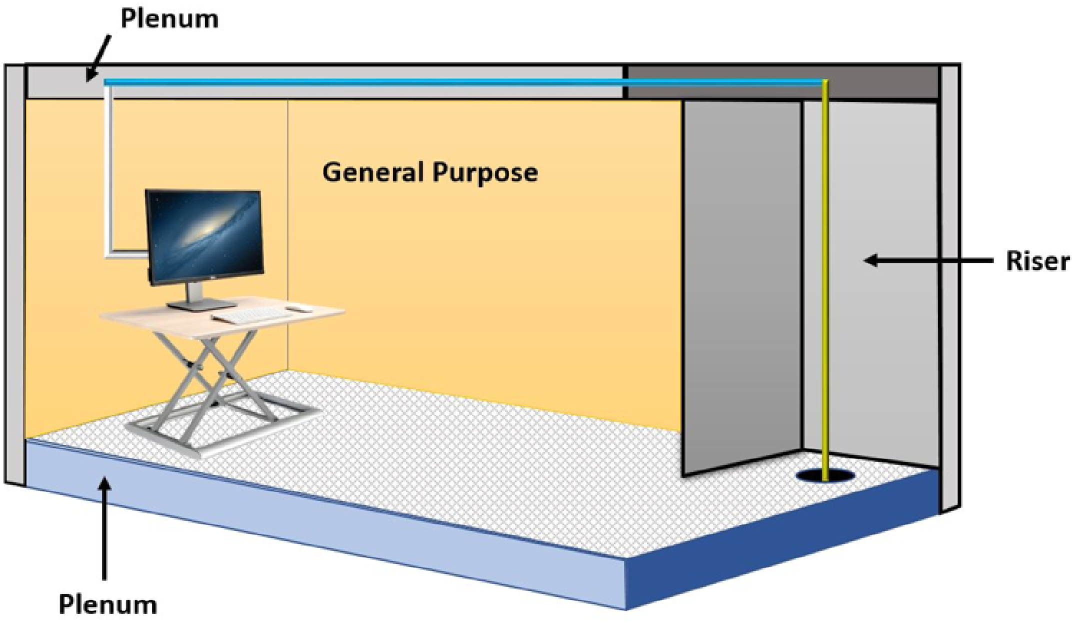
	Non-Fluoropolymer Cable*	Fluoropolymer Cable*
Number of drops of cable†	220	220
Cost per drop ($)	125 - 200	250 – 500**
Total cost of cable ($)	27,500 – 44,000	55,000 – 110,000

Note: *Based upon the relative costs of riser and plenum LAN cable on Graybar (Graybar, 2021[120]) in which LAN cable is between 2 – 2.5x the cost of riser cable; **Calculated by multiplying cost for riser cable by 2 and 2.5. † A 'drop' is a run of cable that originates in a server room and ends in an office, cubicle, or workstation.

Figure 7.3. Case Example: Comparative Cost of Commercial Building Cables

FPs have been shown have been shown to have a consistently higher performance across a broader range of parameters than their non-fluoro competitor materials. However, evidence collected for this study indicates that FPs are not the first choice of material for cable and wire coatings and instead are generally only used where it is the only available material left to satisfy the specification for a particular application (STO, 2020 - 21). A possible explanation for this difference in choice of materials is the relative cost of fluoro- versus non-fluoro-based materials.

Plenum fluoropolymer cables are 2.0 – 2.5 x cost of cost of riser non-fluoro cables



Plenum: Building spaces above a drop ceiling or below raised floors used for air flow or air distribution systems
Riser: Building area such as shafts or ducts that run vertically through one or more floors
General Purpose: All other areas that are not plenum or riser and on the same floor

Estimated cost differential for a commercial building (3,716 m^2) of using fluoropolymer versus non-fluoro cables = $27,500 – 110,000 (see Table 7.3.)

Solar Panels

Direct cost comparisons between fluorinated and alternatives have not been possible from the available information. However, several comparisons have been identified between using and not using anti-soiling coatings in PV modules. These are summarised below.

PV modules are most efficient when 100% of the surface of the solar panel is available, therefore efficiency decreases when there is dust or dirt build up on the surface of the solar panels. This efficiency decrease can occur in two ways, firstly build up on the surface of the PV modules means less sunlight is able to reach the solar panels, and secondly the build-up of dirt necessitates an increased use of water in arid areas in order to clean the solar panels. Therefore, anti-soiling or easy clean coatings on solar panels can yield high economic benefits (Lorenz, Klimm and Weiss, 2014[120]).

The study conducted by (Lorenz, Klimm and Weiss, 2014[120]) modelled the potential earnings of different commercially available anti-soiling solar panel systems which employ three types of anti-soiling coatings (hydrophobic, hydrophilic and super hydrophilic with photoactive properties) to the earning potential of an uncoated solar panel system. The composition or suppliers of the anti-soiling panel systems were not specified in the study, but the suppliers were noted to be ‘two global providers of solar glass’, suggesting they are anti-soiling coatings that have been identified in this project.

UV transmission was observed using FTIR/UV-Vis spectroscopy[20] of uncoated glass substrates compared to substrates coated with anti-soiling coatings and then an economic simulation was carried out to estimate profitability in real life conditions. During the soiling tests, it was determined that the UV transmission values were reduced up to 6.8% for uncoated glass and 1.5% for PV modules coated with anti-soiling coatings. The economic simulation was conducted for three environments in the arid regions of Riyadh, Saudi Arabia and in varying weather conditions over a 1-year period and in this simulation the efficiency of the anti-soiling coating compared to non-coated glass was set at 30%, less the daily dust accumulation on the surface.

The results for a reference year, with an average of five rain events and four sandstorms, showed that an average of 3.2% yearly gain in profitability could be made by using an anti-soiling coating and an optimised cleaning strategy compared using uncoated glass.

Potential savings for EU manufacturers and consumers from improved production efficiency by using ETFE instead of glass in solar panels was calculated (Plastics Europe, 2017[121]). It was assumed that a production efficiency increase of 2% could be achieved if ETFE modules were used instead of glass modules. Taking into account the average price of PV modules and the European production of PV modules, and assuming a hypothetical situation where all PV modules were made of ETFE instead of glass, it was determined that EU PV manufacture with ETFE could yield savings of €43.2 million. Additionally, taking into account how many new PV modules were installed in the EU in 2015 and assuming that the savings from increased production efficiency were passed on the customers, it was determined that EU PV customers could save up to €87.5 million.

A similar study was conducted for the US (Wood Environment & Infrastructure Solutions UK Limited, 2020[122]), however here the savings were higher due to the average PV module price being over 5 times more expensive in the US, as well as the total US capacity of PV modules being over 17 times greater than in Europe. Here the hypothetical situation where all PV modules were made of ETFE instead of glass, yielded potential savings of $4000 million, and for US PV customers, this yielded potential savings of $140 million.

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[20] Fourier-Transform Infrared Spectroscopy/ultraviolet-visible spectroscopy techniques.

7.2. The Efficacy of PFASs and their Alternatives in Household and Architectural Paints

7.2.1. The Performance of PFAS and their Alternatives

To judge the performance of PFAS paints compared to their non-PFAS alternatives, it is essential to consider the properties of PFASs and their functionalities. They are used in household paints as surfactants to lower the surface tension of the paints and therefore function as levelling and wetting agents, provide anti-blocking properties and confer an easy-clean capability (see section 5.3). In the architectural and chemical industry FPs are used for their weatherability properties and resistance to chemical reactivity, respectively (see sections 5. .1 and 5.2).

One of the parameters for measuring the technical performance of surfactants in water is known as the critical micelle concentration (CMC). The CMC refers to the concentration of surfactants above which the surface tension cannot be further lowered i.e. the levelling and wetting effects are at their maximum. It is also the concentration at which micelles (oleophobic molecules arrange themselves in a spherical form) start to form (Dataphysics, 2020[123]) (Kruess, 2020[124]) – hence the name. A lower CMC indicates a lower surface tension that can be achieved using a particular surfactant i.e. the higher performance the surfactant has with respect to levelling and wetting in paints. Surface tension can be measured in dynes/cm. A graph displaying the surface tension with increasing concentration as well as the CMC of a surfactant solution is shown below. Different surfactants have curves with higher or lower CMCs.

Surface tension studies publicly available have compared surface tension measurements of paints with no surfactant, with FSAs and with non-fluorinated alternatives. For example, in one report it was found without surfactants, the lowest surface tension (CMC) in different paints was 38.4 dynes/cm. With hydrocarbon surfactants this reduced to 27.6 dynes/cm, with silicone surfactants this reduced further to a minimum of 22.8 dynes/cm and with a PFAS surfactant this reduced to a minimum of 19.7 dynes/cm. For comparison water has a high surface tension of 72.86 mN/m (equivalent to dynes/cm[21]) (Speight, 2020[125]). Therefore, according to this study FSAs that are used in household paints performed markedly better than their non-PFAS alternatives. This is supported by comments made by stakeholders that FSAs are currently essential for their paints and coatings and the CMC values of alternatives such as hydrocarbon and/or siloxane based surfactants cannot match that of FSAs, even at higher doses (STO, 2020 - 21[17]).

For external paints used in architecture, weatherability consists of several components. FP paints are UV resistant which means their degradation by UV light is minimal and they can tolerate high UV conditions, for example, in high-intensity sunlight environments. This degradation is often related to ‘chalking’, where a chalk-like surface forms on top of the paint, and therefore means that it must be repainted. Degradation can also be thought of in terms of gloss retention, where instead the ability of the paint to retain its gloss-like surface is measured. FP paints are also said to be corrosion-resistant and therefore can

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[21] 1 dyne/cm = 1 mN/m.

withstand harsh weather conditions such as on bridges near oceans where the salt content is high.

Weatherability can be measured using a QUV test[22] which reproduces sunlight, heat and moisture through fluorescent UV lamps and using condensing humidity and/or water spray (Q-Lab, 2020a[126]). There are two types of QUV tests, QUV-A and QUV-B, where either UV-A lamps or UV-B lamps are used. Xenon arc testing is another method of testing which involves the same concept, however, uses xenon arc light sources, humidifiers and heaters to reproduce the weathering effects (Element, 2020[127]). ASTM-G7[23] is a standard for environmental exposure testing of non-metallic materials. It is understood that the weatherability of materials can be different depending on the location and weather conditions, and so results from one exposure in a location cannot be used to determine the overall durability of the material. However, if repeated in several locations under different climates, or if combined with other tests it can provide a basis for durability (Q-Lab, 2020b[128]). Finally, EMMAQUA[24] is an accelerated weathering test which works using natural sunlight along with reflective mirrors (Atlas, 2020[129]). In this test the sunlight is concentrated onto the desired specimen using ten reflective mirrors and is said to provide the intensity of approximately eight suns. It is said to realistically reproduce UV degradation in subtropical conditions and in arid desert environments, as it can provide a spectral match to sunlight (Atlas, 2020[129]).

A variety of weatherability tests have been conducted on fluoroethylene vinyl ether (FEVE) (for example Lumiflon (AGC, 2020[130])) paints which are used in architectural, aerospace, bridges, transportation, marine, industrial maintenance and alternative energy applications. In these tests FEVE was compared to non-fluorinated alternatives and with other PFAS coatings. The results of these tests are summarised below.

A Xenon test measured gloss retention in percentage against exposure time in hours, of Lumiflon compared to PVDF, another FP used in this application; and with acrylic urethane (a type of polyurethane), a non-PFAS alternative. The results show that both Lumiflon and PVDF have much higher gloss retention over time than acrylic urethane. The gloss retention of acrylic urethane decreases to around 28 % remaining in 2000 hours (83 days) which is a significant decrease compared to the gloss retention of both FPs which is around 100 % at this point. The difference between Lumiflon and PVDF seems to grow at around the 6000 hour mark (250 days) where the gloss retention of Lumiflon is still around 100 % whereas the gloss retention for PVDF is around 82 %. Even after 12000 hours (500 days) the gloss retention of Lumiflon was at 95 %. Therefore in this test, FEVE performed slightly better than PVDF, but significantly better than the non-PFAS alternative, acrylic urethane.

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[22] Developed by Q-Lab, QUV stands for Q-Lab Ultraviolet (Q-Lab, 2020b[128])

[23] ASTM G7: Standard Practice for Atmospheric Environmental Exposure Testing of Non-metallic Materials (ASTM, 2020[147])

[24] EMMAQUA: accelerated outdoor weathering test using a solar concentration device that is equatorially mounted with mirrors for acceleration.

An EMMAQUA weathering test was also conducted. Here the gloss retention in percentage was measured against radiant energy[25] (MJ/m^2) for fluorourethane (a Lumiflon material), PVDF and polyurethane. In this test the gloss retention of PU seemed to decline rapidly after 800 MJ/m^2 from 80 % to 22 %. Whereas both FPs at this point still had around 90-100 % gloss retention. At 2800 MJ/m^2 both FPs were around 80 % gloss retention whereas polyurethane at this point had declined below 20 %. This weathering test therefore points to a much higher degradation of non-PFAS paints by UV light.

Finally, a QUV-A test was conducted. The gloss retention in percentage was measured against the hours of QUV-A exposure for FEVE urethane, PS urethane, acrylic urethane and siloxane. FEVE urethane performed the best, retaining 80 % gloss after 15000 hours (625 days). Siloxane performed the second best, retaining around 42 % after around 9000 hours (375 days) whereas at this point PS urethane and acrylic urethane were both at around 20 % gloss retention. Similarly to the previous experiments, the FEVE FP-based coating performed significantly better than its non-PFAS alternatives.

Information provided by another manufacturer (Daikin, 2020[131]) showed similar weatherability results with Zeffle^{TM} a FP resin used in architectural paints (a copolymer of tetrafluoroethylene and vinyl monomer, FEVE) compared to non-PFAS alternatives. In this report it was indicated that not only did their FP coating need to be applied in a thinner layer (45 µm) at the outset than the non-PFAS alternatives, but after 2000 hours the there was no thickness reduction. Whereas with polyurethane, the coating had to be applied at 82 µm and the thickness had reduced to 68 µm after 2000 hours. Scanning electron microscope (SEM) images from weathered coatings showed that initially the FP coating that was applied was much smoother than the non-PFAS alternative acrylic urethane. This suggests that the levelling and wetting of the FP coating was more efficient than in the non-PFAS coating. Secondly, after 6 years the FP coating had remained unchanged according to the SEM images, whereas after 3 years the acrylic urethane coating had significantly degraded.

Late in the preparation of this report comparative performance data was received for PS-based paint formulations in which PS-based paints performed well (up to 70% higher gloss retention) in weathering tests compared to acrylic paints. Comparative performance data for PS-based paints versus paints with FP binders was reportedly in preparation (Eastman, 2021b[132]).

From the above the weatherability and durability of PVDF and FEVE-based resins is better than alternatives, meaning they are likely to perform better in these respects for example in external architectural applications.

7.2.2. Comparison of the Costs of Alternatives

Research and discussions with manufacturers of FP-based architectural paints have indicated their initial cost are higher than the non-PFAS alternatives such as polyurethane. However, this greater initial outlay contrasts with the longer-term expense when considering the frequency and cost associated with recoating. Since the FP-based paints have improved weatherability performance compared to non-PFAS alternatives the use of these alternatives requires more

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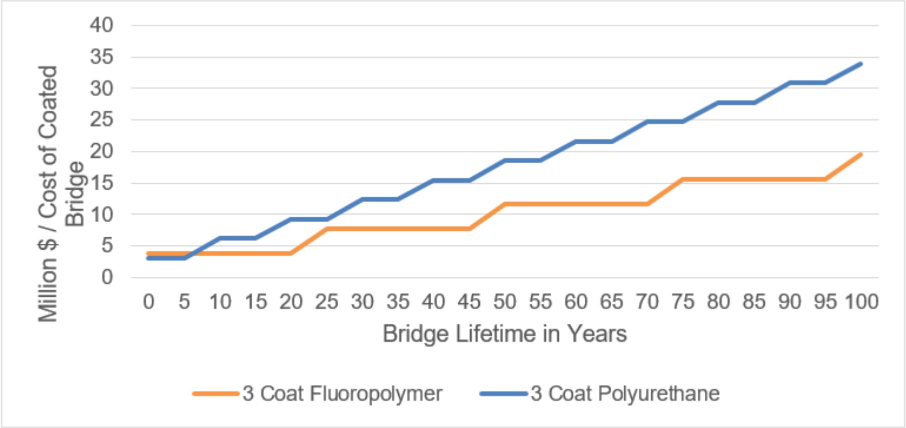
[25] For example, the mean daily global irradiation in January in the UK between 1993-2007 was from 0.5-3.5 MJ/m^2 and in July was between 12-21 MJ/m^2 (Gkousarov, 2014[148]).

frequent recoating, with the additional labour and traffic stoppage costs that re-painting entails. This is shown in the case example below.

Figure 7.4. Case Example: Bridge Painting

FP paints have been used on bridges for their increased weatherability and durability compared to non-PFAS alternatives. They are claimed to be easy to clean, stain-resistant and used on bridges due to their long lifetime. An analysis on the costs over time of field painting a bridge with a FP-based paint (FEVE) system and a non-PFAS alternative (polyurethane), paint system, was conducted (University of Wisconsin-Milwaukee, 2013). The data was based on an estimate of a bridge span of 2000 ft and a total of 650,000 square feet to be painted. The conclusion was that per coating it would cost approximately 26 % more with the FP-based coating compared to polyurethane. However, after 30 years it was concluded that the total cost for the polyurethane coating would cost 16 % more than the FP-based coating, owing to the faster degradation of the non-PFAS coating and therefore a need for more frequent recoating, with associated labour and material costs.

The Cost of Painting a Bridge Over Time with PFAS and Non-PFAS Paints



The above graph represents the increase in cost in the long term for the non-PFAS coating system, polyurethane, due to lower durability and higher recoating frequency.

Source: (University of Wisconsin-Milwaukee, 2013[133])

8. Uptake and Market Penetration of Alternatives

8.1. Market Overview and Penetration of Alternatives

8.1.1. Introduction

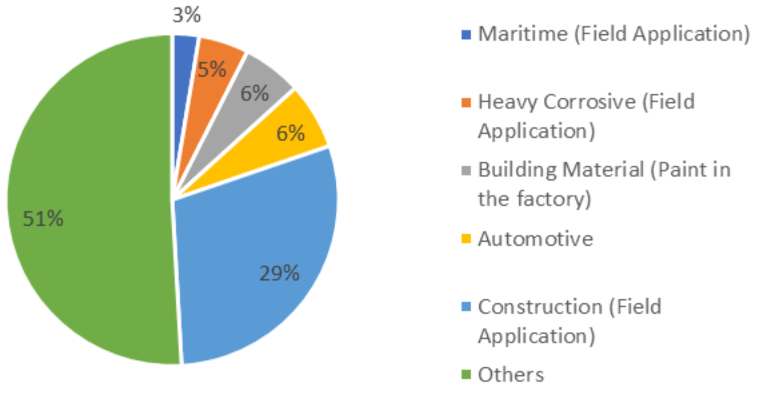
A market overview that comprehensively shows the relative market penetration of alternative substances compared to fluoro-based substances in each of the CPVs segments has not been possible to construct from publicly available information. Commercial reports that would have facilitated such an overview are available (GMI, 2020[134]) (Absolute Reports, 2020[135]), but their costs are prohibitive for use in this study.

Nevertheless, elements of such an overview have been possible from a combination of public information and estimates that have emerged from the stakeholder consultation for this report (STO, 2020 - 21[17]). The results of this are shown below and in order to protect commercial interests the actual sources have not been consistently revealed. Where possible, the information has been divided between PFAS and non-fluoro materials and between paints, coatings and varnishes. However, these distinctions have not always been possible from the available data.

8.1.2. Market Overview

The segmentation of the paint market in Japan, EU, North America & South America and Asia into different applications has been estimated by stakeholders that have contributed to this report (STO, 2020 - 21[17]) and this is shown in Figure 8.1.

Figure 8.1. Segmentation of the Paint Market in Japan, EU, NASA* and Asia (2011)



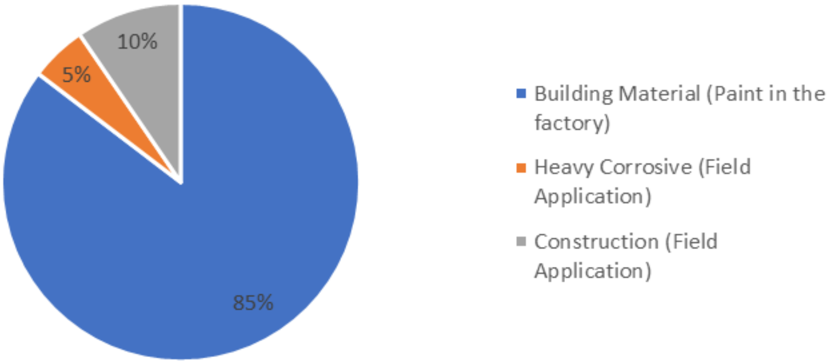
Note: *North and South America.
Source: (STO, 2020 - 21[17])

Figure 8.1. shows that the largest segment of the paint market is for ‘other’ applications which unfortunately is not defined but is likely to include household paints. The second largest application type is that occupied by construction (buildings and other external structures) and heavy corrosive field

applications (bridges, industrial storage or reaction tanks, industrial plants). Building materials painted in factories, automotive paints and paints used in the maritime sector are smaller segments.

Figure 8.2. shows how FPs are used across some of the applications shown in Figure 8.1 for Japan, EU, NASA and Asia. The majority of FP usage occurs in building materials, where the paint is applied not in the field, but in the factory. From Figure 8.1. it can be seen that this category makes up only 6% of the overall paint market, indicating the market size of FP usage in paints makes up a small proportion of the overall paint market - approximately 8%[26] and alternatives to FPs therefore comprise 92%. This is broadly consistent with information from other stakeholders that estimate FPs occupy approximately 1% market share of the ‘architectural protective coatings’ segment (STO, 2020 - 21[17]). The global protective coatings market was an estimated value in 2019 of $16 billion, equivalent to 2.5 billion litres (STO, 2020 - 21[17]).

Figure 8.2. Estimate of Fluoropolymer Use in Paint Applications in Japan, EU, NASA and Asia (2011)*



Note: *Based on two specific fluoropolymers, PVDF and FEVE.
Source: (STO, 2020 - 21[17])

Plastics Europe (Plastics Europe, 2017[121]) report that in 2015 a total of 52,000 tonnes of FPs were sold in the EU for all uses, of which an unspecified portion was CPVs. From the descriptors of the various segments, it appears the market segments below will contain FPs used as CPVs and as illustrated in Figure 8.3:

- Transport applications – including insulation for cables and wires, aircraft interior coatings for flame retardancy, non-fouling and easier cleaning, car manufacturing and manufacturing automotive components.
- Chemical & power sector - used in piping, vessels, fluid-handling components, filters, vents, cable coatings, FPS in linings and components prevent corrosion in demanding environments.

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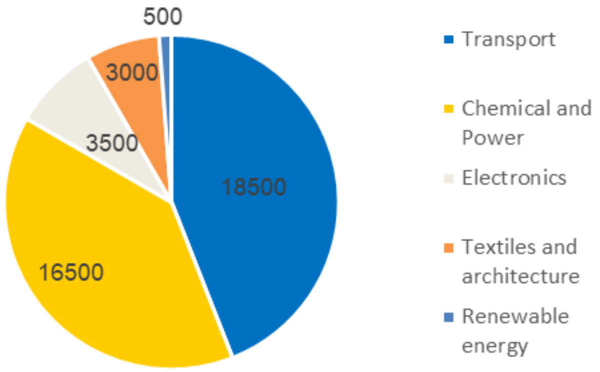
[26] Calculated as follows: (85% of 6) + (10% of 29) + (5% of 5).

- Electronics – for example coatings for semi-conductors, display touch screen panels and coatings.
- Textiles and architecture – construction materials such as bridges and coil coatings used on the external faces of buildings as well as specialised building materials such as that used in stadia domes and cool roofs.
- Renewable energy –the majority of uses were for coatings, for example used in solar panels as well as wind turbine paints and coatings.

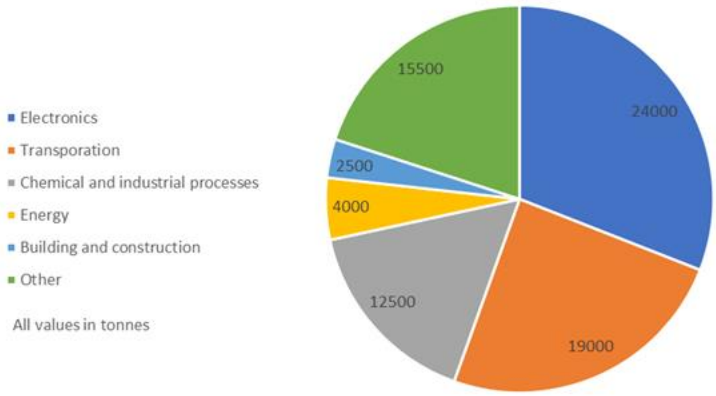
Figure 8.3. Tonnes of Fluoropolymers used in Coatings, Paints and Varnishes in the EU (2015)



Note: Based on (Plastics Europe, 2017[121])

A similar report for the US market (Wood Environment & Infrastructure Solutions UK Limited, 2020[122]) showed a broadly similar segmentation of FPs across various applications – see Figure 8.4.

Figure 8.4. Tonnes of Fluoropolymers Used in the US Market (2018)



Source: Based on (Wood Environment & Infrastructure Solutions UK Limited, 2020[122])

8.1.3. Specific Applications

In the US, a breakdown of the volume of powder coatings (used in the chemical industry, for cable and wires and in architectural applications – see section 4.) consumed by resin type was evaluated by the ChemQuest Group and ChemQuest Technology Institute (ACA, 2019[136]). Here, the largest share was attributed to hybrids (26%), followed by PS TGIC[27](25%), urethane (15%), epoxy (10%) and acrylic and other (7%). TGIC-free PS, super durable PS, PVC and other thermoplastics accounted individually accounted for 5% or less of the market. FPs, specifically PVDF and FEVE combined were estimated to account for only 1% of the market share signifying that FP-based powder coatings are a niche market and 99% of the powder coating market is occupied by non-FP materials.

Specifically for use in cables and wire coatings, stakeholders have commented FPs have a very small percentage of the overall market share in all types of markets, probably of the order of much less than 10% (Stakeholder Consultation, 2020 - 21), therefore more than 90% of coatings for cables and wires are non - FP.

To provide the anti-dirt and anti-fingerprint properties of touch screens, stakeholders estimate that FPs occupy nearly a 100% market share of for example the upper end of the smartphone market. For smartphone models with a lower price it is unlikely FP coatings will be used and either no anti-dirt/fingerprint coatings are used or a non-fluoro coating.

The coil coatings market in the European Economic Area (EEA) was estimated to be worth €500 – 600 million. Coil coatings of either steel or aluminium are used in the construction industry for example on metal roofs and building panels and these applications account for 90% of the coil coatings market (EU, 2016[137]). Stakeholders have estimated FPs such as PVDF and FEVE comprised between 9 – 12% of this market in terms of value in the European Union (EU); and therefore 88 – 91% of the value is for non-FP materials (STO, 2020 - 21[17]). Stakeholder estimates (STO, 2020 - 21[17]) based on the 2021 market are that FPs comprise approximately 3% in the EU and alternatives such as remainder polyurethane, acrylic & polysiloxanes-based coatings occupy the remaining 97% of the market. In North and South America FPs were estimated in 2011 to occupy 17% in terms of value of the overall coil market; therefore non-FPs 83%, FPs 24% and non-FPs 76% in Japan and FPs/non-FPs are approximately 50% in Asia as a whole (STO, 2020 - 21[17]).

8.1.4. Summary of Market Information

From Table 8.1 it can be seen that non-fluoro alternatives generally occupy a significantly larger market share than their FPs. This is particularly apparent for the global/OECD regions paint market, architectural protective coatings and cable & wire coatings markets. However, this data is based on 2011 markets so the current relative market shares could have changed. In particular, the relative market share of PFAS/Non-PFAS may be outdated as there has been an evolution of regulations in the EU that restricts the use of many solvents in paint and as a result PFAS use in paints has grown in the recent years (STO, 2020 - 21). Table 8.1 also indicates that in some segments of the market FPs have a

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[27] TGIC is the curing agent triglycidyl isocyanurate.

larger market share. This is particularly apparent with a niche application such as conferring anti-dirt and anti-fingerprint properties on upper end smartphones and commercial/industrial touch screens.

Table 8.1. Summary of Market Share Information Presented in this Report

	Regions	Year of Data	Alternative Materials Market Share (%)	PFAS Materials** Market Share (%)
Paint Market	EU, NASA††, Asia	2011	92$	8
Architectural Protective Coatings	Global	2021	99	1
Powder Coatings	US	2018	99	1
Cable & Wire Coatings	EU, NASA††, Asia	2021	>90	<< 10
Coil Coatings*	EU	2011	88-91	3-12
	NASA††	2011	83	17
	Japan	2011	50	50
Smart Phone and Touch Screen Coatings (upper end models /commercial/industrial)	Global	2021	~0	~100
Smart Phone Coatings (lower or mid-range models)	Global	2021	~100†	~0

Note: *Coil coatings of either steel or aluminium are used in the construction industry for example on metal roofs and building panels; **PVDF and FEVE are often cited as the fluoropolymers used; †Non-fluoro coatings or no coatings; †† North and South America. $ This data might be outdated as there has been an evolution of regulations in the EU that restricts the use of many solvents in paint and as a result PFAS use in paints has grown in the recent years
Source: (STO, 2020 - 21[17])

8.2. Regulatory Influence on Substitution

It is outside of the scope of this study to carry out a detailed regulatory analysis for the wide range of materials and uses covered by this study. During the course of this study a particular regulatory situation has been identified that demonstrates how regulations can influence either the use of PFAS or its alternatives for CPVs. This is further described below.

One such example is the use of national specifications in Japan (JIS K 5659) that are sufficiently stringent to require the mandatory use of FP-based protective paints for new build and recoating of steel bridges (JIS, 2008[138]). The first versions of this standard advised the use of fluorinated paints but as further data became available it has now become mandatory. Consequently bridge repainting is estimated to only to be carried out every 60 years (STO, 2020 - 21[17]). Conversely, in other countries such as Germany, only non-fluoro protective paints such as PU-based paints are permitted as protective coatings for bridges (BAST, 2020[139])[28].

More generally, there has been a trend and a growing regulatory pressure over the last 20 years to replace LC PFASs, their salts and their potential precursors with alternatives (see section 2.). This trend is largely driven by concerns related to the properties of certain LC PFASs with respect to health and the environment and consequent regulatory decision-making, for example, from the Stockholm Convention (Stockholm Convention, 2021[7]). Some SC PFASs are also now coming under regulatory scrutiny in some regions such as the EU (ECHA, 2019[140]) (ECHA, 2021[141]). However, discussions with contributors to this study have not pointed to this trend as being a particular driver for substitution (STO, 2020 - 21[17]).

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[28] Stakeholders have noted evidence that this may be changing (STO, 2020 - 21[17]).

9. Status of the shift to alternatives and its sustainability

9.1. Cables and Wiring

Considering coatings for cables and wiring, if a high performance is required over a wide range of parameters it could be assumed FPs would be the consistent choice for use in cable and wire coating materials. However, because the majority of cable and wire applications do not require such a wide range of high performance (STO, 2020 - 21[17]), alternative materials appear to be selected over FP coatings.

Contributor stakeholders have commented that the cost differential between FP cables and cables using alternative materials is a very important market driver for this selection. FP cables are only chosen as a last resort where performance requirements such fire safety necessitate their use (STO, 2020 - 21[17]). The example illustrated in Table 7.3 supports this, with FP cables costing between 2 – 2.5 times that of alternatives; a formidable differential when considering an entire building (see case example Figure 7.3).

Market data identified for this study is also consistent with the use of FPs as a last resort. FPs have a very small percentage of the overall market share in the cable and wire coating market, probably of the order of much less than 10% (STO, 2020 - 21[17]), therefore more than 90% of coatings for cables and wires use alternatives.

9.2. Front and Backsheets in Solar Panels

The performance of frontsheet and backsheet materials for solar panels has been assessed in section 7. Based upon the available data, FPs generally outperform non-fluoro alternatives for a longer period of time over a range of parameters such as light and corrosion resistance and are lightweight and flexible (important if the solar panel is being placed on roofs for example). However, the data presented here indicates backsheet defects accumulate in both FPs and non-fluoro materials. Whilst further alternative materials were identified as commercially available, data on the key performance parameters for these was largely absent.

Specific market penetration data comparing PFASs and alternative materials has not been identified in this study. However, it may be expected that as experience with materials for solar panels increases, the relative performance of PFAS versus alternative materials used in front and backsheets will cause a shift in the market towards the most durable, cost-effective and lightweight materials. In fact, some researchers indicate that while the vast majority of solar panels contain PFASs, this has declined from 95 to 80% in recent years (SolarMagazine, 2021[142]).

9.3. Architectural Protection Paints

FP-based paints are commercially available for use on bridges and from the evidence identified in this study their weatherability and durability performance is superior to that of alternatives such as PU. An analysis on the costs over time of field painting a bridge with a FP-based paint (FEVE) system and a non-PFAS alternative (polyurethane), paint system, was conducted (University of Wisconsin-Milwaukee, 2013[133]) and the conclusion was that per coating it would cost approximately 26 % more with the FP-based coating compared to polyurethane. However, after 30 years it was concluded that the total cost for the polyurethane coating would cost 16 % more than the FP-based coating, owing to the faster degradation of the non-PFAS coating and therefore a need for more frequent recoating, with associated labour and material costs.

The initial and longer term cost differentials between PFASs and alternative paints potentially could be factors for bridge owners choosing PFAS or alternative paints. Other factors that influence the shift in the market are the regulatory requirements described in 8. above, such that in some countries only FP-based protective paints are able to meet the specifications, whereas in other countries only or mainly alternatives can be used. Overall, the market penetration for FPs in architectural protective coatings is very low, of the order of 1% (see section 8.1).

10. Policy recommendations and areas for further work

10.1. List of Recommendations

10.1.1. Recommendations for International Organisations and National Governments

- Conduct further work to understand the potential health and environmental risks of PFAS and non-PFAS alternatives used in CPVs throughout their life-cycle;
- Consider systematic collection of market data by countries on the use of PFAS and alternatives in CPVs;
- Consider a further study to evaluate non-chemical alternatives for CPVs.

10.1.2. Recommendations for Industry Associations and Specific Sectors of Industry

- Make robust scientific information available on the human health and environmental risks of PFAS and their alternatives used in CPVs;
- Participate in future policy initiatives by providing information, e.g., collection of market data. This can be done using aggregated figures to protect confidential business information.

10.2. Background to the Policy Recommendations

Section 10.1 above lists the policy recommendations made as a result of this study. These recommendations are divided according to the intended audience. Several areas for further work are also identified for consideration. The following account provides a background to these recommendations.

10.2.1. Recommendations for International Organisations and National Governments

Although outside of the scope of the current study, interest has been raised in understanding the potential human health and environmental risks that may be associated with both the PFAS identified here and their alternatives, possibly through a complementary study to this report. This information is needed to avoid regrettable substitutions. Whilst information is available concerning the potential health and environmental risks of certain specific PFAS and their alternatives, the coverage is often not comprehensive. It is recommended to consider further work to determine the level of understanding of the potential health and environmental risks of PFAS and non-PFAS alternatives used in CPVs.

One aspect that has hampered this study is the absence of market information in the public domain that is free of charge. Data are available from market research companies but at a prohibitive cost and of mixed reliability (STO, 2020 - 21[17]). The result of this absence of data has been the reliance for this study upon stakeholder contributions to better understand the overall marketplace and particular segments within it. To improve the transparency of the marketplace, and to illuminate market issues (see below), it is recommended that better market data is compiled across the countries. Whilst it is recognised that such data may be commercially sensitive, this can be overcome by the use of aggregation or anonymisation approaches.

Additional studies may be warranted to evaluate the extent to which non-chemical alternatives exist and could replace chemical CPVs. During the course of this study very little information has emerged on the possibility of replacing chemical CPVs or CPV additives with a non-chemical (not-in-kind) alternatives. This may be because such alternatives do not exist for applications such as providing weather and corrosion resistance to bridges; or it may be such information is not available in the public domain. Similarly, recognised sources of data on alternatives (ChemSec, 2021[143]) have not be helpful for this study, either because the alternatives are not sufficiently application-specific or suppliers of potential alternatives have not responded.

Historically, it is evident that non-chemical alternatives did exist in at least some of the applications considered in this study and this aspect should be reviewed with a contemporary perspective. One example is the use of cotton as an insulator coating for electric wiring, a common choice in the early days of electricity (Circuits, 2021[144]).

10.2.2. Recommendations for Industry Associations and Industry Sectors

The recommendations in section 10.2.1 above are aimed at industry associations and industry sectors should be seen as complementary to those aimed at international organisations and national governments. They are aimed at manufacturers and members of the value chains for CPV materials, and their trade associations, and can be achieved using aggregated figures to protect confidential business information.

Both recommendations relate to increasing the transparency of the CPV sector. The first follows several requests during the course of this study to consider the possible human health and environmental risks of both PFAS and non-fluorinated alternatives used in CPVs. The evidence presented here suggests the marketplace for CPVs is currently weighted towards non-fluoro materials and hence evaluating what constitutes regrettable substitution in the CPV sector should entail an understanding of the risks of PFASs used and their alternatives.

The second recommendation is linked to the first and is concerned with increasing the transparency of market data in the CPV sector. As described above there is a general absence of publicly available, free of charge market data and improving this transparency is in the interests of all stakeholders.

11. Uncertainties and Limitations of this Report

There are a number of uncertainties and limitations associated with this report. These are mainly related to the lack of publicly available information in the sector that is free of charge. As a result, preparing this study was challenging and reporting a comprehensive view of the marketplace hindered. This is particularly apparent in the following respects:

- Comprehensive market data on the size, market share and geographical variation of the CPV market across OECD countries.
- Specific PFAS and alternative materials used commercially in CPVs are either unavailable publicly and/or commercially sensitive business information.
- Comparative performance data of PFAS and their alternatives used in CPVs. This is particularly apparent for alternatives where the majority of such data are from members of the value chain that are manufacturing or using PFAS.
- Relative costs of using PFAS versus alternative materials in CPVs.

There is a lack of publicly available data on what formulations, PFAS or alternatives, are used as varnishes. Whilst some data has been available (see section 6) it is recognised that the current study would benefit from further information on materials used as varnishes and sufficient data to be able to carry out a relative performance and costs analysis.

The various limitations described here have influenced the methodology for the preparing this report and the level of confidence that can be attributed to the results. Steps have been taken to fill these data gaps (see Section 1.3) where possible, but the results presented here are based upon the available data set. This is particularly relevant for the results presented in Sections 7 - 9.

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Annex A. Table of Fluorinated and Non-Fluorinated Substances Used in Coatings, Paints and Varnishes

(Blank cells indicate no data available)

PFAS (substance or formulation) or Alternative	CAS No.	Chemical Formula	Trade Name / Brand Examples	Use	Function
Fluorinated Coatings					
PVDF	24937-79-9	-(C2H2F2)n-	Fluoplast, Koflux Class II, Kynar	Powder coating	Corrosion resistance, thermal stability, flame resistance, weather resistance, UV durability
				Radiation curable coating	Dirt resistance, scratch resistance, durability
Perfluoropolyether (PFPE) blend (with polyurethane)	76415-97-9	-(C2F5OC2F5)n-	UVX	Radiation curable coating	Dirt resistance, scratch resistance, durability
ECTFE	25101-45-5	-(C2H4•C2ClF3)n-	Halar	Powder coating	Corrosion resistance, thermal stability, flame resistance, weather resistance, UV durability
				Cable and wiring	Corrosion resistance, insulation, thermal stability, flame resistance, moisture resistance

				Renewable energy	Corrosion resistance, weather resistance
ETFE				Cable and wiring coatings	Corrosion resistance, insulation, thermal stability, flame resistance, moisture resistance
				Renewable energy	Corrosion resistance, weather resistance
FEVE	146915-43-7	-(C2F3X•C2H3OR)n-		Powder coating	Corrosion resistance, thermal stability, flame resistance, weather resistance, UV durability
				Renewable energy	Corrosion resistance, weather resistance
PTFE	9002-84-0	-(C2F4)n-		Cable and wiring coatings	Corrosion resistance, insulation, thermal stability, flame resistance, moisture resistance
				Powder coatings	Corrosion resistance, thermal stability, flame resistance, weather resistance, UV durability, lubricity
				Radiation curable coatings	Smudge resistance in electronics, phone and tablet screens
				Anti-graffiti coatings	Corrosion/weather resistance
PFA				Cable and wiring coatings	Corrosion resistance, insulation, thermal stability, flame resistance, moisture resistance
FEP	25067-11-2	-(C2F4)n(C3H6)m-	Teflon FEP films	Cable and wiring coatings	Corrosion resistance, insulation, thermal stability, flame resistance, moisture

			DuPont Teflon Films		resistance
				Solar panel coatings	Anti-soiling/weather resistance
				Powder coatings	Corrosion resistance, thermal stability, flame resistance, weather resistance, UV durability
ETFE	68258-85-5	-(C2H4C2F4)n-	DuPont Teflon Films	Solar panel coatings	Anti-soiling/weather resistance
PFOS	1763-23-1	C8HF17O3S		Formerly anti-reflective coatings in the semi-conductor industry	Surface activity, regulate reflective characteristics of the coating between metal and photoresist layers
PFOA	335-67-1	C8HF15O2		Anti-reflective coatings in the semi-conductor industry	Surface activity, regulate reflective characteristics of the coating between metal and photoresist layers
Short-chain polymeric fluoroalkyl acid ester	661476-43-3	Fluoroalkyl acid ester, homopolymer, hydrolysed	AZ Aquatar 8	Anti-reflective coatings in the semi-conductor industry	Surface activity, regulate reflective characteristics of the coating between metal and photoresist layers
Perfluoropoly-ether and polyurethane blend				Radiation curable coatings	Smudge resistance in electronics, phone and tablet screens
Formulation of fluoro sulphonamides including PBSF and 1,1,2,2,3,3,4,4,4-nonafluoro-N,N-bis(2-hydroxyethyl)butane-1-sulfonamide	30334-69-1 & 34455-00-0	C8H10F9NO4S C4H2F9SO2N	3M	Wind blade coatings	Moisture resistance

Non-Fluorinated Coatings					
Epoxy	90598-46-2	C21H25ClO5		Powder coatings Cable and wiring coatings	Thermal stability, corrosion resistance. Good dielectrical properties.
Polyester	113669-97-9	(C10H8O4)n		Powder coatings Cable and wiring coatings	Weather resistance and durability. Good dielectrical properties.
Polyurethane	9009-54-5	C17H16N2O4		Powder coatings Cable and wiring coatings	Weather resistance and durability. Moisture resistance, corrosion resistance. Mechanical strength.
Polyolefin				Cable and wiring coatings	Thermal stability and corrosion resistance when crosslinked. Good dielectrical properties.
PVC	9002-86-2	(C2H3Cl)n		Cable and wiring coatings	Flame resistant. Good dielectrical properties.
Silica based				Radiation curable coatings. Cable and wiring (silicone)	Dirt resistance, easy clean, scratch resistance, corrosion resistance.
Polyethylene				Cable and wiring	
Chlorosulfonated polyethylene				Cable and wiring	
Chlorinated polyethylene				Cable and wiring	
Polymethylmethacrylate powder	9011-14-7	(C5O2H8)n	TEXTMATTE 6005	Powder coatings,	Thermal stability, corrosion resistance,

				UV coating	durability, matting and texture.
Nylon				Cable and wiring	
Ethylene-propylene rubber				Cable and wiring	
Neoprene				Cable and wiring	
Thermoplastic elastomer				Cable and wiring	
Fluorinated Paints					
PVDF	24937-79-9	-(C2H2F2)n-	Kynar	Paints	Corrosion resistance, weather resistance.
FEVE	146915-43-7	-(C2F3X•C2H3OR)n-	Zeffle Lumiflon	Water and solvent based paints	Corrosion resistance, weather resistance.
ECTFE	25101-45-5	-(C2H4•C2ClF3)n-		Paints	Corrosion resistance, weather resistance.
PTFE	9002-84-0	-(C2F4)n-	AFT Fluorotec – anti corrosion paints	Paints	Corrosion prevention, lubricity
FEP				Paints	Corrosion prevention, weather resistance
C4-fluorinated polyethers (Such as methyl nonafluorobutyl ether and methyl nonafluoroisobutyl ether)	163702-07-6 163702-08-7	C4F9OCH3		Paints	Wetting and levelling properties.
Fluorinated polyether		Trade Secret	Polyfox	Paints	Wetting and levelling properties.
PFBS based fluorosurfactants or additives	e.g. 1017237-78-3	e.g.2-Propenoic Acid, 2-[methyl[(nonafluorobutyl)sulfonyl]amino] ethyl ester,	e.g.: Fluorosurfactant FC-4430	Paints	Wetting and levelling properties.

		telomer with methyloxirane polymer with oxirane di-2-propenoate and methyloxirane polymer with oxirane mono-propenoate			
Fluorotelomer (Such as partially fluorinated alcohol-substituted glycol substances)		Commercially confidential	Capstone (e.g. Capstone FS-35)	Solvent and water based paints	Wetting and levelling properties.
Short-chain PFAS C6: Hexanoic acid, 2,2,3,3,4,4,5,6,6-undecafluoro-	307-24-4	$C_6HF_{11}O_2$	Hexafor	Paints	Weather resistance, wetting and levelling properties.
Short-chain PFAS mixtures (with silicone)				Paints	Wetting and levelling properties.
Short-chain PFAS C2 (ETHENE, CHLOROTRIFLUORO-, POLYMER WITH 1,1-DIFLUOR)	0009010-75-7	-(C_2F_3Cl)n_	Interfine 3399	Paints	Corrosion resistance, durability
Non-Fluorinated Paints					
Polyester	113669-97-9	$(C_{10}H_8O_4)_n$		Paints	Weather resistance, durability,
Polyurethane	9009-54-5	$C_{17}H_{16}N_2O_4$		Paints	Weather resistance, durability, corrosion resistance
Epoxy	90598-46-2	$C_{21}H_{25}ClO_5$	Amercoat 238	Industrial paint applications	Corrosion resistance, weather resistance
Polysiloxane	63148-53-8	$(SiOR_2)_n$		Paints	Weather resistance, durability
Silicone polymers (made of silanes and siloxanes) (For example, non-ionic modified silicone polyether and a mixture of a silicone polyether and a diocylsulfosuccinate in ethanol and water)	67674-67-3 67674-67-3 (10-15%) and dioctylsulfosuccinate (50-55%)	1,1,1,3,5,5,5-Heptamethyl-3-(propyl(poly(EO))hydroxy) Trisiloxane	Worlée Add 340 Worlée Add 345	Paints	Thermal stability, weather resistance.

Sulfosuccinates (Sulfosuccinate mixed with water and 2,2 dimethylpropane-1,3-diol)	577-11-7	(C4H9-CH-(C2H5)-CH2-O-C(O)-CH2)2–CHSO3^{-} Na^{+}	Hydropalat 875	Water based paints.	Wetting agent.
Fluorinated Varnishes					
PTFE	9002-84-0	(C2F4)n	AquaFlon	Overprint varnishes	Weather resistance, lubricity
C4-fluorinated polyether		Trade Secret	PolyFox	Varnishes	Wetting and levelling agents
C4-fluorinated polyethers (Such as methyl nonafluorobutyl ether and methyl nonafluoroisobutyl ether)	163702-07-6 163702-08-7	C4F9OCH3		Varnishes	Wetting and levelling agents
PFBS based (perfluorobutane sulfonic acid)	1017237- 78-3	C4HF9O3S	Fluorosurfactant FC-4430	Varnishes	Wetting and levelling agents
PBSF (perfluorobutane sulfonyl fluoride)				Pavement marking tapes, reflective sheeting e.g. for traffic signs and road markings and screen printing inks	Bead treatment for retroreflection, dirt repellence, durability.
Fluorotelomer		Trade Secret	Capstone (e.g. Capstone FS-35)	Varnishes	Wetting and levelling agents
Short-chain PFAS C6	307-24-4	C6HF11O2	Hexafor	Varnishes	Wetting and levelling agents
Short-chain PFAS mixtures with silicones. (For example, silane,	375-73-5	C4HF9O3S	Silres 38	Varnishes	Wetting and levelling agents

siloxane and PFAS < C8 (1-butanesulfonic acid, 1,1,2,2,3,3,4,4,4-nonafluoro-))					
Salts of fluorinated carboxylic acids				Wood protectors	Weather resistance, durability
Fluorinated hydrocarbons				Wood protectors	Weather resistance, durability
Fluorinated acrylic or methacrylic acid esters				Wood protectors	Weather resistance, durability
Fluoroalkane sulfonic acids				Wood protectors	Weather resistance, durability
Non-Fluorinated Varnishes					
Sulfosuccinates	Sodium diisotridecyl sulfosuccinate: 55184-72-0	C30H57NaO7S	EDAPLAN LA 451, Hydropalat 875	Varnishes	Wetting and levelling agents for water based applications