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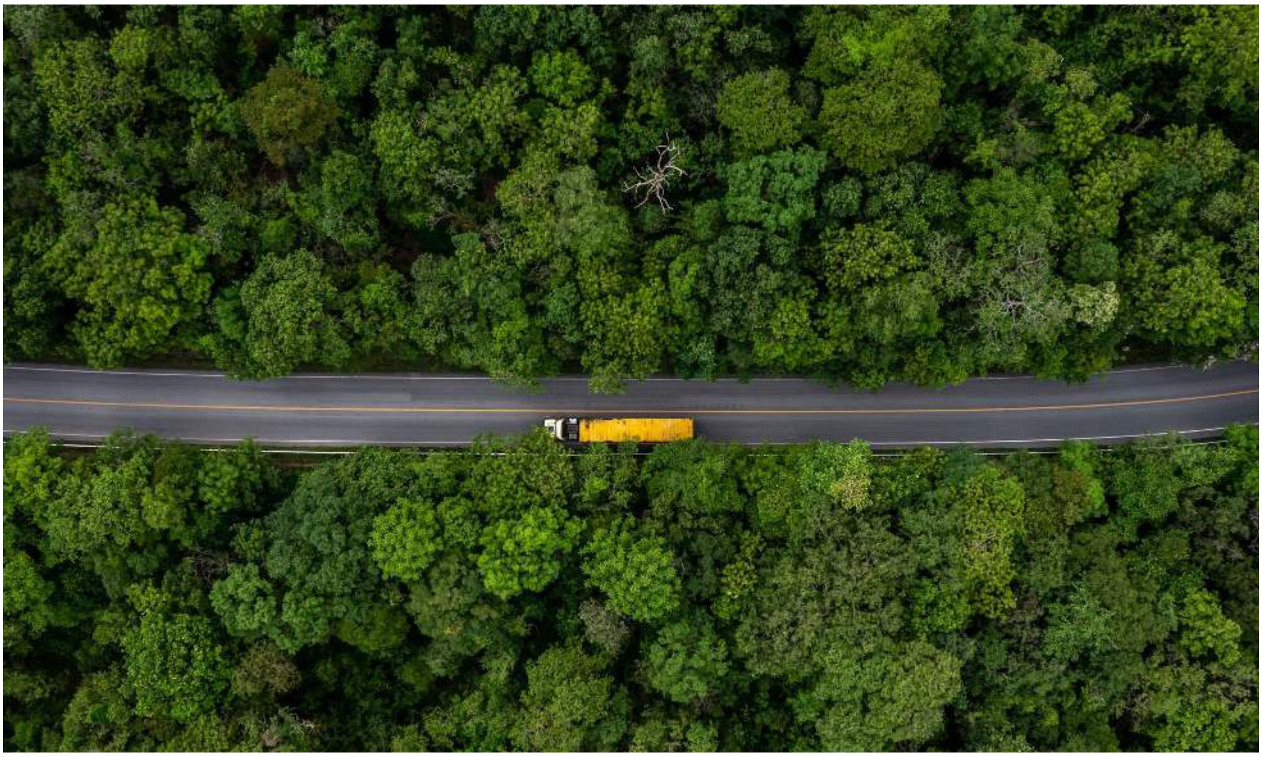
Assessment of Alternatives to Fluoropolymers

For the Transport and Electronics & Semiconductor Sectors



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Assessment of Alternatives to Fluoropolymers

For the Transport and Electronics & Semiconductor Sectors

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The regulatory status of PFAS is continuing to evolve, and the scientific community is generating additional data regarding PFAS properties and potential impact. The conclusions of this report are therefore subject to reassessment as regulations change and additional scientific information regarding PFAS becomes available.

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List of Abbreviations

Abbreviation	**Definition**
ACM	Acrylic Rubber
ACN	Acrylonitrile
AEM	Ethylene Acrylic Rubber
ASTM	American Society for Testing and Materials
AU/EU	Polyester Urethane Rubber/ Polyether Urethane Rubber
bn	billion
CMP	Chemical mechanical planarization
CR	Chloroprene Rubber
DO	Dissolved oxygen
DSC	Differential Scanning Calorimetry
DTA	Differential Thermal Analysis
E10	Gasoline containing 10 % bioethanol
ECHA	European Chemicals Agency
ECO	Epichlorohydrin Rubber
ECU	Engine Control Unit
EPDM	Ethylene Propylene Diene Monomer Rubber
EU	European Union
EUR	Euro
FAM B	Fuels and Additives for Motors B (reference fuel simulating a methanol-containing gasoline blend)
FEP	Fluorinated ethylene propylene
FFKM	Perfluoroelastomer
FKM	Fluoroelastomer
Fuel C	High-aromatic hydrocarbon reference fuel
FVMQ	Fluoro Vinyl Methyl Silicone
GDI	Gasoline Direct Injection
HFP	Hexafluoropropylene
HNBR	Hydrogenated Nitrile Butadiene Rubber

Abbreviation	**Definition**
Hydraulic fluids HFA, HFB, HFC, HFD	Fire resistant hydraulic fluids with high water content (HFA), water-in-oil emulsions (HFB) or water glycol mixtures (HFD)
Hydraulic oils H, HL, HLP	Hydraulic oil without additives (H), with additives for rust and oxidation inhibition (HL), with additives for load-bearing capacity (adding anti-wear properties for high-pressure systems) (HLP)
IIR	Isobutylene-Isoprene Rubber
IR	Infrared
IRM-Oil 309	Industry Reference Material-Oil 309 (reference test oil to test resistance of rubber materials to petroleum-based oils)
ISO	International Organization for Standardization
k	Thousand
NBR	Nitrile Butadiene Rubber
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
PE	Polyethylene
PEEK	Polyether-Ether-Ketone
PFA	Perfluoroalkoxy alkanes
PFAS	Per- and Polyfluoroalkyl Substances
PFHxS	Perfluorohexanesulfonic acid
PFI	Port Fuel Injection
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctanesulfonic acid
PMVE	Perfluoromethylvinyl Ether
POP	Persistent Organic Pollutant
PP	Polypropylene
PVC	Polyvinyl chloride
PVDF	Polyvinylidenfluoride
PTFE	Polytetrafluorethylene
R&D	Research and Development
Ra	Roughness average

Abbreviation	**Definition**
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals (EU Regulation (EC) No 1907/2006)
SBR	Styrene-Butadiene Rubber
SMRE	Semiconductor manufacturing and related equipment
SVHC	Substance of Very High Concern
TFE	Tetrafluoroethylene
Tg	glass-transition Temperature
TOC	Total organic carbon
UPW	Ultra-pure water
USD	United States Dollar
VDF	Vinylidene fluoride
VMQ	Vinyl Methyl Silicone
VOC	Volatile organic compounds

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Executive Summary

PFAS have come under increasing regulatory scrutiny due to concerns about the environmental persistence, bioaccumulation, and toxicity of some individual PFAS. Hence, the EU has implemented substance-specific restrictions for certain PFAS, with ongoing discussions about a group-wide restriction that includes fluoropolymers. Fluoropolymers occupy a distinct and highly specialised position within both the broader polymer universe and the PFAS universe. According to established scientific and regulatory definitions, they are part of the group of polymeric PFAS. At the same time, they differ significantly from many other PFAS because they are high-molecular-weight polymers with a specific set of material properties and use patterns.

Given that fluoropolymers are widely used in critical industries such as automotive, aerospace, electronics & semiconductors, medical, chemical processing, and batteries, a total ban or severe restriction of fluoropolymers would lead to significant challenges in these sectors.

It is therefore important to assess the availability and feasibility of alternative materials or processes that could replace fluoropolymers, factors that should be considered when deciding on restriction conditions and derogation timelines for certain uses.

This report aims to provide an overview on the status of alternative materials for applications critical for two sectors, i.e. Transport and Electronics & Semiconductors.[1] Both of these sectors are of economic and strategic relevance to the EU and comprise a very large number of distinct fluoropolymer uses that have their own unique performance requirements. Illustrative use cases for Transport and for Electronics & Semiconductors have been selected, allowing for a detailed and comprehensive analysis of alternatives. For this, data have been retrieved both from the public domain via an extensive literature research and from relevant downstream fluoropolymer users. The alternatives assessment for each case study follows the general procedure recommended by ECHA for Analysis of Alternatives. In a first step, the most relevant performance criteria that must be met by the substance in question (i.e. fluoropolymers, in this report) for a clearly defined use are identified. These performance criteria form the basis for the assessment of any identified potential alternative, and only those that meet most of the criteria are included for further assessment. This usually includes a hazard assessment to ensure that alternative materials do not result in regrettable substitution, and an assessment of economic feasibility and market availability, as well as other relevant aspects, for example material durability.

Whilst the case study approach is valuable for illustrating the individual steps of alternatives assessment and can facilitate the identification of viable substitutes and substitution strategies, it is important to note that the findings from specific case studies cannot be reliably extrapolated to other uses within the same application area or sector, due to the unique performance requirements and contextual factors involved.

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[1] For details on selection of sectors and case studies and definition according to the ECHA Draft Background Document, see section 2.1

The detailed alternatives assessment is conducted for the following case studies:

Transport	**Electronics & Semiconductors**
Use of fluoroelastomers (FKM) as high-pressure sealing material in gasoline direct injection (GDI) systems Use of fluoroelastomers (FKM) as the inner layer of fuel hoses for high temperature applications in the automotive sector	Use of fluoropolymer-based (PVDF) piping in ultra-pure water (UPW) systems for semiconductor manufacturing

Based on the literature research and on data received from downstream users, the key performance criteria have been identified for the respective fluoropolymer use of each case study, as well as a list of discussed alternatives. The key performance criteria are provided in Table 1, along with a list of potential alternatives (longlist).

Table 1: Key performance criteria of the fluoropolymer for each case study and the list of potential alternatives (longlist)

Case Study	Key Performance Criteria	Potential Alternatives (Longlist)
Use of fluoroelastomers (FKM) as high-pressure sealing material in gasoline direct injection (GDI) systems	Chemical compatibility Temperature resistance Pressure-temperature rating Permeability Long-term sealability	NBR & HNBR ((hydrogenated) nitrile butadiene rubber / acrylonitrilebutadiene-rubber) ACM (polyacrylate) AEM (ethylene acrylic rubber / elastomer) CR (chloroprene rubber) ECO (epichlorohydrin copolymer rubber) VMQ (vinyl methyl silicone rubber)
Use of fluoroelastomers (FKM) as the inner layer of fuel hoses for high temperature applications in the automotive sector	Chemical resistance Fuel Permeability Temperature resistance Physical properties	NBR & HNBR ((hydrogenated) nitrile butadiene rubber / acrylonitrilebutadiene-rubber) ACM (polyacrylate) AEM (ethylene acrylic rubber / elastomer) EPDM (Ethylene propylene diene monomer rubber) ECO (epichlorohydrin copolymer rubber) SBR (Styrene-butadiene rubber) VMQ (vinyl methyl silicone rubber)
Use of fluoropolymer-based (PVDF) piping in ultra-pure water (UPW) systems for semiconductor manufacturing	Low leaching potential Low surface roughness Temperature resistance Fire resistance Mechanical strength Processability & weldability Resistance to sanitization	PP (Polypropylene) PVC (Polyvinyl chloride) PEEK (Polyether-ether-ketone) PE (Polyethylene) Metal piping (e.g. Tantalum, Hastelloy) Elastomers (e.g. EPDM, NBR, silicone) Glass Silicate-based materials

Any alternative that has been discussed in further detail in literature, has been assessed further by downstream users, or has already been used commercially for the discussed case studies, has been shortlisted for a more detailed alternatives assessment against the defined key performance criteria. The results of the assessment of the shortlisted alternatives are provided schematically in Table 2, Table 3 and Table 4. Detailed results are provided in the respective chapters of this report.

Table 2: Result of technical feasibility assessment for the shortlisted alternatives of the case study "Use of fluoroelastomers (FKM) as high-pressure sealing material in gasoline direct injection (GDI) systems". Green indicates that the performance criterion is met by the substance under use condition; orange indicates that the performance criterion is partially met by the alternative under use condition, and red indicates that the performance criterion is not met by the alternative under use condition

Key performance criteria **Alternative / fluoropolymer**	**Chemical compatibility**	**Temperature resistance**	**Pressure-temperature rating**	**Permeability**	**Long-term sealability**
NBR	🟥	🟧	🟧	🟩	🟩
HNBR	🟥	🟧	🟧	🟩	🟩
FKM (fluoropolymer)	🟩	🟩	🟩	🟩	🟩

Table 3: Result of technical feasibility assessment for the shortlisted alternatives of the case study "Use of fluoroelastomers (FKM) as the inner layer of fuel hoses for high temperature applications in the automotive sector". Green indicates that the performance criterion is met by the substance under use condition; orange indicates that the performance criterion is partially met by the alternative under use condition, and red indicates that the performance criterion is not met by the alternative under use condition

Key performance criteria **Alternative / fluoropolymer**	**Chemical resistance**	**Fuel permeability**	**Temperature resistance**	**Physical properties**
NBR	🟥	🟧	🟥	🟩
HNBR	🟥	🟧	🟧	🟩
FKM (fluoropolymer)	🟩	🟩	🟩	🟩

Table 4: Result of technical feasibility assessment for the shortlisted alternatives of the case study "Use of fluoropolymer-based (PVDF) piping in UPW systems for semiconductor manufacturing". Green indicates that the performance criterion is met by the substance under use condition; orange indicates that the performance criterion is partially met by the alternative under use condition, and red indicates that the performance criterion is not met by the alternative under use condition. "NA" indicates that no data was available for the respective criterion

Key performance criteria **Alternative / fluoropolymer**	**Low leaching potential**	**Low surface roughness**	**Temperature resistance**	**Fire resistance**	**Mechanical strength**	**Processability & weldability**	**Resistance to sanitization**
PP	🟧	🟥	🟩	🟧	🟩	🟩	🟧
PVC	🟧	🟩	🟥	🟧	NA	🟩	NA
PEEK	🟩	🟩	🟩	🟩	🟩	🟩	🟧
PVDF (fluoropolymer)	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Table 2 and Table 3 above show that the shortlisted alternatives for the Transport case studies do not meet most of the key performance criteria, and thus fail the technical feasibility assessment. Hence, the currently available alternative materials cannot be used as replacement for fluoropolymers in the discussed Transport case studies and their inherent technical limitations render it unlikely that they can be engineered to do so in the foreseeable future. Furthermore, research efforts to date have not identified any other feasible alternatives. As alternatives are currently not available, substitution for fluoropolymers in the presented Transport case studies is not yet possible. To illustrate the steps needed to identify suitable substitutes for fluoropolymers in typical automotive applications, a description on the substitution on sector level based on publicly available substitution plans from applications for authorisations under EU REACH submitted by the automotive sector has been included in the present report. The assessment concludes that a minimum of approximately 20 years is needed from the initial stages of basic research to develop alternative materials until full replacement of fluoropolymers within the described automotive applications.

As shown in Table 4, for the case study of PVDF-based UPW piping used in semiconductor manufacturing, shortlisted alternatives like PVC and PP do not meet the key performance criteria and thus show no substitution potential. PEEK was identified to be a promising alternative for the investigated case study, even if currently no supporting testing data is available that allow for a conclusive result on the technical feasibility. Developments and newly published data for PEEK should thus continue to be monitored. In addition, downstream users need to test PEEK under use conditions to be able to determine its technical feasibility, as well as to understand the substitution timeline and associated costs were PVDF to be replaced with PEEK for UPW piping. The present report provides a description for the substitution process on case-study level. The timeline for substitution is estimated to be roughly 10 years based on information provided by downstream users, assuming that a suitable alternative material is identified quickly. However, there are also organizational and economic challenges for fluoropolymer substitution within semiconductor manufacturing. PVDF-based piping is only one example of parts/processes within semiconductor & electronics manufacturing that rely on fluoropolymers. Other applications have differing technical requirements, which may be higher compared to UPW piping systems, and substitution would need to consider the whole semiconductor manufacturing system. In addition, stringent requirements as well as cost-intensive changes to the overall production system are estimated to result in expenses of at least EUR 50 million for substitution of PVDF-based UPW piping alone within the semiconductor manufacturing sector.

This report highlights the demanding technical requirements that fluoropolymers must meet in strategically important sectors, such as Transport and Electronics & Semiconductors. It further shows that these requirements are set by industrial standards, legal frameworks and product requirements, which provide the foundation to use and operate fluoropolymer-dependent applications safely, efficiently and for long periods of time under demanding conditions. The alternatives reviewed in the selected case studies either failed to meet the key performance criteria or are still lacking sufficient test data and thus cannot be considered as use-ready technically feasible solutions. The alternatives assessment and the description of the substitution process presented in this report shows that there are currently no alternatives available. A significant drawback of discussing the substitution of fluoropolymers for a particular use in complex products that contain more than one fluoropolymer application, as is the case in automotive vehicles or semiconductor manufacturing facilities, is that any realistic substitution must consider the substitution potential of all individual fluoropolymer components and the potential impacts on the entire product, spanning the full supply chain and all life stages. Gathering the necessary data for such a holistic assessment is both intricate and time-consuming, and coordination among a wide array of stakeholders introduces yet another layer of complexity. As a result, substitution processes for complex products may prove considerably more challenging than for simpler applications.

1. Introduction

Fluoropolymers and their place in the PFAS universe

According to scientific authorities like Buck et al. (Buck et al., 2011) and the Organisation for Economic Co-operation and Development (OECD) (OECD, 2021), fluoropolymers are classified as Per- and Polyfluoroalkyl Substances (PFAS).

PFAS are a vast group of organic fluorine compounds that also include various pharmaceuticals and agrochemicals. They have attracted regulatory attention due to the persistence of some of them in the environment, tendency to accumulate in living organisms, and potential to degrade into persistent metabolites. Certain PFAS are also concerning because of their potential toxicities, bioaccumulation potential, and capacity for long-range environmental transport.

PFAS comprises non-polymeric and polymeric substances, including gases, liquids and solids (Henry & Timmer, 2025). Polymeric PFAS can further be split into fluoropolymers, perfluoropolyethers, and side chain fluorinated polymers (Buck et al., 2011; OECD, 2021).

Substance specific restrictions for PFAS

In the European Union, certain PFAS have been regulated through specific legislative measures such as the F-Gas Regulation and the Mobile Air Conditioning (MAC) Directive. Certain PFAS such as perfluorooctanesulfonic acid (PFOS), perfluorooctanoic acid (PFOA) and perfluorohexanesulfonic acid (PFHxS) are listed under Persistent Organic Pollutants (POPs) Regulation (EU) 2019/1021, which implements the Stockholm Convention and effectively bans or severely restricts their production, use, and release. Additionally, PFAS have been subject to the Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) Regulation, which has played a key role in restricting substances like PFOA and related C8 compounds[2].

Following the restrictions on C8 chemistry, some industrial users shifted towards short-chain alternatives, such as C6 chemistry, which includes compounds like perfluorohexanoic acid (PFHxA). Germany submitted an Annex XV restriction dossier on PFHxA and its related substances in December 2019, and this process has now resulted in Regulation (EU) 2024/2462, adopted on 19 September 2024. The regulation introduces a new entry 79 in Annex XVII to REACH and restricts PFHxA, its salts and related substances in a wide range of uses, entering into force on 10 October 2024 and starting to apply from 2026 onwards. In parallel, long-chain perfluoroalkyl carboxylic acids with 9–14 carbon atoms (C9–C14 PFCAs) and their related substances are already restricted under entry 68 of Annex XVII, with the main provisions applying from 25 February 2023.

So far, substance specific restrictions have not been envisaged for fluoropolymers.

Group restriction for PFAS

On 22 March 2023 the European Chemicals Agency (ECHA) published a proposal for a universal ban on approximately 10,000 PFAS substances, including fluoropolymers. The proposal aims to restrict the manufacture, marketing, and use of PFAS to minimize their risks to human health and the environment. After an initial public consultation that ran from March to September 2023, ECHA's Risk Assessment Committee (RAC) and Socio-Economic Analysis Committee (SEAC) are currently reviewing the restriction proposal. These regulatory actions on PFAS are expected to have significant impacts on the manufacture, importation, marketing, and use of fluoropolymers within the EU. The

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[2] The term C8 is used for a subgroup of PFAS with a chain of eight carbon atoms; most prominently PFOA and PFOS.

proposed scope covers non-polymeric (e.g., perfluoroalkyl carboxylic acids, perfluorocarbons) and polymeric PFAS (e.g., fluoropolymers, perfluoropolyethers) (REACH-CLP-Biozid Helpdesk & Bundesanstalt für Arbeitsschutz und Arbeitsmedizin (BAuA), 2025).

As explained above, fluoropolymers are a dedicated group within the broad PFAS group and even within the group of polymeric PFAS. Discussions are ongoing whether fluoropolymers differ from other PFAS due to their distinct properties, and it is questioned if they should be regulated in the same manner as other polymers, rather than being subjected to the stringent regulations applied to PFAS.

Given that fluoropolymers are widely used in critical industries such as automotive, aerospace, semiconductor manufacturing, electronics, medical, chemical processing, and batteries, a total ban or severe restriction of fluoropolymers would lead to significant challenges in these sectors.

Fluoropolymers and their place in the polymer universe

Fluoropolymers occupy a distinctive and well-defined position within the wider polymer landscape, both structurally and functionally. While some can be considered plastics, fluoropolymers can be regarded as specialised subset. Most of the conventional polymers consist of linked hydrocarbon backbones surrounded largely by hydrogen atoms. Most prominent examples are polyethylene, polypropylene or polystyrene.

Fluoropolymers, by contrast, are based on monomers in which some or all of the hydrogens have been replaced by fluorine atoms. In materials such as PTFE, the backbone is essentially a repeating $–CF_2–CF_2–$ structure. This dense fluorination has two immediate consequences. First, the carbon–fluorine bond is one of the strongest single bonds in organic chemistry, which makes the resulting polymer chain resistant to thermal and chemical attack. Second, the outer “skin” of fluorine around the carbon chain creates a low-energy surface that does not interact easily with other materials. Together, these features produce polymers that are inert, non-stick and stable under conditions where many other plastics would soften, swell, crack or burn. Fluoroelastomers (such as FKM and FFKM) – synthetic rubbers made by co- or terpolymerising combinations of typical monomers like vinylidene fluoride - are one of the main subcategories of the fluoropolymer family and are widely used in the sectors discussed in this report.

Placed against the broader landscape of polymers, many fluoropolymers are part of the family of high-performance or specialty polymers. Commodity thermoplastics like polyethylene or PVC are produced in very large volumes and are designed to be cheap and versatile. Engineering plastics such as polycarbonates offer better mechanical performance and heat resistance for more demanding uses (Robert (R.) Lee, 2025). Above these sit high-performance polymers, including polyimides, polyphenylene sulphide or polysulfones and the fluoropolymers (Abbey Polymers Ltd, 2024). This group is characterised by the ability to tolerate high temperatures, aggressive chemicals or demanding mechanical loads for long periods.

Fluorinated polymers vs. fluoropolymers

Within the polymer universe there is sometimes confusion about “fluorinated polymers” and “fluoropolymers”. Fluoropolymers are a subset of fluorinated polymers. The main difference between the two lies again in the chemical structure and more particular where the fluorine atoms are bonded within the polymer.

Fluoropolymers are polymers in which fluorine atoms are directly bonded to the carbon backbone. This characteristic carbon-fluorine (C-F) bond is the strongest and the most stable of covalent bonds as explained above, which gives fluoropolymers their unique properties.

Fluorinated polymers on the other hand is a broader term for any polymer that contains fluorine atoms in its structure. Not all such polymers exhibit the properties of fluoropolymers.

Speciality uses

In terms of function, fluoropolymers are mainly used wherever reliability under harsh conditions is critical. They line pipes and vessels in chemical plants to resist strong acids and oxidising media. They insulate wires and cables in environments where a combination of high temperature, electrical performance and fire safety is essential. They are found in seals, gaskets and membranes that must maintain performance over many years without creeping, cracking or being attacked by the process fluids.

Derogations for fluoropolymer applications

After reviewing the comments received during the 2023 public consultation, the dossier submitters of the group restriction proposal have updated their restriction proposal in the so-called (draft) background document, which was made available online on 20 August 2025 (ECHA, 2025b). This document now provides adjusted derogations for several fluoropolymer applications, as well as a time-unlimited derogation for the manufacture of fluoropolymers under controlled conditions. Table 5 provides a summary of proposed regulatory measures for some selected fluoropolymer applications.

The proposed time-limited derogations for certain fluoropolymer applications are to some extent based on information regarding the availability and feasibility of non-PFAS alternatives received during the public consultation. The upcoming SEAC public consultation will request further information on alternatives and the potential for substitution. However, for a detailed alternatives assessment it is not sufficient to address the question of alternatives' availability alone. Instead, any potential alternative must be assessed against multiple criteria, among others for their technical and economic feasibility, for risk reduction potential and safety. In addition, substitution of fluoropolymers with alternative materials or technologies can often mean substantial changes to existing processes, plants, supply chains and qualification / certification schemes. Hence, substitution is in many cases a complex, cost- and time-intensive process that requires collaboration within the entire supply chain.

Objective of report

This report provides an assessment of alternatives for selected case studies for the Transport and Electronics & Semiconductor sectors. The assessment is based on data retrieved from extensive literature research as well as from downstream users of fluoropolymers from the respective sector. Each case study is a defined and specific fluoropolymer application, hence allowing a clear description of the fluoropolymer type, its use in the discussed case study and the technical performance criteria demanded. In addition, the rationale of the required technical performance criteria is provided. These can be industry standards, legal requirements or customer demands that define the performance characteristics set on the necessary material or component for each defined case study. The report further provides an overview of potential alternatives, which have been either identified from the literature review or provided by downstream users. Based on an initial assessment, the most promising alternatives have been shortlisted for a more detailed assessment of their technical feasibility against the defined technical performance criteria. Where technical feasibility was promising, the shortlisted alternatives have also been assessed against further criteria, such as hazard, economic feasibility and market availability. Following the evaluation of the shortlisted alternatives, the potential substitution process has been described either on sector- or on case study level.

The report thus aims to showcase the variety of fluoropolymer applications on the one side while providing detailed information on their applications, performance and substitution processes using specific use cases. It therefore provides insights into the multitude of aspects that need to be assessed when identifying, evaluating and introducing alternatives as a replacement for fluoropolymers.

Table 5: Overview on proposed restriction conditions for fluoropolymer-relevant applications / uses

Derogation of 6.5 years after EiF*	**Derogation of 13.5 years after EiF***	**Other**
• Fluoropolymer processing aids used in flexible plastic film extrusion • Fluoropolymer non-stick coatings in industrial bakeware • Fluoropolymer -based separator coatings for batteries • PTFE nozzles in high voltage (>145 kV) switchgears and circuit breakers • Fluoropolymer -containing front- and backsheets in photovoltaic cells • Fluoropolymer -containing blisters for solid oral dose formulations • Industrial use of fluoropolymers in filtration and separation media for water treatment and purification	• Polymer additives used for fire safety purposes in construction products • Fluoropolymer -based implantable medical devices • Fluoropolymer -based invasive medical devices • Fluoropolymer -based packaging for medical devices • Fluoropolymer -based heat transfer fluids for industrial and professional use of vapor phase soldering for electronics • Fluoropolymer wires and cables (incl. connectors) • Fluoropolymer insulation material of electronic components • Fluoropolymer anti-drip agent in plastics of electronic components • Fluoropolymer for fuel cells and electrolysers • Fluoropolymer -containing bridge and building bearings • Fluoropolymer -based sealing applications in industrial uses • Fluoropolymer -dependent machinery applications in industrial uses • Fluoropolymer coatings in release liners and backing film in transdermal patches • Fluoropolymer coated rubber stoppers in vials/flasks for injectable medicinal products • Fluoropolymer coated canisters in pressurized metered-dose inhalers (pMDIs) • Fluoropolymer coated plungers in pre-filled syringes • Fluoropolymer containing pre-filled injection pens & autoinjectors • Fluoropolymer containing explosives in military applications	• Production of PFAS with or without the use of fluorinated polymerisation aids in the production of polymeric PFAS under controlled conditions with average emission factors not exceeding: i. 0.0090 % to air, 0.0010 % to water and 0 % to soil for emissions of non-polymeric PFAS residues from polymerization aid technology in FP manufacturing → until end of 2030 ii. 0.0030 % to air, 0.0006 % to water and 0 % to soil for emissions of non-polymeric PFAS residues from polymerization aid technology in FP manufacturing → from end of 2030 onwards iii. 0.01 % to all compartments for all PFAS emissions not mentioned above from sites from sites manufacturing polymeric and non-polymeric PFAS → 6.5 years after entry into force (EiF) • Fluoropolymer -based vehicle systems, components or separate technical units subject to EU vehicle type approval if type approval was obtained within 13.5 years after EiF* • Fluoropolymer -based vehicle systems, components or separate technical units not covered by above 13.5 years after EiF, if use of FP is strictly necessary for safety or environmental performance of those vehicles*

*Fluoropolymer applications / uses listed in this table must establish a site-specific management plan to be able to make use of the proposed derogations.

2. Methodology

The present chapter explains the chosen approach for the selection of the evaluated case studies and for the collection and identification of data sources. The limitation of the present study is detailed in section 2.3.

2.1 Selection of Sectors and Case Studies

Due to the ubiquitous application of fluoropolymers, it was important to select sectors and respective use cases that are as representative as possible and at the same time allowing for a detailed alternatives assessment. Finally, two sectors were selected for this report: *Transport* and *Electronics & Semiconductors*, for the following reasons:

- Fluoropolymers are widely used in the Transport sector and any regulatory measures towards fluoropolymers will consequently have an immediate impact on the sector
- The same is true for the fluoropolymers in Electronics & Semiconductors. The demand for these applications is expected to see a steep increase in the next decade across the globe
- Both sectors are of strategic economic relevance to the EU and linked to EU-wide climate targets, such as greenhouse gas emissions, circularity and strategic autonomy
- Both sectors show a high overlap with other sectors and thus have been assigned to other sectors, such as sealing applications in the ECHA’s Draft Background Document. Examples of overlaps are:
    - fluorinated gases, electronics & semiconductors, energy, lubricants, sealing applications, technical textiles for Transport
    - medical devices, transport, energy, printing applications, machinery applications, military applications for Electronics & Semiconductors

Hence, results generated for both sectors can to a certain extent be extrapolated to other sectors and therefore illustrate why fluoropolymers are used widely in many sectors.

To allow for a detailed alternatives assessment, it is necessary to not remain on the sector level but instead evaluate the availability and feasibility of specific fluoropolymer uses. Therefore, case studies have been selected for each sector. A case study is a clearly defined and specific use/application of a single fluoropolymer type, which provides the foundation for a comprehensive analysis of alternatives, in which the key performance criteria of the fluoropolymer for the defined use needs to be detailed and any alternative must be assessed against these criteria. This approach allows for a systematic approach to discuss the availability and feasibility of alternatives and is the recommended approach of ECHA when evaluating substances to be subject to restriction when applying for substance authorisation under REACH.

Since the selected sectors have many different fluoropolymer uses, it was necessary to limit the number of case studies per sector. Similar to the selection of the investigated sectors, the aim for the selection of case studies was to include uses that are as representative of the sector as possible and have sufficient data for a comprehensive analysis. The present study therefore started with a selection of four case studies, out of which the final case studies were selected.

The four pre-selected case studies are shown in Table 6.

Table 6: Overview of pre-selected case studies

Sector	**Pre-selected Case Studies**[3]			
Transport	Cables & Wiring	Sealing Systems	Hoses and Liners	Batteries
	Use of fluoropolymers for wire insulation within airplanes' flight control systems, providing thermal stability, mechanical durability, chemical resistance, and weight efficiency.	Fluoropolymer-based O-rings used in engine systems (e.g., fuel injector) to prevent leakage of fuels. Ensuring thermal and chemical resistance under dynamic operating conditions.	Fluoropolymer-based hoses, providing low permeability, high flex life withstanding flexing, pressure fluctuations and vibrations.	Fluoropolymer-Binders used in batteries, particularly in dry electrode manufacturing for EV and ESS markets.
Electronics & Semiconductors	Cables & Wiring	Semiconductor Manufacturing		Electronic Components
	Fluoropolymer-based resins used in cabling (signal cables, power cables, fibre optic cables) in data centres or high-performance computing centres.	Use of fluoropolymer in ultra-pure water (UPW) equipment (e.g., fittings, piping, transportation), essential for rinsing and cleaning steps in semiconductor manufacturing.	Use of fluoropolymer in semiconductor manufacturing-specific components (valves, fittings, gaskets, seals, liners, trays, pump components) of wet benches and etching stations.	Fluoropolymer-based laminates for high-frequency and high-speed PCBs in radars and telecommunications.

The selection of the final case studies was based on the following criteria:

1.) Economic relevance to the EU (qualitative)
2.) Criticality of application determined for example by safety aspects, importance for infrastructure or energy supply
3.) Representing the main sub-groups within fluoropolymers, i.e. fluorothermoplastics and fluoroelastomers
4.) Data availability allowing for a comprehensive alternatives' assessment
5.) Availability of suitable downstream user interview partners
6.) Coverage of the case study by other groups / initiatives
7.) Complexity of substitution

The results of the evaluation of the criteria for each case study are provided in Figure 1 (note the colour coding used in the evaluation table: red=”high”, orange=”medium”, yellow=”low”; for the column “Well represented?”[4] the meaning of the colours is reversed, i.e. red for “low” and yellow for “high” ; NA – not available due to lack of data) and the final case study selection is provided in Table 7.

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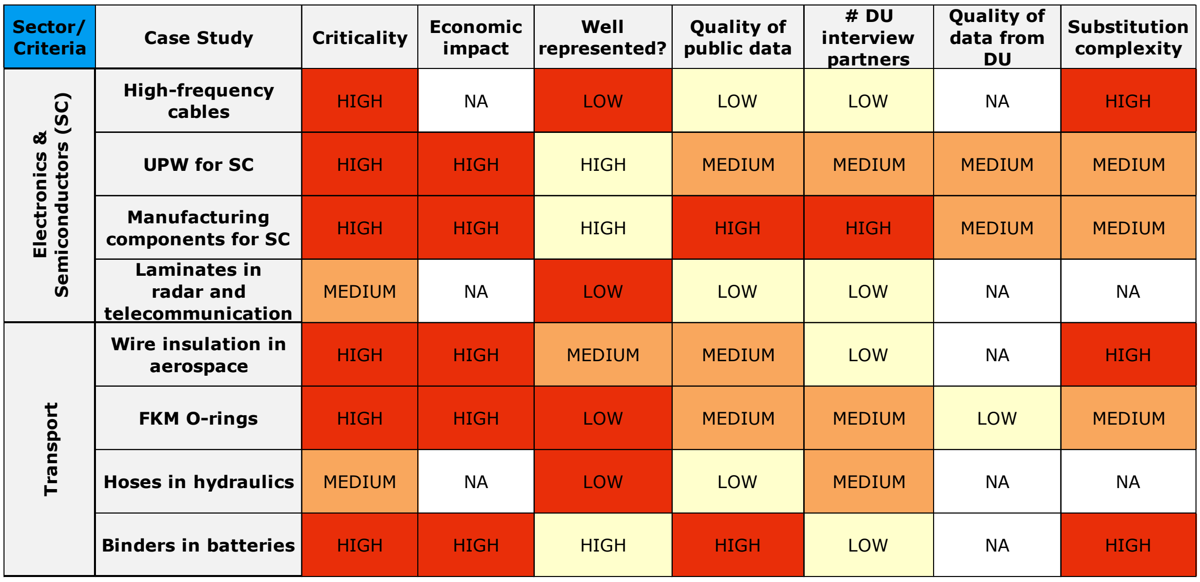
[3] Please note that certain case studies assigned to the Transport or Electronics & Semiconductor sectors in Table 6 have been assigned to the sector Sealing applications in ECHA's Draft Background Document.

[4] This means that a case study is already discussed in detail by other stakeholders.



Sector/ Criteria	Case Study	Criticality	Economic impact	Well represented?	Quality of public data	# DU interview partners	Quality of data from DU	Substitution complexity
Electronics & Semiconductors (SC)	High-frequency cables	HIGH	NA	LOW	LOW	LOW	NA	HIGH
	UPW for SC	HIGH	HIGH	HIGH	MEDIUM	MEDIUM	MEDIUM	MEDIUM
	Manufacturing components for SC	HIGH	HIGH	HIGH	HIGH	HIGH	MEDIUM	MEDIUM
	Laminates in radar and telecommunication	MEDIUM	NA	LOW	LOW	LOW	NA	NA
Transport	Wire insulation in aerospace	HIGH	HIGH	MEDIUM	MEDIUM	LOW	NA	HIGH
	FKM O-rings	HIGH	HIGH	LOW	MEDIUM	MEDIUM	LOW	MEDIUM
	Hoses in hydraulics	MEDIUM	NA	LOW	LOW	MEDIUM	NA	NA
	Binders in batteries	HIGH	HIGH	HIGH	HIGH	LOW	NA	HIGH

Figure 1: Evaluation results of pre-selected case studies.

Table 7: Final case studies

Transport	**Electronics & Semiconductors**
Use of fluoroelastomers (FKM) as high-pressure sealing material in gasoline direct injection (GDI) systems	Use of fluoropolymer-based (PVDF) piping in ultra-pure water (UPW systems) for semiconductor manufacturing
Use of fluoroelastomers (FKM) as the inner layer of fuel hoses for high temperature applications in the automotive sector	

2.2 Data Sources

The study is based on data, which is both publicly available as well as based on industry-internal knowledge and experience. It therefore compiles information from the public domain with new information gathered from interviews with downstream users of the selected case studies on fluoropolymer applications, standards or alternative materials / technologies.

2.2.1 Literature Research

A comprehensive literature search and review was carried out as part of the project, focusing on the use of fluoropolymers in the transport and electronics & semiconductor sectors, any technical standards relevant for the application (e.g. industry testing standards, ISO norms) or required properties for a material to be used in this application and potential alternatives. The review relied on publicly available data. The aim was to identify potential applications suitable for case studies and to gather detailed information relevant to a (pre)-selected number of these cases and both sectors. All information identified during the search was compiled in an Excel-based database, enabling systematic documentation and facilitating efficient retrieval of the collected data. Several data sources were utilized to ensure a robust literature search:

Scientific Literature Database (SCOPUS)

SCOPUS[5] is a scientific abstract and citation database by the academic publisher Elsevier. It covers academic journals, preprints, books, and conference proceedings, encompassing over 100 million records.

For the search in SCOPUS, various search terms were developed using keywords connected by Boolean operators such as "AND" and "OR." These search terms were constructed by linking synonyms for the material with terms for alternatives and/or specific applications.

An example of a general search term is as follows:

(fluoropolymer* OR ectfe OR fep OR pfa OR ptfe OR pvdf OR pctfe OR ptfce OR pfpe OR etfe OR ffkm OR ffpm OR fkm OR fpm OR (pfas AND polymer*))

AND

(alternative* OR replacement)

Specific search terms for various applications are provided in Annex I Search Terms. The timeframe for searches was typically limited to a maximum of 15 years for specific applications and 5 years for general searches. If a high number of irrelevant publications were identified based on a brief screening (usually publications that are not related to the application of interest like e.g. biological studies), the search terms were refined further by excluding keywords of limited relevance to the research topic, such as "Pharmacology." All the publications found were assessed for relevance by screening their titles and abstracts. Only those that were potentially relevant to one of the sectors or applications of interest were included in the database for further evaluation.

Publicly Available Databases on Alternatives

Databases such as ZeroPM[6] and ChemSec Marketplace[7] were used to gather information on alternatives to fluoropolymers for the selected sectors.

PFAS Restriction Proposal and Public Consultation Comments

The PFAS restriction proposal and its updated background documents[8] were reviewed for information on alternatives applicable to the transport, electronics, and semiconductor sectors.

Stakeholders provided a large amount of information during the public consultation phase. The non-confidential content was uploaded by ECHA and made publicly accessible. Comments were organized into separate Word files, some of which included links to additional documents (e.g., PDFs or ZIP files). An overview sheet lists all comments and references the corresponding Word files.

Given the large number of comments and documents gathered during the public consultation, it was impractical to manually review all comments. Therefore, two strategies were employed to extract relevant information:

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[5] Scopus | Abstract and citation database | Elsevier

[6] Welcome to ZeroPM - ZeroPM

[7] The Marketplace | ChemSec Marketplace

[8] Registry of restriction intentions until outcome - ECHA Last accessed 18.11.2025

- The overview sheet was searched for submissions by well-known companies and associations active in the transport or semiconductor sectors. These comments were then examined in detail.
- An AI-assisted approach was used to scan the Word files for information on alternatives relevant to the semiconductor and transport sectors. The AI-generated findings were subsequently verified by team members to ensure accuracy and relevance.

General Desk Research

Additional desk research was carried out to collect data from industry (reports, technical data sheets, etc.), publications by non-governmental organizations (NGOs), and authoritative sources. This process primarily involved targeted internet searches to complement the information sourced from specialized databases, ensuring a more comprehensive collection of relevant data.

The following table summarises the number of entries in the database that have been identified and reviewed for each data type and selected case study.

Table 8: Number of entries in database per data type and case study.

	Number of Entries in Database			
Data type	**Transport**		**Electronics & Semiconductor**	
	O-rings gasoline injection	**Fuel hoses and liners**	**UPW Piping for SC**	**Total[1]**
PFAS Restriction (Public Consultation)	8	4	2	55
Reports (Industry, Authority, NGO, other)	2	0	7	97
Testing Standards	2	0	12	26
Technical data sheet	9	1	11	50
Conferences	0	2	0	14
Websites	49	4	11	164
Scientific Literature	10	2	14	226
ChemSec Marketplace/ SIN Database	1	1	0	35
Zero PM Database	0	0	1	37
Other	6	3	4	55
SUM	87	17	62	759

[1] Please note that the total number of entries does not match the sum of the entries for the selected case studies, as it also includes a significant number of entries for pre-selected case studies and both sectors in general.

2.2.2 Stakeholder Interviews

Downstream users are the first level of industrial actors that handle, process and use fluoropolymers for their specific applications. They are therefore usually the most knowledgeable on the key performance criteria and the standards/requirements that fluoropolymers need to fulfil. In addition, downstream users are the bridge between fluoropolymer manufacturers and the customers who are using fluoropolymer-containing articles. Hence, downstream users also provide valuable information on required substitution steps and their respective timeline. Consequently, they were the main target group for the stakeholder interviews.

To be able to engage as many downstream users as possible, the respective trade associations of each sector were contacted (see Annex II List of Downstream User Associations) and asked to provide a background information document to their members. The background document provided information on the project and its objectives, as well as asking support from downstream users on data collection for the alternatives assessment and substitution description. Furthermore, a webinar for downstream users from each sector was held to provide additional opportunity to ask questions.

Initial interviews were held with downstream user companies that volunteered to provide a first insight into fluoropolymer applications for each sector and for the pre-selected case studies. After the final case studies were selected, suitable downstream user companies (i.e. companies manufacturing / processing / using the fluoropolymer-containing articles from respective case studies) were contacted and asked for their participation.

Downstream user companies that agreed to provide information were sent a questionnaire with questions relevant to the respective case study. The provided answers and remaining data gaps were then discussed in an interview with each of the downstream user company. An overview on conducted interviews for each case study is provided in Table 9 below. Note that the table also includes interviews, which were conducted before the final selection of case studies ("pre-selected case studies").

Table 9: Number of Stakeholder interviews for each case study

Case Study	**Total stakeholder interviews**	**Information on Stakeholders (type and size)**
Use of fluoroelastomers (FKM) as high-pressure sealing material in gasoline direct injection (GDI) systems	4	Fluoropolymer Manufacturers (Company size: < 10,000 people) Downstream Users (Company size: 1k to 100k people, 1 to 50 bn EUR revenue)
Use of fluoroelastomers (FKM) as high-pressure sealing material in gasoline direct injection (GDI) systems	4	Fluoropolymer Manufacturers (Company size: < 10,000 people) Downstream Users (Company size: 50k to 100 k people; 5 to 50 bn EUR in revenue)
Use of fluoropolymer-based (PVDF) piping in UPW systems for semiconductor manufacturing	4	Fluoropolymer Manufacturers (Company size: < 10.000 people) Downstream Users (Company size: < 10,000 people; 10 to 50 bn EUR in revenue)

Information from the interviews above are referenced in the report using a code with the format "Ixy", where xy is an interview number in the internal system. Please note also that several more interviews were conducted during the scoping phase of case study selection, however this information was not included in the final report, since these interviews are related to applications that were not selected.

2.3 Limitations

The present study acknowledges the limitations listed below. These need to be considered when interpreting the results.

1. Data collection based on defined search terms:
   - The data evaluated in this study is based on defined search terms used to gather publicly available information and information from scientific papers. This methodology may exclude information that does not explicitly match the chosen search terms.
2. Screening of comments from the 2023 public consultation of the universal PFAS restriction proposal:
   - Comments for a detailed evaluation were selected based on the submitting entity, i.e. comments submitted by associations from the respective sectors as well as comments from companies producing or using fluoropolymers subject to the pre-selected case studies. By default, comments submitted confidentially or by a confidential entity have not been included for evaluation. This approach might exclude comments with relevant information and should thus be considered a limitation of the study.
3. Data from downstream users:
   - The data received from downstream users is limited, as it is based on companies that volunteered information. Hence, it may not include input from companies with differing data. As a result, the findings might lack a wider perspective. In addition, the report includes data received from downstream users based on third-party information (e.g. standards, literature data). In cases, where Ramboll could not verify the sources (or the content thereof), the information is highlighted in Grey.
4. Selection of case studies:
   - Despite the aim to select case studies that are as representative as possible, the limited number of evaluated case studies cannot cover all potential fluoropolymer applications. The variability of fluoropolymer uses in the evaluated sectors may result in cases that are not represented (partially) by the selected case studies and that certain aspects are thus not addressed.

In summary, the report provides relevant information on the status of alternatives to specific fluoropolymer applications and on the challenges of substitution. While the data is not statistically representative, it exemplifies the challenges relevant for many other fluoropolymer applications.

3. Transport Sector

3.1 Sector overview

The European transport sector is fundamental to the EU economy, contributing approximately 5 % to GDP and employing more than 10 million people (EUROSTAT, 2025; ReportLinker, 2024). In 2023, transportation revenue in Europe was estimated at approximately EUR 542 billion. Current forecasts indicate a slight decline to around EUR 530 billion by 2028, corresponding to an average annual growth rate of 0.9 %. Germany represents the largest national market, generating an estimated EUR 147 billion in transportation revenue, followed by France, Italy, and Spain. When the broader transportation and logistics sectors are considered, the total industry turnover exceeds EUR 1.3 trillion (ReportLinker, 2024).

The European transport system is characterized by extensive modal diversity, with each mode fulfilling distinct roles in both freight and passenger mobility.

- **Road Transport:** Road transport dominates the European mobility landscape, accounting roughly 77 % of inland freight movements and more than 70 % of passenger journeys (EUROSTAT, 2025). In 2024, the European road freight market was valued at EUR 428 billion, including EUR 297.9 billion in domestic transport and EUR 130.4 billion in international transport. The sector is projected to grow by 2.0 % in real terms in 2025 (Ti Insight, 2024).
- **Rail Transport:** Rail represents around 5.5 % of EU freight (measured in tonne-kilometres) and carries more than 400 billion passenger-kilometres annually (EUROSTAT, 2025; Transport & Environment, 2024). Intermodal and combined transport is expected to expand at a compound annual growth rate of 3.7 % between 2023 and 2040, reflecting increasing policy emphasis on sustainable and integrated logistics chains (2024 Report on Combined Transport in Europe, 2024; EUROSTAT, 2025).
- **Aviation:** Although passenger volumes have not yet fully recovered to pre-COVID-19 levels, aviation remains essential for European and global connectivity. It plays a critical role in high-value and time-sensitive freight transport (Transport & Environment, 2024)**.**
- **Maritime Transport:** Maritime transport handles more than two-thirds of total EU freight volume and serves nearly 400 million port passengers each year, underscoring its central importance for trade, mobility and supply chain continuity (Transport & Environment, 2024).

The sector’s development is shaped by several structural drivers: economic expansion, increasing logistics demand, digitalization (including smart mobility and automation), and the push for more resilient supply chains (European Commission. Directorate General for Mobility, 2024). Two major regulatory trends are currently sculpturing sector dynamics:

a) Circularity requirements

The EU has introduced comprehensive circularity measures through the proposed Regulation on Circularity Requirements for Vehicle Design and End-of-Life Management. Key provisions include:

- **Design mandates**: Vehicles must achieve at least 85 % reusability/recyclability by mass or 95 % reusability/recoverability by mass, within six years of regulation entry (Guillaume Ragonnaud, 2025).
- **Recycled content targets**: Plastic components in new vehicles must contain minimum 20 % recycled content within six years, rising to 25 % within 10 years, with at least 25 % sourced from end-of-life vehicles.
- **Extended producer responsibility**: Manufacturers must cover collection and treatment costs for end-of-life vehicles (Guillaume Ragonnaud, 2025).

- **Digital vehicle passports:** Required to track material composition and enable better material recovery at the End-of-life stage (Guillaume Ragonnaud, 2025).

b) Greenhouse Gas (GHG) Emissions reduction

The transport sector remains a critical focus as it is the only major sector in the EU where emissions have risen compared to 1990 levels. As of 2025, transport accounted for approximately 29 % of total EU greenhouse gas emissions (up from 25 % in previous estimates) (European Environment Agency (EEA), 2025). Road transport continues to account for roughly 73 % to 75 % of all transport-related emissions (PwC, 2025). In response, the EU has set ambitious decarbonization objectives:

- 2030: 55 % net GHG emission reduction vs. 1990 levels (Fit for 55) (European Environment Agency (EEA), 2025).
- 2040: 90 % net GHG emissions reduction vs. 1990 levels (European Environment Agency (EEA), 2025).
- 2050: Climate neutrality, including a targeted 90 % reduction in transport-related GHG emissions (European Commission, 2025).

Key policy instruments include the Euro 6/7 standards, the Alternative Fuels Infrastructure Regulation (AFIR), and sector-specific sustainable fuel mandates such as ReFuelEU Aviation and FuelEU Maritime. These measures significantly increase demand for advanced materials capable of withstanding new fuel blends, higher operating temperatures, and significantly stricter emissions requirements (European Alternative Fuels Observatory, 2025).

Fluoropolymer Use in Transport

Transport is the second-largest fluoropolymer-consuming sector in the EU counting for roughly EUR 300 million in value and more than 18,000 tonnes of material per year. Within this, the automotive fluoropolymer segment alone is estimated at USD 1.5 billion in 2025 and is projected to reach around USD 2.3 billion by 2032, representing the highest growth rate among all major fluoropolymer applications.

Fluoropolymers provide high chemical and fuel resistance, stability across temperatures from - 200 °C to 260 °C, and extremely low permeability, helping prevent evaporative emissions. According to the Fluoropolymers Product Group (FPG) of Plastics Europe, they can double or even triple component lifetimes (failure rates < 0.1 %) and contribute to an estimated EUR 40 million in annual fuel savings across EU automotive fleets. Industry analysis indicates that these properties are essential for compliance with stringent emissions standards (Euro 6/7), high-voltage insulation in EVs, durable membranes in hydrogen fuel cells, and industry-specific safety requirements (Fluoropolymer Product Group of PlasticsEurope et al., 2022; Holscot Fluoropolymers, 2022; PlasticsEurope, 2023). Illustrative examples of fluoropolymer applications and their functionalities in Transport sector are presented in Table 5 below.

Table 10: Exemplary Fluoropolymer Applications Across Transport Modes

Transport Mode	Fluoropolymer-Containing Components	Key functionalities
Road/Automotive	Fuel hoses and lines, brake lines (ABS), O-rings in fuel injectors, engine gaskets, turbocharger hoses, shaft seals, wire/cable insulation, battery binders (EVs), hydraulic hoses	Chemical resistance, high-temperature stability, permeation barrier, emission control (Euro 6/7 compliance), leak prevention
Rail	Tank wagon seals for hazardous goods, wire/cable insulation, hydraulic system seals	Leak prevention, chemical resistance
Aviation/Aerospace	Wire/cable insulation, hydraulic system seals, O-rings, fuel system components, engine seals	Fire safety, weight reduction, thermal/electrical stability
Maritime	Chemical transport tank linings, fuel lines, seals, coatings	Chemical resistance, corrosion protection, durability in marine environments

Primary fluoropolymers (and corresponding components made of them) used in transport include:

- PTFE (Polytetrafluoroethylene): Fuel lines, seals, O-rings, gaskets, wire insulation, emission control components
- ETFE / FEP (Fluorinated Ethylene Propylene): Wire/cable insulation, fuel cell components
- PFA (Perfluoroalkoxy Alkane): High-purity tubing, gaskets, seals for aggressive chemical environments
- PVDF (Polyvinylidene Fluoride): Battery binders in lithium-ion batteries, coatings, membranes
- FKM/FFKM (Fluoroelastomers): O-rings, seals, gaskets in fuel systems, hydraulic systems, turbocharger (TCH), fuel lines and exhaust gas recirculation (EGR) parts, as well as engine components
- FVMQ (Fluorosilicone): Seals for extreme temperature applications (Guillaume Ragonnaud, 2025)

These fluoropolymers enable functions such as chemical resistance to fuels, lubricants, and aggressive automotive fluids; sealing and durability performance under high pressure and temperature; low friction and wear for longer component life; thermal stability to maintain performance in engine and under-hood environments; and inherent flame retardancy contributing to safety and reliability in transport systems (Fluoropolymers Product Group (FPG), 2025a; Holscot Fluoropolymers, 2022).

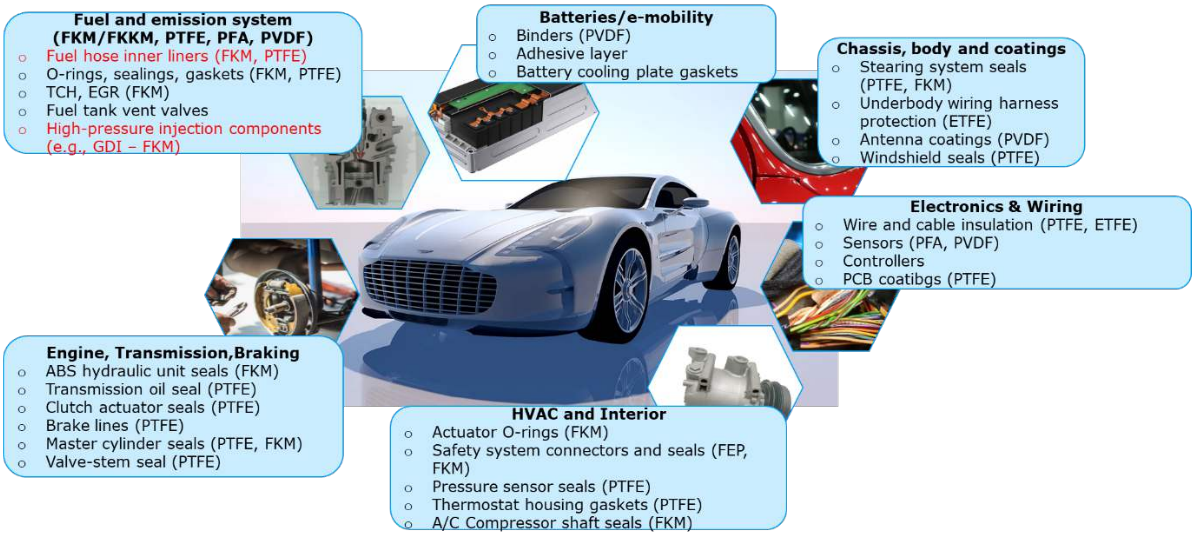

Figure 2: Use of fluoropolymers in vehicle's components (non-exhaustive examples).

Transport Sector in the Annex XV Proposal

As mentioned in section 2.1 above, the Annex XV restriction proposal report includes Transport as one of the main sectors of PFAS use. The Background Document proposes derogations for applications where PFAS are currently critical to safety or environmental performance and where PFAS-free alternatives cannot yet meet performance requirements (applications have low substitution potential) (ECHA, 2025a; REACH-CLP-Biozid Helpdesk & Bundesanstalt für Arbeitsschutz und Arbeitsmedizin (BAuA), 2025). These proposed derogations affect:

- Direct transport uses: Components in road vehicles, rail, aviation and marine systems where PFAS are used for sealing, insulation, thermal and chemical resistance.
- Related machinery and equipment: Production machinery, compressors, pumps and hydraulics used to manufacture or service vehicles, which often rely on PFAS-based seals, gaskets, valves and lubricants (Thomas Delille et al., 2025).

The Draft Background Document explicitly recognises that many PFAS applications relevant to Transport are cross-sectoral: sealing systems, machinery applications, technical textiles and fluorinated gases are used across construction, energy, electronics, medical and broader industrial sectors as well as transport.

For the automotive and industrial vehicle value chain this means, for example:

a) Vehicle components depend on PFAS-containing electronics and semiconductors, wiring, batteries and insulation (electronics and energy sectors).
b) Seals, gaskets, hoses and diaphragm components rely on fluoropolymers assessed under sealing and machinery sectors but are installed in engines, drivetrains, braking systems and fuel systems of road, rail, marine and aviation applications.
c) Technical textiles and coatings used for hoses, bellows, filters, protective garments and interior materials in vehicles are regulated within the technical textiles sector.

As a result, PFAS restriction and applicable derogations in these adjacent sectors will have direct implications for transport OEMs and suppliers, especially where safety-critical parts or regulatory compliance (e.g. emissions, fire safety) depend on PFAS-based materials (ECHA, 2025a; Thomas Delille et al., 2025).

In the following two chapters two selected case studies, demonstrating specific use of fluoropolymers in transport sector, are described:

(1) Case study "Use of fluoroelastomers (FKM) as high-pressure sealing material in gasoline direct injection (GDI) systems" (section 3.2)
(2) Case study "Use of fluoroelastomers (FKM) as the inner layer of fuel hoses for high temperature applications in the automotive sector" (Section 3.3)

More details on the reasoning behind the selection of the case studies can be found in the section 2.1.

3.2 Case study "Use of fluoroelastomers (FKM) as high-pressure sealing material in gasoline direct injection (GDI) systems"

3.2.1 Overview of the application, its relevance and description of key components

With the rising demand for fuel-efficient, yet high performing engines driven by client demands and increasingly stringent regulatory standards on CO_2 emissions (e.g., EU 2019/631) (*REGULATION (EU) 2019/ 631 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL - of 17 April 2019 - Setting CO2 Emission Performance Standards for New Passenger Cars and for New Light Commercial Vehicles, and Repealing Regulations (EC) No 443 / 2009 and (EU) No 510 / 2011*, 2019) the application of GDI systems have become prominent in Europe's and global automotive markets (Data Bridge Market Research, 2025). In particular, manufacturers have adopted GDI technology swiftly, with its presence in new vehicles rising from about 5 % in 2010 to more than 50 % in 2023 across major automotive markets. Market projections suggest that by 2030, nearly 80 % of new internal combustion engines will feature direct injection technology, with *"hybrid architectures combining GDI with electrification representing the fastest-growing segment"* (Patsnp Eureka, 2025). The aforementioned tightening emissions regulations and planned bans on internal combustion engines are shaping R&D priorities, pushing manufacturers to balance near-term compliance with long-term plan for electrification (Patsnp Eureka, 2025).

The fuel injectors of the GDI system directly inject fuel into the combustion chamber at very high pressures (typically between 2,000 and 3,000 psi) (Universal Technical Institute, 2024). The injection timing, quantity and pressure is precisely controlled by the engine control unit (ECU) improving the combustion efficiency and allowing a more precise fuel-air mixture control. Apart from fuel saving, this principle allows downsizing of engines by enabling higher compression ratios producing comparable or greater power than larger conventional engines. As the injection nozzles reach all the way into the combustion engines, as opposed to port fuel injection systems (PFI), the sealing material applied between the injector and cylinder head needs to withstand harsh conditions such as high pressures, temperatures up to 200 °C and need to be resistant to various fuel compositions.

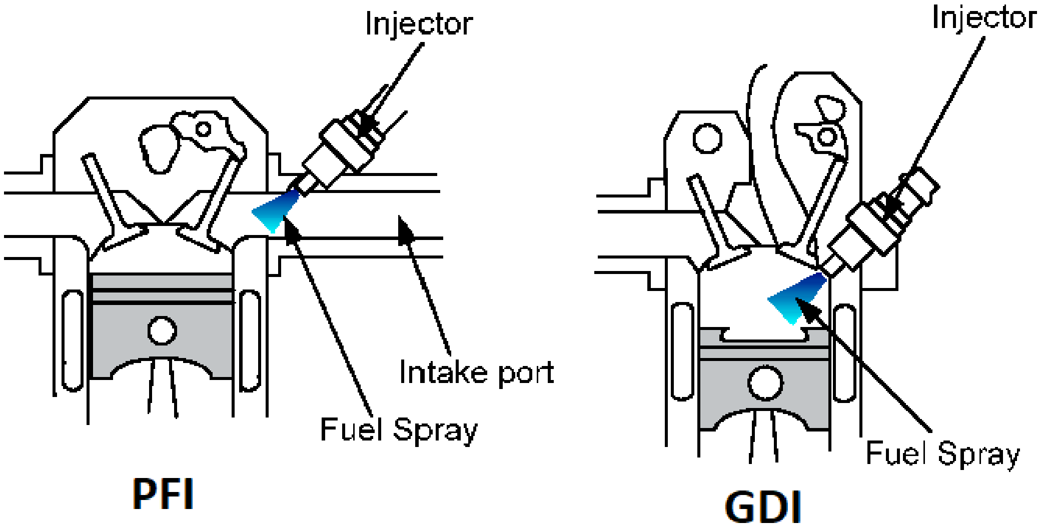

Figure 3: Comparison between PFI and GDI engine configurations (Kalwar & Agarwal, 2020).

Fluoropolymers, especially (F)FKM and PTFE, are the materials of choice for O-rings within GDI systems, as their unique properties entail high durability under the described conditions preventing fuel leakages and increasing service life of the system (see section 3.2.2). At the upper end of the injector, near the fuel rail, which receives pressurized fuel from the pump and distributes it to the injectors, typically FKM sealings are preferred (see Figure 4).

The material resists vibration tolerances by retaining elasticity. FFKM is typically not used in commercial vehicle applications - it is rather used in highly specialised scenarios e.g., custom-built racing engines.

PTFE on the other hand is used in O-rings at the lower end of the injector closest to the combustion engine, as it can withstand even higher temperatures and features a higher wear resistance. In the following, the case study focuses on FKM applied in GDI systems of commercial vehicles.

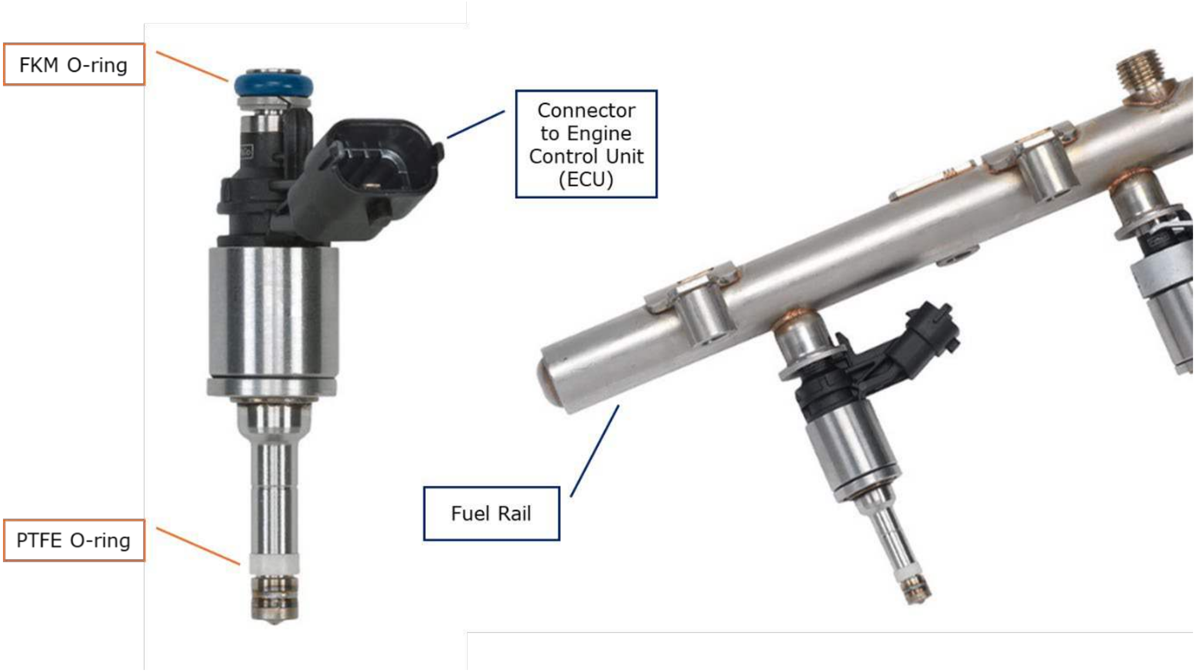

Figure 4: Types of O-rings used within a fuel injector of an GDI System & its connection to the fuel rail (Bosch GmbH, 2026).

The failure of the specified high-pressure seals can lead to external fuel leaks, a loss of rail pressure, and drivability issues. In addition to a decrease in performance, escaping fuel may mist or drip onto hot engine components, posing a fire risk. Hence, the reliability of the O-ring material is an important safety factor.

3.2.2 FKM types, their properties and Key functionalities within the application

Fluoroelastomers (FKM) are divided into five different types based on their chemical composition as defined by ASTM D1418 and ISO 1629:

- Type 1: Binary Copolymers of Hexafluoropropylene (HFP) and Vinylidene fluoride (VDF)
- Type 2: Ternary Copolymers of Tetrafluoroethylene (TFE), HFP, and VDF
- Type 3: Ternary Copolymers of TFE, Perfluoromethylvinyl Ether (PMVE), and VDF
- Type 4: Ternary Copolymers of TFE, Propylene, and VDF
- Type 5: Quinary Copolymers of TFE, HFP, Ethylene, PMVE, and VDF (Jimmy, 2024)

The different types vary in their fluorine content and inherit different properties (ERIKS, 2025a). FKM Type 1 (also known as Type A and often marketed as Viton™ A) is used primarily in the automotive sector, as they have a balanced set of mechanical and chemical properties, providing good resistance to a wide range of chemicals and high temperatures, while being the most cost-efficient option. However, for more demanding applications other types may be favoured, e.g. Type 3 performs better in cold temperatures, as PMVE improves the elasticity of the material needed to maintain the sealing properties in these conditions. Below, an exemplary set of properties of a standard grade FKM co-polymer is provided.

Table 11: Exemplary specifications of an O-ring made of FKM Type 1 (NH O-RING GmbH & CO. KG, 2025)

Specification	**Typical Value**
Hardness	70 ± 5 Shore A
Temperature Range	-25 °C to 200 °C
Tensile Strength	10.5 MPa
Elongation at Break	230 %
Compression Set	13 % (22 h at 200 °C)
Density	1.91 ± 0.03 g/cm^3

The following key functionalities (Table 12) are derived from the application of FKM as O-ring material in GDI Systems. A detailed description of the identified key functionalities and (if applicable) test procedures is provided below.

Chemical Compatibility

OEM standards specify that O-ring material in the GDI system is chemically resistant against complex fuels, additives and lubricants under varying temperatures and pressures for reliable sealing performance. Immersion tests according to ISO 1817 or ASTM D471 are applied to assess the compatibility of a material, while the specific test criteria may vary depending on the use case. As a standard procedure, the O-ring is immersed in test fuels for 72 – 168 h at the upper continuous temperature limit (around 100 °C) or the maximum continuous use limit (typically 150 °C). Afterwards, changes in the materials properties such as volume (swelling), weight, hardness, tensile strength and elongation are assessed. Those changes need to remain in defined limits to demonstrate compatibility with the tested fluid (Richter, 2014). The key parameter in this context presents the volume swell, which should not exceed 10 % for Class K materials (defined by ASTM D2000), which e.g. FKM materials are attributed to (*ASTM D2000 Test Standard Explained* | *Eastern Seals UK*, 2023).

Table 12: Key functionalities of FKM O-rings in GDI systems

Key functionalities	Technical Requirements	Justification
Chemical Compatibility	Resistance to the respective fuel type, i.e. gasoline and additives in varying blends with ethanol or methanol including decomposition products formed during storage and transit (I16[9]). This is typically tested via immersion tests as outlined in e.g., ISO 1817. Test set-ups are defined by OEM specification, e.g. O-ring needs to demonstrate resistance against ethanol, methanol, Fuel C, diesel and E10 for 168 h at 150 °C (I14)	Poor chemical compatibility can lead to swelling, cracking or degradation of the material which can lead to fuel leakage. Fuel leakage in a GDI system presents a safety risk, including the potential for a fire hazard. Specified in OEM standards, such as: WSD/WSE M2D401 (Ford), TL 52666 (VW) or N28 GW13-067 (Bosch) (I16).
Temperature resistance	The material needs to withstand -20 °C to 200 °C (or higher) at the point closest to the combustion chamber inlet and -20 °C to 100 °C (or higher) at the fuel rail side of the injector (I16). Methods for testing accelerated thermal aging of rubber materials in air are outlined in ISO 188 as well as ASTM D865 (ERIKS, 2015). Test set-ups are defined by OEM specification, e.g. heat aging for 70 h at 250 °C (I14).	Accelerated heat aging causes changes of hardness, elongation at break and tensile strength. If those changes increase to an unacceptable degree, leakage can occur. Fuel leakage in a GDI system presents a safety risk, including the potential for a fire hazard. Specified in OEM Standards.
Pressure-Temperature Rating	At the maximum fuel demand the fuel pressure can reach near 200 bar. Combined with a start-up in cold conditions, this can lead to a shift of the glass-transition Temperature (Tg) of the material towards a 15 °C increase compared to standard (temperature) conditions and pressures (I16). Hence, depending on the application, the Tg needs to be sufficiently low. Specific requirements and test methods are defined by ISO 11367-2, ISO 6721-11, ASTM E1356 and OEM specifications.	A low Tg ensures that the material does not become rigid and brittle in cold environments and maintains its mechanical properties (e.g., elasticity and sealing performance) avoiding fuel leakage. Fuel leakage in a GDI system presents a safety risk, including the potential for a fire hazard. Specified in OEM Standards.
Permeability	Low permeability to liquids and gases. Test methods are defined by ASTM D1434 and ISO 15105.	Permeation of fuel vapor at any temperature and pressure is not permitted due to safety concerns related to fires. (I16) Specified in OEM Standards.
Long-term sealability	The material needs to possess a high elastic recovery (i.e., low compression set & low compression stress relaxation values) at operating temperatures and over the life of the vehicle to maintain its sealing ability. Testing standards comprise e.g. ASTM D1414.	The elastic recovery enables the O-ring to regain its original shape after deformation due to exposure to stress e.g., pressure fluctuations or thermal cycling typical for GDI systems. Maintaining the integrity of the seal throughout the entire service life of the vehicle is important to preventing failures. Fuel leakage in a GDI system presents a safety risk, including the potential for a fire hazard. Specified in OEM Standards.

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[9] I16 refers to interview partner number 16. See section 2.2.2 for more details

Temperature resistance

As FKM O-rings are installed close to the combustion chamber, high-temperatures must be tolerated by the material, at the same time, the material must perform during cold-starts in cooler environments. Hence, a broad temperature resistance range must be covered, typically between -20 °C to 200 °C for most commercial vehicles. However, the range may be extended in both directions, depending on the specific system design and application.

ISO 188 and ASTM D865 specify test methods to investigate accelerated heat aging and heat resistance of thermoplastic rubbers. Thereby, the test specimen is exposed to elevated temperatures and defined air circulations for a defined duration, ranging from short (24 - 72 h) to long-term (multiple days or weeks) aging. The temperature is chosen based on the intended application. Comparable to the procedure described under "Chemical Compatibility" basic physical parameters are determined before and after the exposure and changes of the properties are used to evaluate the suitability for the foreseen service life and temperature-critical sealing application (cf. Table 13)

Table 13: Acceptable limits of change after an air oven aging test for different material properties (I21)

Property	Acceptable limit of change	Test method
Hardness	≤ 10 Shore A	ASTM D2240
Tensile strength	≤ 50 %	ASTM D412
Elongation at Break	≤ 50 %	ASTM D412

Pressure-Temperature Rating

The glass transition temperature (Tg) is defined as the point of transition of an amorphous material from a hard, brittle, "glassy" state to a soft, flexible "rubbery" state (Biron, 2016). If the O-ring materials temperature falls below the Tg, it cannot maintain proper sealing abilities. Hence, the Tg defines the lower boundary for application in low-temperature environments. High-pressure increases the Tg of elastomers, and the low-temperature limit of the material effectively rises (GMORS, 2019). Standards for Tg test methods comprise e.g. ASTM E1356, ISO 11357-2 and ISO 6721-11.

Tg is usually determined via Differential Scanning Calorimetry (DSC) or Differential Thermal Analysis (DTA). The material sample is heated or cooled in a controlled rate, typically around 10-20 °C/min together with a reference sample. The heat flow is continuously measured in relation to the temperature. For DSC, the Tg is determined based on the recorded endothermic or exothermic peaks and changes in the heat capacity. The older DTA method uses the temperature differences between the reference sample and the test material as measurement signal (QA Group, 2025).

Permeability

Permeability is an important property of O-rings in GDI systems because it directly influences the seal's ability to prevent the transmission of gases and vapours through the material, allowing for maintaining system integrity, efficiency, and safety. Leakage of gasoline vapours and fuel creates a risk of fire or explosion by forming mixtures with air. ASTM D1434 and ISO 15105 are standards defining test methods for the measurement of gas permeability.

A commonly used method for determining gas permeability is the differential pressure technique, employing a gas permeation test cell. This permeation cell consists of two compartments separated by the elastomer sample (either an O-ring or a representative test sheet). The high feed concentration compartment receives and vents the testing gas, while the lower permeate concentration compartment collects the corresponding gas and channels it to a gas pressure detector. Test parameters such as temperature, gas pressure, and sample area are carefully controlled to mimic service conditions similar to those in GDI systems. Under steady-state conditions, this method yields data on permeability, diffusion coefficient, and solubility (Jung, 2024).

FKM possesses very low permeation coefficients, e.g. FKM Viton® A, with 0.05 to $0.7*10^{-8}$ sccm-cm/sec-cm^2-atm units for N_2 and $5*10^{-8}$ sccm-cm/sec-cm^2-atm units for CO_2 (Marco Sealing Solutions, 2025).

Long-term sealability

Apart from withstanding thermal or chemical degradation, the elastic recovery ability of a material is a key parameter for sealing performance over the whole life span of the vehicle. ASTM D1414 defines testing methods to assess the elastic recovery and associated parameters such as compression set and compression stress relaxation.

The Elastic Recovery (Tension Set Test) involves stretching an O-ring specimen to 100 % elongation and maintaining this strain for 10 minutes using a tension test machine or a specialized fixture. Following this holding period, the specimen is released and allowed to recover for additional 10 minutes. Subsequently, the inside diameter of the O-ring is measured post-recovery to assess the extent of permanent deformation. The tension set percentage is then calculated by comparing the permanent elongation to the original inside diameter, serving as a measure of the loss in elasticity or elastic recovery (Manager, 2010, p. 141).

The Compression Set Test involves compressing a specimen, typically a segment of an O-ring or a similar piece, to 75 % of its original thickness between two plates at a specified temperature for a certain duration, usually several hours. After undergoing compression and heat exposure, the specimen is cooled, and its thickness is measured to determine the extent of permanent deformation. The compression set percentage is then calculated based on the difference between the original and final thickness under no load, reflecting the degree to which the O-ring remains deformed after prolonged compression (Manager, 2010, p. 141). This parameter is important for assessing the O-ring's ability to maintain its sealing force under long-term static stress.

The Compression Stress Relaxation test involves compressing a specimen under a constant strain and measuring the decline in stress (force) over time at defined temperatures. This test indicates how the sealing force diminishes due to molecular relaxation and material flow under sustained load conditions. Lower stress relaxation values suggest better maintenance of the sealing force under continuous compression (Manager, 2010, p. 141).

Acceptance limits for these values are typically defined by OEM specifications. For compression set, acceptable values are generally between 10 to 25 %, while values above 40 % impair the longevity of the O-ring and should be avoided (NH O-RING, 2025). The compression stress relaxation should result in less than a 25 % reduction in sealing stress (Rogers Corporation, 2025).

3.2.3 Standards, regulations and other drivers of FKM use within the application

The material selected for O-rings as part of GDI Systems is directly or indirectly affected by different regulations addressing emission requirements, material quality and performance expectations in automotive components.

GDI Systems have become a central technology to comply with requirements around the reduction of CO_2 emissions such as EU 2019/631. The regulation (EU) 2019/631 aims towards road transport decarbonisation setting out CO_2 emission performance requirements for new passenger cars and light commercial vehicles for 2030 and beyond contributing to the goals of the Paris Agreement. Compared to 2021, this translates to an EU fleet-wide average reduction of CO_2-emissions by 15 % for the 2025-2029 period; 55 % for new cars and 50 % for light commercial vehicles by 50 % for the 2030-2034 period and by 100 % from 1 January 2035 onwards. Manufacturers exceeding their specific emissions target will have to pay an excess-emission premium of EUR 95 per g/km for each new vehicle registered (*Reduction in CO2 Emissions of New Passenger Cars and of New Light Commercial Vehicles | EUR-Lex*, 2035; *REGULATION (EU) 2019/ 631 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL - of 17 April 2019 - Setting CO2 Emission Performance Standards for New Passenger Cars and for New Light Commercial Vehicles, and Repealing Regulations (EC) No 443 / 2009 and (EU) No 510 / 2011*, 2019). The improved fuel efficacy of GDI systems (around 12-20 % compared to traditional PFI systems, reducing CO_2 emissions by up to 15 %), based among others on the precise fuel delivery, and enablement of downsizing of engines due to higher specific power allowed for a significant reduction in CO_2 and NOx emissions, compared to older multi-port injection systems and therefore, serve as an effective bridging technology, e.g. as part of hybrid vehicles (Duronio et al., 2020; Patsnp Eureka, 2025).

Regulation (EU) 2024/1257, also known as Euro 7, sets stringent type-approval requirements for motor vehicles, their engines, systems, components, and separate technical units, emphasizing emissions and battery durability. It harmonizes emission limits for both light-duty and heavy-duty vehicles, imposing stricter controls on pollutants such as NOx, CO, and particulate matter, including emissions from brakes and tires. It mandates durability requirements to ensure emissions control systems and batteries maintain their performance over the vehicle's lifetime. Apart from the emission reduction aspects outlined in relation to regulation (EU) 2019/631, FKM O-rings allow for the achievement of standards set over the vehicle’s lifetime. For light-duty vehicles, the main lifetime is defined as 8 years or 160,000 km, whichever comes first, and 200,000 km or 10 years additional service life. During this period, the vehicle must comply with the set emission limits; and temperature resistance as well as chemical compatibility of the sealing materials must be given. Hence, impairments of the material within this timeline, leading to malfunction of the GDI system and consequently increased emissions must be excluded.

Furthermore, automotive OEM specifications establish detailed performance and quality standards for sealing components, including threshold values for tension set, compression set, chemical resistance, and temperature resilience specifically tailored to GDI system demands. These specifications translate technical and regulatory requirements into defined material and product acceptance criteria. FKM is the key material that allows GDI systems to realize their intended benefits in fuel economy and emissions reduction and meeting the stringent properties outlined in OEM standards. Also in light of the (technical) liability, OEMs tend to refrain from lowering the set standards.

In conclusion, while the regulatory guidelines do not explicitly refer to specific sealing materials, the demands on vehicle lifespan and emission limits outlined above can currently only be realistically fulfilled by applying direct injection technologies in combustion engines including fluoropolymer containing sealing materials (CarExamer, 2025).

3.2.4 General overview of alternatives

Regarding alternatives for O-ring sealings in the transport sector in general, a number of potential alternatives were identified, drawing from both literature and industry sources. Many of those are mentioned in the PFAS restriction proposal background document, as well (ECHA, 2025a). However, through examination of literature and interviews with downstream users, it is evident that the vast majority of these alternatives are not considered suitable for O-ring sealings in GDI systems, given the harsh conditions the material needs to withstand.

A critical requirement for any suitable alternative is to meet the defined and case study specific key functionalities defined in chapter 3.2.2. At this stage, the pre-screening of alternatives and more thorough alternative assessment relies on available information from data searches of publicly available resources and considerations from downstream users where available. It is to be noted that actual testing data of the materials within components is generally not available. Oftentimes, the materials are excluded in preliminary screening tests or based on comparison of the technical data by the automotive component manufacturers, as the properties cannot reach the internal standards.

In Figure 5 and Figure 6 a general overview of the common elastomers, i.e., rubber materials and their operation temperature ranges as well as swelling in oil under maximum working temperature is given, respectively.

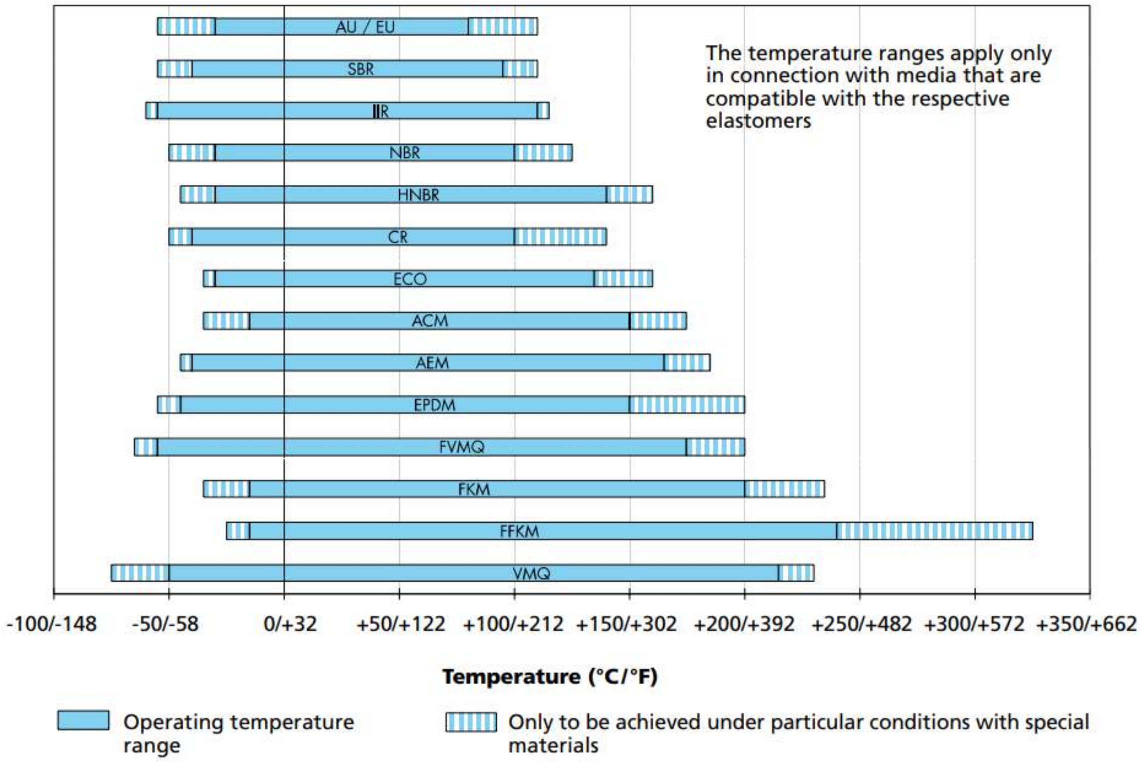

Figure 5: Temperature range of various elastomers.

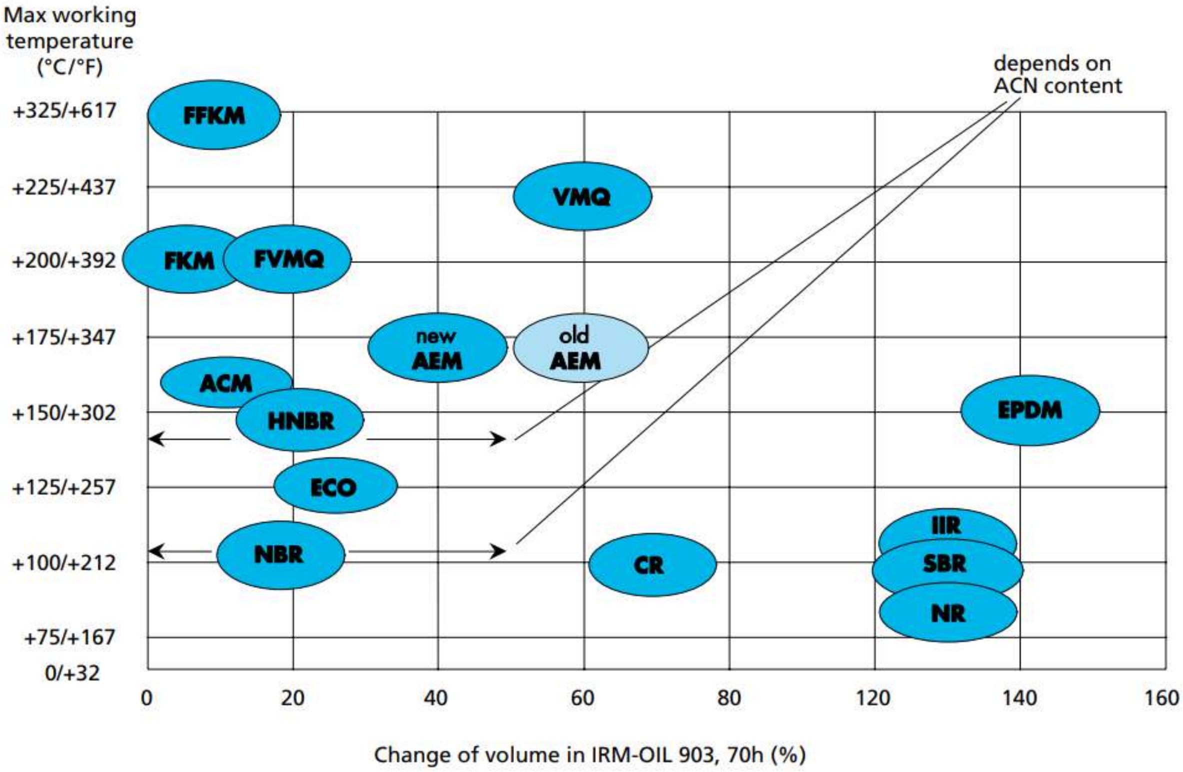

Figure 6: Change of volume in IRM-Oil 309 (reference test oil to test resistance of rubber materials to petroleum-based oils) (Trelleborg Sealing Solutions, 2012).

As outlined in section 3.2.2, temperature resistance and chemical compatibility are two of the key functionalities a material must perform to be applied in a GDI system. At cold start and normal engine operation the fuel temperature, which also approximates the temperature the O-ring between the fuel rail and injector needs to withstand, range between 20 °C to 90 °C. Extreme temperatures investigated to test material limits and operation in severe climates range between -20 °C (and lower) to 115 °C (Ding et al., 2001; Infineum International Limited, 2016). While several rubber materials falls in this temperature range, some show strong changes in volume (i.e., > 10 %), when immersed in petroleum-based oil.

Hence, among the potential alternatives to FKM, only one - available in two variants - has been categorized as a shortlisted alternative and is, therefore, considered in the detailed alternative assessment (section 3.2.5) for further evaluation. These variants are NBR (nitrile butadiene rubber / acrylonitrilebutadiene-rubber) and HNBR (hydrogenated nitrile butadiene rubber).

The following section provides an overview of the general alternatives (longlist) available, including materials with moderate fuel resistance (i.e., volume change), though they are not further assessed in this context.

Table 14: overview of potential alternatives for fluoropolymer-based O-ring sealings in GDI systems

Alternative	**Categorized**
(H)NBR ([hydrogenated] nitrile butadiene rubber / acrylonitrilebutadiene-rubber)	Shortlisted, chapter 3.2.5
ACM (polyacrylate)	Longlisted
AEM (ethylene acrylic rubber / elastomer)	Longlisted
CR (chloroprene rubber)	Longlisted
ECO (epichlorohydrin copolymer rubber)	Longlisted
VMQ (vinyl methyl silicone rubber)	Longlisted

ACM

ACM elastomers consist of polar acrylic acids including various monomers, such as ethyl acrylate, butyl acrylate, methoxyethyl acrylate or ethoxyethyl acrylate (Freudenberg FST GmbH, 2025; RADO Gummi GmbH, 2025a). The characteristics of acrylic rubber are affected by the chemical makeup of the ester groups and the composition of the comonomers. For example, the glass transition temperature significantly decreases with an increase in the chain length of the ester group, whereas the resistance to oils increases accordingly (RADO Gummi GmbH, 2025a). ACM has an operating temperature ranging from -20 °C to 150 °C (for a short period of time up to 175 °C). There are special compositions, which can be applied down to -35 °C (Trelleborg Sealing Solutions, 2012). HT-ACM grades were developed to cover even broader temperature ranges (-40 °C to 185 °C/200 °C short term) (RADO Gummi GmbH, 2025a).

Available hardness ranges from 25 – 85 Shore A, elongation at break up to 450 %, albeit the strength is described as moderate and the elasticity is low (Clwyd Compounders Ltd., 2023; Freudenberg FST GmbH, 2025). ACM is resistant in petroleum-based oils and fluids (e.g. for engines) but are not stable in hot water, steam, fuels, polar solvents or brake fluids (Freudenberg FST GmbH, 2025). Hence, in the automotive industry, ACM is typically applied when high temperature and oil resistance are required e.g., as seals or O-rings in engines, steering systems or transmissions (Kremer Technology GmbH, 2025).

Due to its incompatibility with fuel contact, ACM is not deemed suitable as substitute for the FKM O-ring at the fuel rail/ injector connection.

AEM

AEM, often branded as Vamac®, is a copolymer of ethylene and methyl acrylate with a cure-site monomer (RADO Gummi GmbH, 2025c). It is characterized by its notable thermal resistance within a temperature range of -40 °C to 180 °C (Precision Polymer Engineering Ltd., 2023). Furthermore, it exhibits strong physical traits including hardness from 35 to 95 Shore A, tensile strength of 500 to 3,000 psi, elongation up to 850 %, good abrasion and tear resistance, low compression set, and superior vibration damping (RADO Gummi GmbH, 2025c; Rahco Rubber, Inc., 2025b).

In terms of chemical compatibility, AEM provides good fluid resistance, against oils, lubricants, glycols, water, and dilute acids/alkalis. However, it is not recommended for exposure to concentrated acids, aromatic hydrocarbons, gasoline, ketones, brake fluids and phosphate esters (Apple Rubber Products, 2025).

While it is frequently used in the automotive industry as sealing material, e.g. as engine and transmission seals or oil filter gaskets, it is not applied in GDI systems due to its poor compatibility with fuels (RADO Gummi GmbH, 2025c). Hence, it fails to meet the requirements for approximately 90 % of current fluoroelastomer ((F)FKM/PTFE) applications, as stated by one DU (I15).

CR

CR, often marketed as Neoprene®, is a synthetic elastomer polymerized from chloroprene monomer. It provides a thermal resistance with a wide temperature range of -35 °C to 90 °C and can tolerate up to 120 °C for short periods. Special types of CR also function down to -55 °C (Trelleborg Sealing Solutions, 2012). The Tg is also very low (around -45 °C) which yields a good performance in cold environments (DLSEALS, 2024). Based on DU (I15) experience this (upper) range is however not sufficient to comply with OEM standards as higher temperatures can occur within GDI systems under real-life conditions.

CR features beneficial mechanical properties with a hardness from 20-95 Shore A, tensile strength of 500 – 3,000 psi, elongation up to 800 % as well as good abrasion resistance and tear strength (Rahco Rubber, Inc., 2025a).

Regarding chemical compatibility, as known from literature, CR provides good resistance to aliphatic hydrocarbons, water and alkalis, yet it has poor resistance to polar solvents and swelling is observed in aromatic hydrocarbons (Precision Polymer Engineering Ltd., 2023; Rahco Rubber, Inc., 2025a). Additionally, CR is highly susceptible to damage by both non-aged and aged B10[10] (Weltschev et al., 2015). While one DU acknowledges some flexibility and moderate resistance to fluids, this material fails in terms of thermal endurance and long-term exposure to oils and solvents (I15).

ECO

ECO comprise copolymers of epichlorohydrin and ethylene oxide. Its operating temperature ranges from -40 °C to 135 °C (short term exposure up to 160 °C), with excellent low-temperature flexibility (RADO Gummi GmbH, 2025b; Zeon Chemicals L.P., 2025).

ECO exhibits a typical hardness range from 40 to 90 Shore A, with tensile strength between 500 to 2,500 psi, depending on the formulation. Elongation at break is high, between 200 to 800 %. In addition, it has very good compression-set behaviour, particularly at moderate temperatures (below 140 °C) (Elastotech Srl, 2025; Rahco Rubber, Inc., 2025c).

It shows resistance to fuels and hot oils and possess sufficient resistance to methanol-based motor fuels. Conversely, it is not compatible to aromatic and chlorinated hydrocarbons, glycol based fluids and polar solvents (Elastotech Srl, 2025; RADO Gummi GmbH, 2025b). ECO offers significant resistance to air permeation and also shows excellent resistance to the permeation of other inorganic gases (Zeon Corporation, 2025). However, it needs to be noted that the material can have a corrosive effect on certain metals (BRP Manufacturing, 2025).

While many key functionalities for the application in GDI systems are fulfilled, FKM or HNBR are prioritized for high-pressure connections due to their superior heat resistance, minimal swelling in aggressive fuels/additives, and better long-term sealing under extreme pressures (up to 200 bar). ECO has poor compression set limits, meaning that its integrity drops significantly after prolonged exposures above 140 °C (Clwyd Compounders, 2023). Hence, its application in the automotive sector is focussed on low to medium temperature applications such as fuel hoses and liners (i.e., outer and middle linings), cooler hoses or fuel pump diaphragms (RADO Gummi GmbH, 2025b; Zeon Corporation, 2025).

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[10] B10 is defined as heating oil with 10% biodiesel.

VMQ

VMQ refers to a category of elastomeric materials composed of silicone, oxygen, hydrogen, and carbon (ERIKS, 2025b). It can withstand temperatures ranging from -55 °C to 200 °C, with temporary resilience up to 230 °C. The cold flexibility of the material is notable. (Freudenberg Sealing Technologies, 2024; Precision Polymer Engineering Ltd., 2023; Trelleborg Sealing Solutions, 2012).

Silicones, as a group, generally exhibit low tensile strength, tear resistance, and abrasion resistance. However, specialized compounds have been created that offer outstanding heat resistance and compression set resistance. While high-strength silicones have also been developed, their durability does not match that of traditional rubber (ERIKS, 2025b). This was also confirmed by one DU, highlighting the thermal resistance at moderate levels but stressing the lack of thermal durability (I15).

Regarding chemical compatibility, silicone rubber possesses poor resistance to oils, solvents and hydrocarbons, making it incompatible with harsh automotive engine environments (I15; Precision Polymer Engineering Ltd., 2023). However, resistance to E85 was reported at 20 °C and 40 °C (Weltschev et al., 2015). Specific formulations can withstand aliphatic engine and gear oils, water up to 100 °C, and high-molecular chlorinated hydrocarbons (Precision Polymer Engineering Ltd., 2023; Trelleborg Sealing Solutions, 2012). Conversely, it is not resistant to fuels, aromatic mineral oils, steam (short-term up to 120 °C possible), silicone oils and greases, acids, and alkalis (Precision Polymer Engineering Ltd., 2023).

In conclusion, based on its relatively low mechanical properties compared to other elastomers (Freudenberg Sealing Technologies, 2024) and lack of chemical compatibility to fuels its application as sealing material in GDI systems is limited. Applications in the automotive sector comprise mainly static seals, e.g. in boots, oil filter valves, or gaskets in light (GMORS, 2025).

3.2.5 Assessment of (H)NBR as alternative to FKM in O-rings in GDI systems

3.2.5.1 Description

NBR is a synthetic polymer made from butadiene and acrylonitrile and possesses several important properties such as resistance to oils, fuels, and other aliphatic hydrocarbons (I15). NBR remains flexible across various temperatures and offers good mechanical stability. These properties make NBR a popular choice as potential alternative to FKM for O-ring sealings in automotive applications.

HNBR is a hydrogenated version of NBR, achieved by saturating the double bonds in the polymer structure. Since, similar to NBR, its properties depend on the ACN (acrylonitrile) content ranging between 18 to 50 % as well as the degree of saturation, this hydrogenation significantly enhances HNBR's heat and oxidation resistance, enabling it to withstand high temperatures and making it highly resistant to thermal aging (I15; Trelleborg Sealing Solutions, 2012). Specific details are provided in Table 15.

HNBR also provides improved chemical resistance, particularly against fuels, oils, and ozone, and possesses good mechanical properties, including high tensile strength and elasticity (Freudenberg Sealing Technologies, 2024).

HNBR is used in similar applications as NBR (both possible as a drop-in option for many applications) but is suited for more demanding environments requiring higher temperatures and chemical resistance. Due to its enhanced properties compared to NBR, it is frequently employed in high-performance applications. While HNBR can be considered an advanced technology, it does not necessitate fundamentally new processes for implementation, although existing production processes may need optimization to accommodate its premium characteristics (Precision Polymer Engineering Ltd., 2023).

Both NBR and HNBR provide solid options for O-ring sealings in various industries, providing a cost-effective (7-8 times less expensive than a high performance FKM) and straightforward solution, and with HNBR suitable for more demanding applications (I14; Freudenberg Sealing Technologies, 2024; Precision Polymer Engineering Ltd., 2023). Both materials can be implemented without significant changes to existing production processes, although HNBR may require process optimizations due to its higher performance capabilities (I15; Trelleborg Sealing Solutions, 2012).

3.2.5.2 Technical performance

The following table summarises the performance of NBR and HNBR according to the key functionalities that were defined for O-ring sealings in the chapter 3.2.2.

Chemical Compatibility

An overview of NBR's and HNBR's performance on the chemical resistance is provided in Table 15, followed by a more detailed description below.

NBR exhibits good chemical compatibility, as literature indicates its good resistance to several chemicals and fluids detailed in Table 15. However, NBR is documented to be poorly resistant to various substances, including polar solvents (e.g., methanol and acetone), ozone, and fuels with high aromatic content, as referenced in Table 15.

HNBR provides improved resistance to hydrocarbons, ozone and steam, but has similar impairments as NBR in contact with certain fuel types.

GDI engines generally require high-quality, detergent-rich gasoline with a higher octane rating to prevent carbon buildup on intake valves and clogging of the fuel injectors and optimize performance, which in turn improves fuel economy (Universal Technical Institute, 2024). However, the aromatic additives in high-octane fuels are incompatible with (H)NBR as outlined previously. Moreover, fuels blended with ethanol or methanol further reduce compatibility with (H)NBR.

NBR and HNBR compounds often contain processing aids like stearates and plasticizers like phthalates to aid moulding and flexibility. These low-molecular-weight additives typically remain in the cured seal, as they do not fully migrate out during vulcanization. Fuels, particularly aromatic components in gasoline, extract these residuals by swelling the rubber, causing hardening, embrittlement, and eventual seal failure under compression. This extraction mechanism is a distinct failure mode in nitrile seals beyond simple thermal aging (Apple Rubber, 2016; Levine et al., 2023). A related aspect is that (H)NBR is compounded with metal oxides that react with acidic decomposition products from aging fuel. In the long-term, these reactions further compromise the seal integrity, which makes (H)NBR a less suitable option compared to FKM. Additionally, the resilience of (H)NBR to oils and fuels is significantly influenced by the ACN content. While a high ACN content is pivotal to attain optimal resilience, it adversely impacts the material's performance at low temperatures (HEPAKO GmbH, 2020).

Table 15: Key functionalities for O-ring sealings as defined in chapter 3.2.2 and performance of (H)NBR

Key functionality	Requirement(s)	Performance of NBR	Performance of HNBR
Chemical Compatibility	• Resistance to the respective fuel type, i.e. gasoline and additives in varying blends (I16). • Resistance against ethanol, methanol, Fuel C, diesel and E10 for e.g. 168 h at 150 °C (I14)	Compatible/ Resistance for: • (aliphatic) Hydrocarbons (Freudenberg Sealing Technologies, 2024; Precision Polymer Engineering Ltd., 2023) • mineral oil-based lubricating oils and fuels • silicone oils • greases • hydraulic oils H, HL, HLP, • flame- retardant hydraulic fluids HFA, HFB, HFC, • water up to approx. 80 °C (Freudenberg Sealing Technologies, 2024) Not compatible / poor resistance for: • Ethanol, Methanol, Fuel C, E10 (standard gasoline with 10 % ethanol) (I14) • Polar solvents (Freudenberg Sealing Technologies, 2024; Precision Polymer Engineering Ltd., 2023) • ozone (Precision Polymer Engineering Ltd., 2023) • (non-)aged B10 (highly damaged) (Weltschev et al., 2015) • aromatic and chlorinated hydrocarbons • fuels with a high aromatic content • glycol-based brake fluids • flame-retardant hydraulic fluids HFD (Freudenberg Sealing Technologies, 2024)	Compatible/ Resistance for (in addition to those listed under NBR): • Hydrocarbons • Ozone (Precision Polymer Engineering Ltd., 2023) • Steam to about 140 °C (HEPAKO GmbH, 2020) Not compatible / poor resistance for: • Ethanol, Methanol, Fuel C, E10, FAM B (I14)
Temperature resistance	• closest to the combustion chamber inlet: -20 °C to ≥ 200 °C • fuel rail side of the injector: Cold start and normal engine operation between 20 °C to 90 °C Extreme conditions between -20 (and lower) and 115 °C (Araneo et al., 2000; Infineum International Limited, 2016)	• -40 °C to 100 °C (I14) • for a short period of time up to 120 °C, some formulations down to -60 °C) (Trelleborg Sealing Solutions, 2012)	• -40 °C to 150 °C (I14) • for a short period of time up to 160 °C, special types down to -40 °C (Trelleborg Sealing Solutions, 2012) • max. 125 °C for continuous operation (I21)

Key functionality	**Requirement(s)**	**Performance of NBR**	**Performance of HNBR**
Pressure-Temperature Rating	• maximum fuel demand: approx. 200 bar • shift of glass-transition Temperature (Tg) towards a 15 °C increase compared to standard (temperature) conditions and pressures (I16); sufficiently low Tg, depending on the application	• NBR 70 O-rings withstand working pressures up to 100 bar (no backup) and up to 345 bar with backup ring (Rubber & Seal, 2025) • Tg between -40 °C to 5 °C, depending on ACN content (NETZSCH Polymers, 2025)	• HNBR seals withstand working pressures up to 160 bar (Key Solutions Group, 2025) • Tg between -30 °C to -10 °C depending on ACN content (NETZSCH Polymers, 2025)
Permeability	• Low permeability to liquids and gases	• low gas permeability (Freudenberg Sealing Technologies, 2024)	• low gas permeability (NH O-RING GmbH & Co. KG, 2022)
Long-term sealability	• high elastic recovery (i.e., low compression set & low compression stress relaxation values) at operating temperatures and over the vehicle lifetime	• high abrasion resistance • hardness between 45 to 95 Shore A • mechanical properties dependent on ACN content (HEPAKO GmbH, 2020)	• High mechanical resistance, improved abrasion resistance and low compression set (PTFE Competence Center GmbH, 2025) • Tear resistance and elongation at break depend on saturation (HEPAKO GmbH, 2020) • mechanical properties dependent on ACN content (HEPAKO GmbH, 2020) • Hardness between 45 to 95 Shore A (HEPAKO GmbH, 2020)

Internal testing performed on HNBR by a DU confirmed the low chemical compatibility with two types of fuels through aging tests (I14). HNBR was tested in two variants (standard and high-performance) against a high-performance 80-FKM suitable for low-temperature applications. The test was carried out in Fuel C and FAM-B under the conditions of 168 hours at 60 °C. Tested parameters included changes in hardness, tensile strength, elongation, and volume. Results indicated around 3 to 4 times higher swelling of HNBR compared to standard FKM, with noticeable reductions in elongation and elasticity (test data for Fuel C & FAM B).

According to another DU, HNBR and NBR are already used in most fuel and oil systems; they generally perform well but are not suitable for high injector temperatures (I13). FKM is much more stable and possesses no recorded failures in diesel injectors.

According to the defined requirements, it can be concluded that there is a compatibility given for petroleum-based fuels and several types of liquids although compatibility with aromatic hydrocarbons and fuel blends with methanol or ethanol is considered to be limited. Information from stakeholder confirm that NBR and HNBR do not sufficiently fulfil this key functionality under the tested conditions.

The discussed chemical compatibility data clearly indicate the inadequate performance of NBR and HNBR under application conditions. Hence, further testing is not required, and downstream users may refrain from investing resources in product developments based on these materials. Suppliers of (fluoropolymer and non-fluoropolymer) O-rings, do not offer NBR or HNBR O-rings for the application in GDI systems to date [I16].

Temperature resistance

For temperature resistance, an overview of the general performance of NBR and HNBR is given in Table 15 as well. According to literature, NBR and HNBR provide a minimum temperature limit of -30 °C, with special types reaching as low as -60 °C for NBR and -50 °C for HNBR (Precision Polymer Engineering Ltd., 2023). A DU confirmed the practical limit of -40 °C for both materials (I14). As mentioned under "Chemical Compatibility", a lower ACN content enabling good performance in cold environments comes with limitations in the chemical resistance for the respective grades.

For maximum temperature limits, NBR is known in literature to withstand up to 100 °C, which was confirmed by the DU (I14). For HNBR, the maximum limit is more variable; while literature mentions 140 °C, another source reported a maximum of 175 °C (Precision Polymer Engineering Ltd., 2023). The DU confirmed that HNBR can handle up to 150 °C (I14; (Trelleborg Sealing Solutions, 2012).

Both variants can resist even higher temperatures for short periods: NBR up to 120 °C and HNBR up to 160 °C (Trelleborg Sealing Solutions, 2012). However, according to the DU, HNBR cannot resist 200 °C as it quickly degrades at this temperature level (I14).

HNBR is reported to pass heat aging tests for 70 h at 150 °C, e.g. HNBR90 (Global O-Ring and Seal, LLC, 2025). A study evaluating deterioration of HNBR from temperatures between 100 °C to 150 °C in air (air oven aging) after 168 h, 504 h and 1008 h exposure showed a significant reduction of the elongation capacity at 150 °C (up to 87 %). The testing laboratory concluded that while performance at 125 °C was acceptable, the material should only be used for limited service at 150 °C (I21). Two additional tests investigating the aging properties of HNBR over similar exposure durations at temperatures between 100 °C to 130 °C, while immersed in different variants of 75W90 gear oil (according to ASTM D471), confirmed accelerated reduction of the elongation capacity, starting at 110 °C (I22; I23). This loss of elasticity signals a poor long-term heat resistance and emphasises the significance of evaluating the material in long-term tests and under realistic conditions (i.e., while immersed in relevant media).

With respect to the defined requirements, it can be concluded that based on the currently available data this key functionality not fulfilled. There is still a significant gap to the performance of FKM in view of (long-term) heat resistance in combination with chemical compatibility: NBR and HNBR tend to harden due to thermal aging and fuel exposure at nominal operating temperatures of GDI systems, leading to cracking after relatively short exposures. FKM demonstrates superior heat and chemical resistance, resisting hardening and cracking far longer. As outlined in Table 12, maintaining seal integrity is vital for preventing fuel leakage, which poses a significant safety risk. The data discussed in this paragraph also reinforce the potential reluctance of downstream users towards investments on further testing on HNBR mentioned under "Chemical Compatibility".

Pressure-Temperature Rating

Relevant parameters to assess the pressure-temperature rating are displayed in Table 15 for NBR and HNBR, respectively. While the working pressure NBR sealings can withstand is quite limited (around 100 bars without backup ring), HNBR reaches much higher values with around 160 bars. Conversely, the hydrogenation leads to an increase of the Tg of HNBR compared to NBR, making it slightly less flexible in cold environments. Backup rings are oftentimes made of PTFE, which in itself is also a fluoropolymer.

In conclusion, the cold flexibility of the materials generally fulfils the requirements. The working pressures, especially of NBR are considered too low for application in GDI systems, where pressures can reach 200 bar at maximum fuel demand. However, the publicly available data was rather limited, and this parameter highly depends on the specific O-ring design. Hence, testing data within the relevant component would be needed to make a final determination on the appropriateness.

Permeability

The gas permeability of both, NBR and HNBR is low and therefore fulfil the respective requirement.

Long-term sealability

The mechanical properties of NBR significantly depend on its acrylonitrile content. Lower acrylonitrile improves compression set, but higher acrylonitrile content can be beneficial for other mechanical properties e.g., tensile strength. NBR offers very good abrasion resistance and typically ranges from 30 to 95 Shore A in hardness (HEPAKO GmbH, 2020).

HNBR offers excellent tear and very good abrasion resistance, outperforming NBR in these areas. It's a strong choice for applications needing high dynamic resilience. Tear resistance varies by HNBR type, with unsaturated (partially hydrogenated) compounds offering better tear resistance and elongation at break than saturated types. The compression set of HNBR is average but improves with peroxide crosslinking (about 20 % for 70 h/150 °C). HNBR compounds are available in hardness levels from 45 to 95 Shore A.

For both materials, lower acrylonitrile content, which enhances compression set, reduces fuel resilience, posing a challenge for automotive seals requiring both properties. Testing under real-life conditions need to be performed to address this discrepancy and investigate if the material can be altered in a way that it would fulfil the key-functionality (HEPAKO GmbH, 2020). However, as outlined in the sections "Chemical Compatibility" and "Temperature Resistance", the likelihood of downstream users investing additional resources in this area seems low.

3.2.5.3 Economic feasibility

As stated in the Introduction, fluoropolymers are rarely chosen for everyday consumer items. Instead, they are mainly used wherever reliability under harsh conditions is critical. Hence, price is usually not the decisive factor when choosing fluoropolymers for an application. In fact, most polymers including high performance / specialty polymers have significantly lower prices in comparison to fluoropolymers.

For the present application and for the shortlisted alternatives NBR & HNBR, economic considerations are not of relevance. Both materials are much more affordable than FKM and a potential use of (H)NBR O-rings in engine systems would additionally not result in extensive changes to the production process. The limiting factor for (H)NBR thus remains the technical feasibility.

3.2.5.4 Hazard Assessment

Appropriately formulated NBR and HNBR compounds are generally considered non-toxic in their final cured state, as demonstrated by their approvals for specific food-contact and medical applications. However, the monomers used for the production of (H)NBR, i.e. acrylonitrile and 1,3-butadiene, are both hazardous monomers with established carcinogenic potential. 1,3-butadiene also shows mutagenic effects.

Degradation of (H)NBR by chemicals, aging or heat can generate hazardous degradation products, potentially including low-molecular fragments related to the original monomers. Therefore, using (H)NBR as a sealing material under severe conditions (aggressive media, elevated temperature and pressure) could pose health risks if degradation products migrate into occupied areas or media in contact with humans. This needs to be considered when discussing the feasibility of (H)NBR as alternative to FKM as high-pressure sealing material in GDI systems.

3.2.5.5 Assessment of suitability

NBR and HNBR appeared to be the most suitable alternatives for O-ring sealings, given their broad resistance to oils, petroleum-based fuels, and other hydrocarbons, while providing a wide operating temperature range. However, literature and testing data revealed some shortcomings in comparison to FKM:

Chemical compatibility assessments indicate that (H)NBR exhibit poor resistance to ethanol, methanol, and fuels with high aromatic content. Internal testing by stakeholders confirmed significant swelling and reduced elasticity in HNBR compared to high-performance-FKM when exposed to Fuel C and FAM-B. Furthermore, the higher content of aromatic hydrocarbons in octane-rich fuels, which are beneficial for the operation of GDI systems, are less compatible with (H)NBR

While especially HNBR can handle the required temperature ranges for a limited duration, heat aging tests for up to 1008 h at up to 150 °C, revealed significant reduction in elongation indicating that the seal integrity would suffer over time. As mentioned previously, seal failure leading to fuel leakage possesses a safety risk for the driver including a fire hazard. As FKM is proven as long-lasting material in high-pressure and temperature applications, it is currently the favoured option for application in GDI systems.

Data on pressure-temperature rating, permeability, and long-term sealability is sparse. Initial indications suggest potential fulfilment of key functionalities, but comprehensive testing is needed. The acrylonitrile content significantly influences material properties, and optimal compositions need to be identified through targeted testing.

In conclusion, NBR and HNBR fail to demonstrate adequate performance for the application in GDI systems, given the limitations in chemical compatibility and temperature resistance under operational conditions. In light of the currently available options (i.e., formulations of HNBR), downstream users may refrain from investing in further testing, as the performance gaps compared to FKM appear to be significant, based on the data already available.

3.2.6 Substitution timeline at the Case study level

There is no detailed information available from downstream users or other stakeholders regarding the timeline for substitution Fluoropolymer-base O-rings in GDI systems. Generally applicable processes & timelines for the automotive sector are discussed in section 1.1.

3.2.7 Conclusion on Case study "Use of fluoroelastomers (FKM) as high-pressure sealing material in gasoline direct injection (GDI) systems"

This case study on O-ring sealings in GDI systems has explored the performance and viability of alternative materials such as NBR and HNBR. While short-term tests on these alternatives are available, long-term studies are often missing. Testing these materials is costly, as they need to be evaluated as part of the entire component assembly to accurately mimic the relevant conditions. Furthermore, components may need to be re-designed to accommodate for the alternatives' properties as none of the assessed materials fulfilled the key functionalities in the same extent as FKM. This option is highly time and cost extensive. Stakeholders highlight, that GDI engines are highly specialised and changing of its configuration (e.g., size) may undermine its benefits in terms of fuel efficacy and reduced CO_2 emissions. This in turn can cause challenges for the compliance with the regulatory standards outlined in chapter 3.2.3.

There have been limited movements within the transport sector, with some fluoropolymer producers exiting the market, and there is a lack of promotion of alternative solutions by polymer producers (I15). Despite this, OEMs are open to the recertification of materials. In some cases, they are willing to decrease specifications to enable the use of alternatives (I15). However, car manufacturers must reduce the temperature environment for seals to a maximum of 140 °C to 150 °C or even lower and switch to fuels that are less aggressive towards rubber materials, which are not currently available (I14).

Fluoropolymers remain the highest-priced materials, but their usage in the industry suggests that they are deemed necessary due to their superior performance characteristics compared to alternatives (I14). As an example, the substantial portion of one downstream user's business tied to fluorinated materials underscores the impact any substitution would have on their operations (I14).

In conclusion, based on the data considered for this assessment, no alternative material could be identified that fulfilled the defined key functionalities. Extensive research, realistic testing conditions, and industry-wide adjustments must be conducted to find an adequate alternative material and determine its suitability for long-term use in GDI systems. The transition to alternative materials is complex and will require coordinated efforts from polymer producers and OEMs (automobile manufacturers and their suppliers, respectively) to ensure the reliability and performance of these substitutes.

3.3 Case study "Use of fluoroelastomers (FKM) as inner layer of fuel hoses for high temperature applications in the automotive sector"

3.3.1 Overview of the application, its relevance and description of key components

Fuel hoses and fuel lines are critical components in automotive systems, playing a pivotal role in ensuring the efficient and safe delivery of fuel from the tank to the engine. As such they have a direct impact on the vehicle's performance, reliability and safety. Due to their direct contact to the fuel, and the various substances contained therein, and due to the conditions, they are exposed to, they must fulfil multiple criteria to be suitable for the transport of fuel.

Most impertinent to its function as a fuel transportation media, the fuel lines must be resistant to the permeation of different kinds of fuel even at elevated temperatures. This includes that they also need to have a certain chemical resistance at prolonged exposures and elevated temperatures. Further, the fuel lines should demonstrate some flexibility for the absorption of shocks during operating the vehicle but still have inherent stability. Considering all these factors limits the type of material that is suitable for this use. Pure steel fuel lines for example would have a good resistance to fuel diffusion and temperature, both factors that are regulated through norms, but would have insufficient shock absorption properties, a factor not regulated through norms. Hence, steel-based fuel lines would be prone to breakage leading to a safety hazard. To be able to fulfil the multitude of criteria, fuel hoses and lines are not made from one bulk material but have several layers made of different materials, which in combination meet the requirements needed.

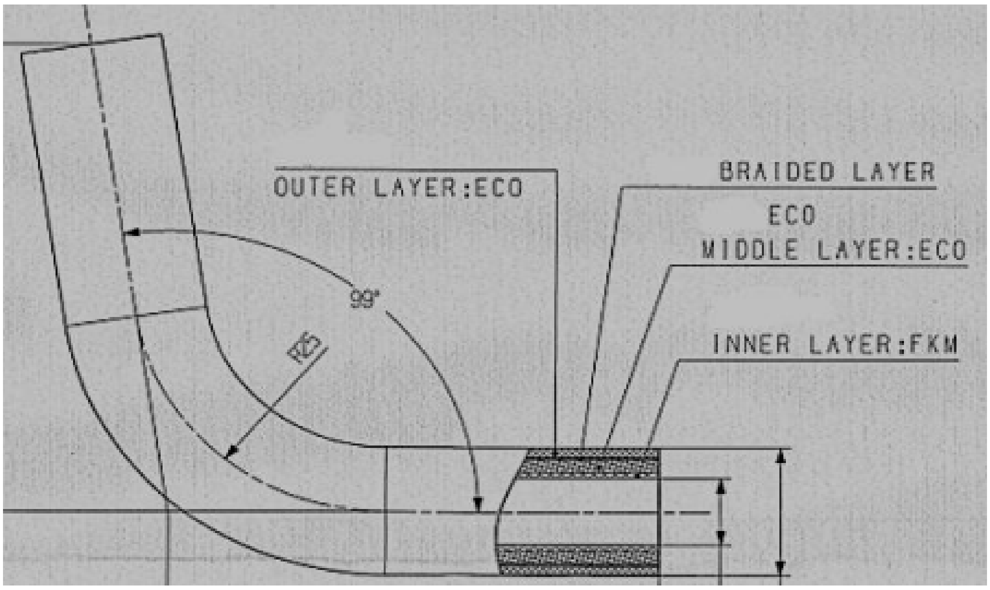


Figure 7: Schematic exemplary overview of the layer build-up of fuel tubing as they are used in cars (Mule et al., 2013).

The number of layers can vary depending on the materials used and the conditions of use. The typical layout of a fuel hose or line is as follows:

The innermost layer's purpose is to be chemically inert against the fuel while also not "bleeding" impurities into the fuel. Further it should be limiting the possible diffusion of the fuel through the hose while simultaneously being as thin as possible. Because of these requirements the innermost layer is the part of fuel lines in which fluoropolymers are typically used. The thickness of the innermost layer is usually kept between 0.4-1 mm while maintaining the highest results in resistance to fuel diffusion or chemical resistance (Shinobu Kanbe et al., 2004). In some cases, and depending on the material of the innermost layer, a second layer is needed as an intermediary binding layer to bind to the innermost layer and allow for adhesion with the third layer. This third layer has the function to give the fuel line stability while maintaining flexibility and can consist of either textiles made from different materials or woven metal. The outermost layer does not only also add onto the stability of the fuel hose but is impertinent to the protection of the whole tube against external forces or conditions. As such it usually consists of a type of rubber.

Although the innermost layer, which is typically composed of fluoroelastomers, constitutes only a minor proportion of the total thickness, it performs the most critical function within the hose-system. It effectively contains the fuel by exhibiting exceptionally low permeation rates and prevents the introduction of impurities due to its chemical stability, even at elevated temperatures where alternative materials may become permeable. Furthermore, due to the increasing global use of biofuels, the technical demands to the innermost layer are more stringent, as bio-based fuels introduce other chemical constituents to the fuel, which have an even higher possibility to permeate through common tubing materials at normal and elevated temperatures. Thus, the resistance to the diffusion of fuel through the hose and chemical stability are becoming the key criteria to control.

3.3.2 FKM types, their properties and Key functionalities within the application

As described in chapter 3.3.1, fluoropolymers are used as innermost layer to provide the chemical resistance against the different fuel types and to limit the diffusion of fuel into the other layers and through the tubing as a whole. Various types of FKM materials can be used in fuel lines, and their specific characteristics, such as heat resistance, low temperature resistance, low fuel permeation, flexibility, bonding strength to the second layer, depend on both their fluorine content and the curing method. These differences influence how well each FKM material meets the requirements for fuel line performance.

Examples for different kinds of FKM materials used as innermost layer in fuel hoses are:

- Copolymers [hexafluoropropylene and vinylidene fluoride] curable with:
  - Bisphenol AF
  - Peroxides
- Terpolymers [hexafluoropropylene, vinylidene fluoride and tetrafluoroethylene] curable with:
  - Bisphenol AF
  - Peroxides
- Terpolymers [vinylidene fluoride, tetrafluoroethylene and perfluoromethylvinyl ether (PMVE) or similar vinyl ether monomers] (Apple Rubber, 2023)
- Terpolymers [vinylidene fluoride, tetrafluoroethylene, propylene or propylene derivatives] (Apple Rubber, 2023)
- Copolymer with 5 different monomers [hexafluoropropylene, vinylidene fluoride, tetrafluoroethylene, PMVE, ethylene or combinations thereof] (Solvay, 2014)

There are key functionalities that the fluoropolymer must fulfil (e.g. heat resistance, chemical resistance, initial fuel diffusion, cohesive resistance) and key functionalities that must be met by the tube as a whole when taking all layers into account (e.g. swelling through fuel diffusion and total fuel diffusion).

Table 16: Overview on the key functionalities of the fluoropolymers

Key functionality/properties	Technical requirements – minimum requirements	Criticality/importance
Chemical resistance	Chemical resistance against gasoline and diesel or blends thereof with ethanol, oxygenated species or possible additives is needed. Tests on the fuel hose are performed through immersion testing at set temperatures for an extended time period. Minimal requirements are based on the OEM chosen standard, but tests are for example performed in accordance with SAE J30, ISO 4639-1 or ASTM D471.	If the materials are not chemically resistant against their content, swelling, cracking or degradation of the tubing can occur resulting in fuel loss.
Fuel permeability	Fuel lines need a sufficient resistance against fuel permeability to allow for a loss-free transport of fuel. As materials can become more porous at elevated temperatures, the area close to the engine is relevant for permeability tests. Standard tests can be conducted according to SAE J1737, SAE J30 section 9, or ISO 8469 for fire-resistant fuel hoses and ISO 7840 for fire resistant fuel hoses.	Diffusion of fuel within the fuel line may result in a reduction of system pressure, thereby reducing fuel transport efficiency. More critically, it can cause fuel loss and increase the risk of explosion or fire, especially in high-temperature zones within the vehicle.
Temperature resistance	There are different temperature ranges fuel lines must be able to work in depending on the external conditions and their placement in the automotive layout. The minimum range for hoses is typically -40 °C to 80 °C/90 °C. Testing can be conducted according to standards such as SAE J30, ISO 7840.	At increasing temperature, the pressure resistance of the material decreases, and the porosity increases, thus making it less resistant against fuel diffusion or physical stress.
Physical properties (e.g. cohesive resistance)	There are no direct specifications for this functionality, however it encompasses the flexibility of the fuel tubes, maintaining their structure after elevated temperature and strain from high pressures (also in combination with elevated temperatures). There are standards that refer to the maximum allowed swelling (chemical resistance) or maximum allowed elongation or deformation after stress testing. For the cohesive resistance, ASTM D413 specifies the requirements, in addition to the different adhesion forces that must be met.	If the physical properties of the tubing cannot stay consistent under the use conditions, they can fail through cracking or loosening on joints all leading to a loss of function and fuel.

Chemical resistance

Chemical resistance as being one of the factors allowing for longevity of the fuel hoses needs to be high enough against gasoline and diesel or blends thereof with ethanol, oxygenated species or possible additives. Tests on the fuel hose are usually performed through immersion testing at set temperatures for an extended time. Minimal requirements are based on the OEM chosen standard, but tests are for example performed in accordance with SAE J30, ISO 4639-1 or ASTM D471.

After immersion of the materials the norms describe different maximal allowed values for a change in tensile strength, hardness or elongation depending on the testing criteria and fuel blends used. SAE J30 limits the Elongation change at break and tensile strength change to a maximum of ≤ 50 %.

Fuel permeability

Fuel permeability is a critical parameter to limit loss of fuel and fuel pressure to allow for optimal working conditions and transport of fuel to the motor. Further permeation of fuel or fuel gases through the fuel hose can lead to the formation of flammable air fuel mixtures, leading to hazardous situations. The permeability of fuels can be tested according to SAE J30 or DIN 53508.

Therefore, parts of the fuel hose are filled with fuel mixtures specified in the norms and kept in specific apertures to simulate aging at operational conditions when in contact with fuel. The loss of fuel is then measured after testing, and the permeability is determined in g/cm^2 or $g/m^2/day$. To pass this test the fuel loss or permeability must meet the criteria set in the corresponding norm, which is once again different for each specific use or norm. Further there are slight differences in accepted permeation rates based on the material that is used for the fuel hose.

Temperature resistance

In comparison to O-rings, which must be able to resist a very broad temperature range due to the high temperatures they are exposed to while the vehicle is in operation, fuel hoses do not have to cover such a broad range towards the upper end of the temperature scale. While they still need to be temperature resistant up to 150 °C with bursts up to 175 °C, when being employed close to the motor they must also be able to tolerate cold conditions better than O-rings as low as -40 °C, due to their position within the vehicle being closer to the exterior than for example in the case of O-rings.

Temperature testing can be performed according to ASTM D 573 in which the material is artificially dry aged in ovens over specified times at specified temperatures. After the aging process, the reduction in tensile strength and elongation must not exceed the limit values described in SAE J 30. The standard limit values for the fuel hoses depend largely on the specification for its specific use though and can thus vary.

3.3.3 Standards, regulations and other drivers of FKM in Fuel hoses in automotive sector

Fuel tubes are regulated in different standards based on the country or region of the automobile manufacture. However, as can be seen in the table below the set requirements among different standards are very similar.

Table 17: Key criteria for fuel hoses based on different standards

Standard	Fuel permeability	Chemical resistance	Temperature tolerability
DIN 73379	10g/100cm²/day (NBR) 8g/100cm²/day (FKM)	Different depending on fuel used and material used for testing	-40 °C to 150 °C (with bursts up to 175 °C)
SAE J30	< 15 g/m²/day (acc. to section R9)	No clear swell limit	-40 °C to 100 °C (125 °C, 135 °C, 150 °C depending on classification)
ISO 8469	< 15 g/m/day (Type1) < 100 g/m²/day (Type2)	< 35 % swelling (after 40 °C for 2 days immersion)	Not stated

Fuel Permeability

Depending on the norm used there are different limit values for fuel permeability. These are also sometimes dependent on the material in use such as for DIN 73379, where different values are given for NBR or FKM. The fuel permeability is usually given in g/cm²/day or g/m²/day depending on the norm.

Chemical Resistance

The chemical resistance is measured through the change in tensile strength, elongation or swelling after exposure to fuel or fuel mixtures according to the norms. According to DIN 73379, the materials are tested according to VDA 266-100. Here as well the limit values differ depending on the use and the material used.

Temperature Tolerability

Temperature tolerability is tested for dry heat in ovens at set temperatures and times. The limit values for change in tensile strength and elongation after heat aging once again differ by norm and use of the host/material but only minimally. Elongation and tensile strength change should not exceed 50 %.

Cohesive resistance

The cohesion resistance must also be considered for fuel hoses, especially during exposure to fuel or fuel mixtures, as fuel hoses consist of different layer as described in section 3.3.1, and a separation of the layers would impact not only the stability of the fuel hose but also its chemical resistance and fuel permeation. These criteria can be tested according to ASTM D413. The norms also specify different adhesion forces that must be met according to the material tested and the use of the material (e.g. for low or high pressure uses).

Other relevant legal frameworks

Furthermore, in the EU the regulations EU 2019/631 and EU 2024/1257 will further play a major role for the automotive sector and hence for many of the components included in vehicles, such as fuel lines. Therefore, these regulations are described here.

The regulation EU 2019/631 aims towards road transport decarbonisation setting out CO_2 emission performance requirements for new passenger cars and light commercial vehicles for 2030 and beyond contributing to the goals of the Paris Agreement. Compared to 2021, this translates to an EU fleet-wide average reduction of CO_2-emissions by 15 % for the 2025-2029 period; 55 % for new cars and 50 % for light commercial vehicles by 50 % for the 2030-2034 period and by 100 % from 1 January 2035 onwards. Manufacturers exceeding their specific emissions target will have to pay an excess-emission premium of EUR 95 per g/km for each new vehicle registered. As permeative emissions from fuel hoses and lines are a relevant source of CO_2-emissions, high-performing fuel transport systems can thus support in meeting these targets by reducing evaporative emissions (European Union, 2024b; Martini et al., 2012).

Regulation (EU) 2024/1257, also known as "Type approval of motor vehicles and engines and of systems, components and separate technical units intended for such vehicles, with respect to their emissions and battery durability (Euro 7)", sets stringent type-approval requirements for motor vehicles, their engines, systems, components, and separate technical units, emphasizing emissions and battery durability. It harmonizes emission limits for both light-duty and heavy-duty vehicles, imposing stricter controls on pollutants such as NOx, CO, and particulate matter, including emissions from brakes and tires. It mandates durability requirements to ensure emissions control systems and batteries maintain their performance over the vehicle's lifetime. For light-duty vehicles, the main lifetime is defined as 8 years or 160,000 km, whichever comes first. Hence, fuel hoses and lines do not only need to comply with the durability requirements but also support in meeting the emission limits by limiting emissions from the fuel systems based on ultra-low permeation rates.

3.3.4 General overview of alternatives

Various rubber materials have been discussed as potential materials to be used as the innermost layers in fuel hoses and lines. Below is an overview on commercially available rubbers and their performance in fuel lines.

Table 18: Overview on alternative materials

Alternative	Categorized
(H)NBR ([hydrogenated] nitrile butadiene rubber / acrylonitrilebutadiene-rubber)	Shortlisted, chapter 3.2.5
ACM (polyacrylate)	Longlisted
AEM (ethylene acrylic rubber / elastomer)	Longlisted
EPDM (Ethylene propylene diene monomer rubber)	Longlisted
ECO (epichlorohydrin copolymer rubber)	Longlisted
SBR (Styrene-butadiene rubber)	Longlisted
VMQ (vinyl methyl silicone rubber)	Longlisted

It must be noted that most of the listed materials are not commonly used in this application, as the performance is insufficient. Currently, no new alternative materials for the use in fuel lines are subject to research and development (R&D) activities.

Acrylic rubber (ACM)

ACM while demonstrating good thermal stability and being employed as combinational outer layers with FKM inner layer, is not well suited for fuel contact itself and as such would not be a suitable as inner layer (Kelly (K.) C, 2025).

Acrylic ethylene copolymer (AEM)

While being characterized by its notable thermal resistance and exhibition of strong physical traits including hardness from 35–95 Shore A, tensile strength of 500 to 3,000 psi and elongation up to 850 % its use as inner layer of fuel hoses is not recommended due to its poor stability against aromatic hydrocarbons or fuels.

Ethylene propoylene diene monomer rubber (EPDM)

EPDM has good temperature performance. However, chemical resistance is insufficient (Haseeb et al., 2011).

Epichlorhydrin rubber (ECO)

ECO has not been evaluated in detail as an alternative as it swells significantly after prolonged exposure to aromatic and chlorinated hydrocarbons.

Nitrile butadiene rubber (NBR)

NBR is commercially used as material for the innermost layer of fuel lines for certain application. As such, it is discussed in more detail in the section below.

Hydrogenated nitrile-butadiene rubber (HNBR)

NBR is commercially used as material for the innermost layer of fuel lines for certain application. As such, it is discussed in more detail in the section below.

Styrene-butadiene rubber (SBR)

SBR does not exhibit the sufficient temperature resistance to be used in fuel transport systems.

Silicone rubber (VMQ)

While silicone rubber exhibits excellent resistance to high temperatures, the swelling behaviour of silicone is severe and therefore unacceptable for the use in fuel lines.

3.3.5 Assessment of (H)NBR as alternative to FKM in Fuel hoses in the automotive sector

3.3.5.1 Description of alternative

Nitrile butadiene rubber or NBR and its close variant hydrogenated nitrile butadiene rubber, are high performance synthetic rubbers made up from acrylonitrile and butadiene with the double bonds being saturated in the HNBR alternative. Both have specific advantages and disadvantages based on the saturation of the double bonds. NBR remains flexible while being resistant to oils, fuels, and other aliphatic hydrocarbons (I15). HNBR on the other hand has a higher temperature application due to its largely saturated polymer chain. While this is true for gasoline and diesel, the applicable temperature use when diesel is used is lower than for gasoline with being capped at 80 °C. Further it is more stable against oxidation and has an even better chemical resistance, particularly against fuels, oils, and ozone. (Freudenberg Sealing Technologies, 2024)

Fuel hoses that have an NBR- or HNBR-based innermost layer are already commercially available and are used in some vehicle- and non-road mobile machinery applications (I19). However, for many applications NBR does not achieve the required performance for temperature tolerability, chemical resistance and fuel permeability, as defined in section 3.3.3.

Table 19: Technical performance details of alternatives (H)NBR

	NBR	**HNBR**
Temperature resistance (range)	-30 °C to 100 °C (with bursts up to 110 °C)	-30 °C to 110 °C (80 °C with diesel)
Chemical stability	Resistant against: (aliphatic) Hydrocarbons (Freudenberg Sealing Technologies, 2024; Precision Polymer Engineering Ltd., 2023), mineral oil-based lubricating oils and fuels, silicone oils, greases, water up to approx. 80 °C (Freudenberg Sealing Technologies, 2024)	Additional to NBR: Hydrocarbons and Ozone
Fuel permeation	Moderate 669 g/m²/day (Fuel C according to ASTM standard) (OringsUSA, 2021) Increasing values with increasing ethanol content (OringsUSA, 2021)	Better than NBR but also moderate (OringsUSA, 2021) 230 g/m²/day (Fuel C according to ASTM standard) (OringsUSA, 2021) Increasing values with increasing ethanol content (OringsUSA, 2021)

3.3.5.2 Technical performance

The technical properties of (H)NBR have been presented in detail in section 3.2.5, specifically in Table 19. Below a summary on the three key performance criteria for the innermost layer of fuel hoses are provided.

Temperature tolerability

NBR is used in low temperature applications of < 100 °C, while HNBR has a higher tolerance towards elevated temperature working conditions of up to < 110 °C (I19). According to DIN 73379-07.2014 HNBR is thus only able to be used for class A fuel tubes with operating conditions of 90 °C with burst temperatures up to 110 °C. Other fuel tube classes already require higher operating temperatures (type B 125 °C with bursts up to 150 °C and type C 150 °C with bursts up to 175 °C) making HNBR an unfitting material for the required application of class B and C fuel tubes. The exact conditions of class B and class C fuel tubes can be found in DIN 73379.

However, HNBR’s temperature tolerance is lower compared to FKM and is therefore not suitable for fuel hoses in high-temperature applications. For these applications, fluoropolymers remain the only suitable material that fulfil the temperature- and the other performance requirements.

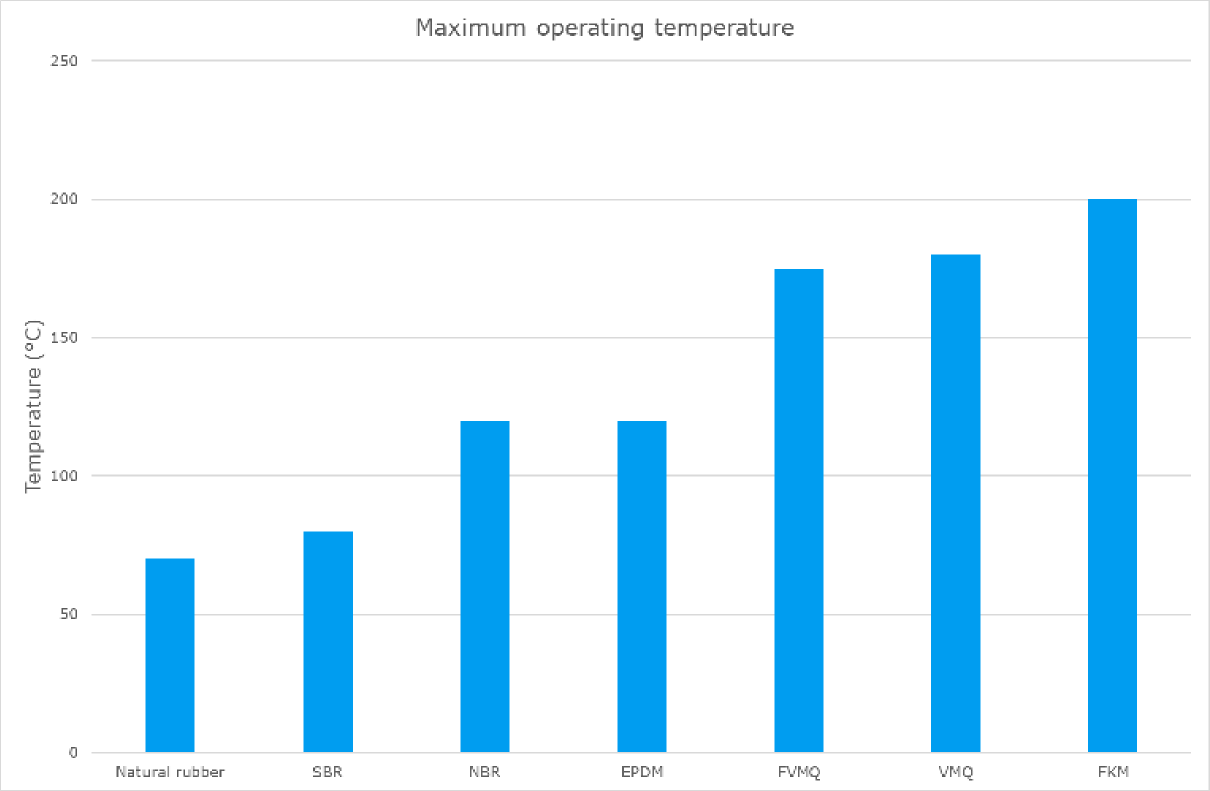


Figure 8: Maximum operating temperatures of rubbers (REIFF Technische Produkte GmbH, 2025).

Chemical resistance

(H)NBR provides sufficient chemical resistance towards most fuel types and has therefore been commercially available for fuel hoses for many years. However, the rise of bio-based and renewable fuels has introduced chemical constituents into the fuel against which (H)NBR is not inert. For example, diesel fuels may contain up to 7-10 % of biofuel, which include ester components. These ester functional groups react with the nitrile functional group of the (H)NBR resulting in degradation of the fuel hose system over time (I17).

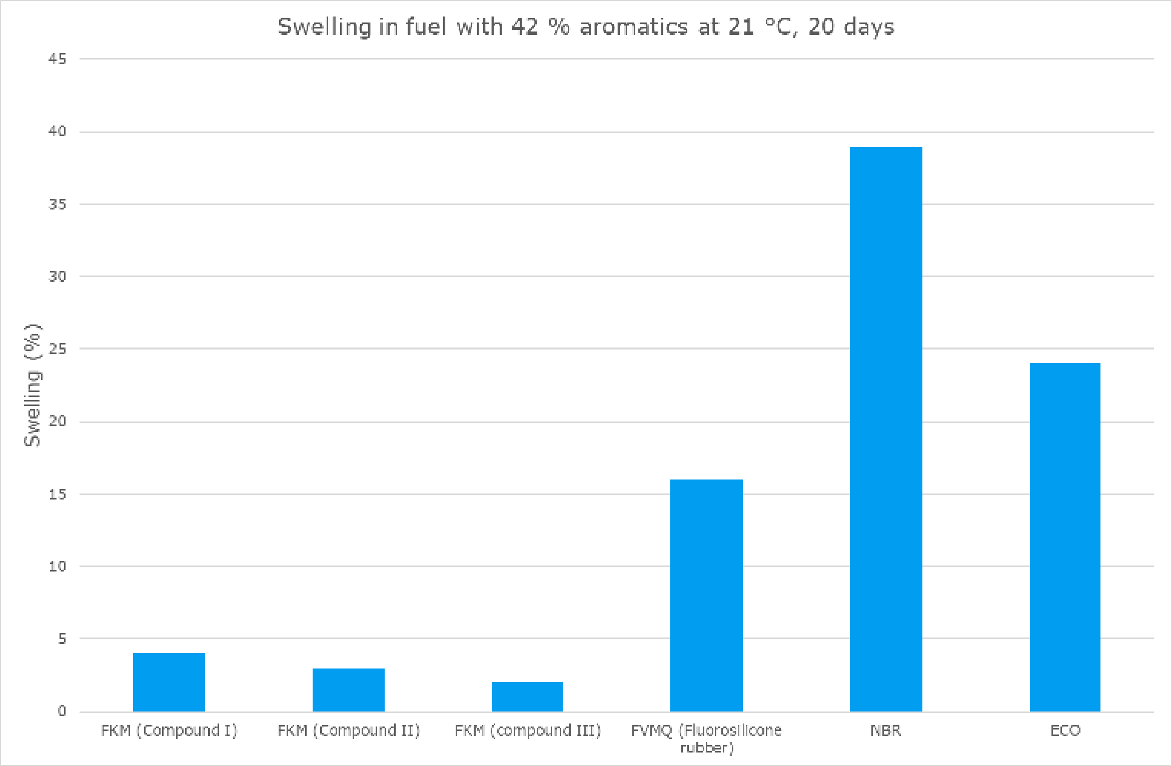


Figure 9: **Volume swelling of rubbers in fuel (42 % aromatics) (I18).**

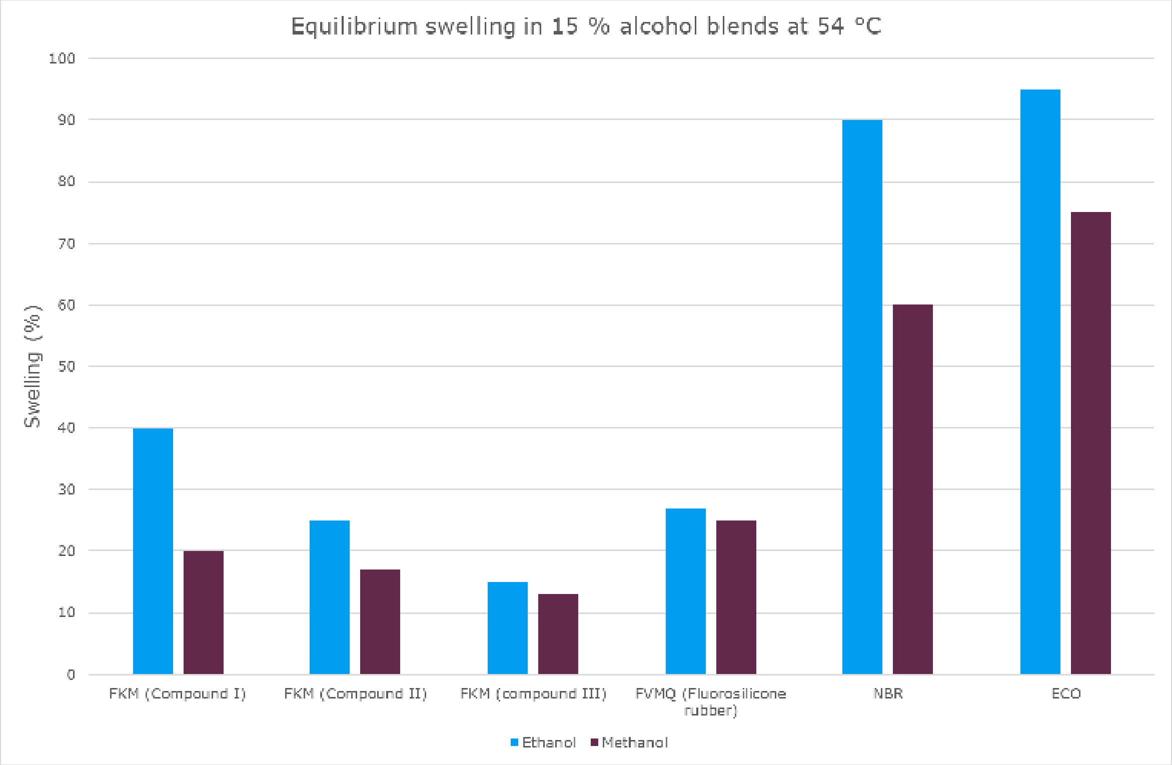


Figure 10: **Volume swelling of rubbers in fuel (15 % alcohol) (I18).**

Fuel permeability

The fuel permeability of (H)NBR is insufficient for certain applications and do not fulfil the regulatory requirements. For example, in the USA fuel hoses for CE10 fuels must fulfil the maximum permeation rate of 15 g/m²/d, which cannot be met by (H)NBR (I18). Furthermore, much higher permeability rates were observed with ASTM test fuels for NBR compared to ECO and FKM materials.

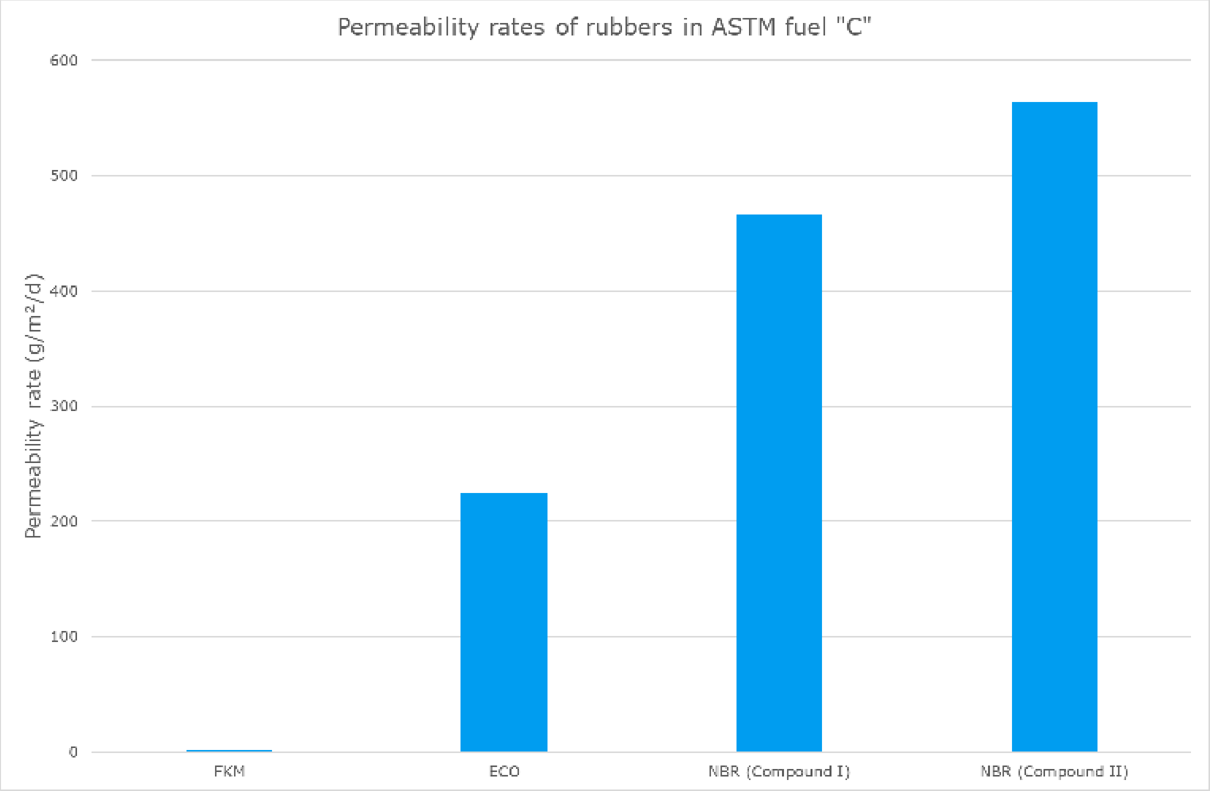


Figure 11: Permeability rate of rubbers. Composition of ASTM fuel "C" (according to ASTM D 471): 50 % Isooctane, 50 % Toluene (I18).

Other factors

(H)NBR contains plasticisers that leaches out of the rubber material, thereby leading to hardening and shrinking (I18). This increases the risk of breakage and leakage and is thus critical for the overall safety.

Apart from the technical feasibility (H)NBR should be assessed for its economic feasibility, market availability, safety and sustainability aspects.

With regard to its economic feasibility, (H)NBR is significantly cheaper than FKM, and is therefore the preferred material for less demanding applications. However, as stated by a DU, FKM is sometimes chosen over (H)NBR despite its higher price, because they cannot exclude that their provided fuel transportation components may not end up in high-demanding applications (I17).

(H)NBR is further sufficiently available on the market, as it is used for various industrial applications, including fuel hoses and lines.

Hence, neither the price nor the market availability of (H)NBR are obstacles to the use in fuel hoses and lines. The main challenge lies with the limited technical performance, as outlined above. The lacking performance has further an impact on safety and sustainability if (H)NBR is used in demanding high-temperature applications. Swelling, shrinkage and cracking of (H)NBR results in increased potential for leakage and thus to increased safety risk. Moreover, it also results in a shorter durability of the fuel transport system and thus may result in a higher environmental footprint.

3.3.5.3 Economic feasibility

As stated in the Introduction, fluoropolymers are rarely chosen for everyday consumer items. Instead, they are mainly used wherever reliability under harsh conditions is critical. Hence, price is usually not the decisive factor when choosing fluoropolymers for an application. In fact, most polymers including high performance / specialty polymers have significantly lower prices in comparison to fluoropolymers.

For the present application and for the shortlisted alternatives NBR & HNBR, economic considerations are not of relevance. Both materials are much more affordable than FKM and a potential use of (H)NBR as inner layer in fuel hoses would additionally not result in extensive changes to the production process, as these (H)NBR-based fuel hoses are already commercially available for applications under less demanding conditions. The limiting factor for (H)NBR thus remains the technical feasibility.

3.3.5.4 Hazard Assessment

Appropriately formulated NBR and HNBR compounds are generally considered non-toxic in their final cured state, as demonstrated by their approvals for specific food-contact and medical applications. However, the monomers used for the production of (H)NBR, i.e. acrylonitrile and 1,3-butadiene, are both hazardous monomers with established carcinogenic potential. 1,3-butadiene also shows mutagenic effects.

Degradation of (H)NBR by chemicals, aging or heat can generate hazardous degradation products, potentially including low-molecular fragments related to the original monomers. Therefore, using (H)NBR as inner layer of fuel tubing under severe conditions (aggressive media, elevated temperature and pressure) could pose health risks if degradation products migrate into occupied areas or media in contact with humans.

This needs to be considered when discussing the feasibility of (H)NBR as alternative to FKM as inner layer for fuel tubing.

3.3.6 Substitution timeline at the Case study level

There is no detailed information available from downstream users, regarding the timeline for substitution of FKM-based inner linings in fuel tubing systems in cars. Hence, a substitution timeline is proposed for the case study in a separate chapter based on automotive assessment for alternatives publicly available. Thus, for further information on substitution timelines see chapter 1.1.

3.3.7 Conclusion on Case study "Use of fluoroelastomers (FKM) as inner layer of fuel hoses for high temperature applications in the automotive sector"

Alternative materials for the innermost layer of fuel hoses and lines in automotive applications are readily available on the market and in use for certain applications. While these materials do show promising characteristics and have been used for certain applications as fuel tubing, they are not able to fulfil all the criteria needed for the use as fuel tubing material in all possible applications. Especially for applications where the fuel transport system is exposed to high temperatures and to fuel types containing various different additives, especially a higher alcohol (ethanol or methanol) content as is present in the new alternative fuels, (H)NBR-, VMQ-, EPDM-, ACM-, AEM- or SBR-based fuel lines cannot fulfil the technical requirements. Aside from a lower maximum tolerable operating temperature these materials can endure, they demonstrate higher fuel permeabilities and higher swelling compared to FKM materials.

Especially considering the stricter limit values introduced with the new Euro 7 norm, achieving the limit values proposed in the norm is not achievable with the existing alternatives in their current state as stated above if used as inner layers.

Even though, NBR and HNBR- based fuel hoses are already commercially in use and provide good technical performance for certain applications, they do not meet the technical requirement for high-temperature fuel hoses applications. Their intrinsic material properties, especially the limited temperature resistance, prohibit their use in the investigated case study. Hence, manufacturers, OEMs and polymer producers would need to invest time and efforts in developing an alternative material that could replace FKM in fuel hoses.

In the meantime, FKM based multilayer hoses remain the only option for many applications, as FKM does not only provide resistance to a wide temperature range but also to a wide range of fuel types and components. The low permeability of FKM results in increased durability, increased safety and reduced emissions into the environment compared to currently available alternatives.

3.4 Substitution timeline at the sector level

The following section describes the theoretical substitution process within the automotive sector. As no detailed information on substitution for the selected case studies was available, the information presented here is based on publicly available Substitution Plans, which have been submitted by automotive companies as part of an Application for Authorisation under REACH. The Substitution Plans used are for various applications and products to allow for generalised description of steps needed to substitute a restricted or banned substance. The time periods provided for each step are thus also typical values.

3.4.1 Factors affecting substitution

Factors affecting substitution of fluoropolymers in high-pressure sealing materials in GDI systems and as inner layer of fuel hoses for high temperature applications comprise the following aspects:

3.4.1.1 Technical considerations

To achieve successful substitution, alternative materials must meet all key functionalities defined by the respective application and justified by sector- and/or region-specific standards and regulations. The most relevant key functionalities for the use of **FKM as high-pressure sealing material in GDI systems** and for the use of **FKM as inner layer of fuel hoses for high temperature applications in the automotive sector** are described in more detail in sections 3.2.2 and 3.3.2. However, please find an overview below:

- Chemical Compatibility / Resistance
- Temperature Resistance / Tolerability
- (Fuel) Permeability
- Pressure-Temperature Rating (only O-Rings)
- Long-term Sealability (only O-Rings)
- Physical Properties (only fuel hoses)

With respect to O-ring sealings in GDI systems, Nitrile Butadiene Rubber (NBR) and Hydrogenated Nitrile Butadiene Rubber (HNBR) were shortlisted as potential alternatives, but still face challenges with chemical compatibility, temperature resistance, and the integrity of sealing over time. Similarly, for the inner layer of fuel hoses in high-temperature automotive applications, NBR and HNBR show some promise as alternatives, but also still suffer from issues such as insufficient fuel permeability, chemical degradation by biofuels, limited temperature resistance compared to FKM, and long-term safety concerns related to material hardening and leakage. For more detailed information, please refer to sections 3.2.2 and 3.3.2.

Due to these technical limitations, it must be therefore assumed that none of the shortlisted alternatives are currently under consideration for actual substitution and thus subject of the subsequent phases of a substitution plan (please refer to section 3.4.2 for a detailed description).

The substitution of the discussed case studies must therefore include an initial R&D phase that aims to identify and test new materials as potential alternatives. Delays in the development of these alternatives can impede the substitution process, as subsequent phases cannot be initiated without a viable option.

Moreover, if technical failures occur during later stages, such as field testing, the process will revert to the first phase of a substitution plan, necessitating a re-evaluation and restart in the R&D for a suitable alternative.

3.4.1.2 Economic considerations

The substitution of fluoropolymers in automotive systems necessitates careful economic considerations across multiple areas.

Importantly, identifying and developing a suitable alternative, as well as implementing it across relevant applications, demands significant investment. Although the raw material for potential alternatives is notably cheaper (i.e. "7-8 times less expensive than a high-performance FKM" (section 3.2.5.1)), these initial costs for R&D must be accounted for.

With respect to operational costs, there is currently no available information associated with the alternative materials. This aspect will need thorough evaluation to ensure a comprehensive understanding of the economic impact of transitioning away from fluoropolymer.

3.4.1.3 Customer acceptance and market situation

Customer acceptance is a bottleneck for successfully implementing an alternative to fluoropolymer. Validation through tests at clients' sites and approvals by Original Equipment Manufacturers (OEM) are needed and should be planned for a validation and approval phase of a substitution plan. Any failure or negative feedback during these tests could result in drawbacks, necessitating a re-evaluation of alternative options.

To ensure successful transition, a thorough market assessment should be conducted. Producers must also consider their contractual obligations with customers and OEM, as they are required to provide support and warranty for several years on products approved at the initial contract stage. These contractual commitments must be considered and carefully managed during the transition phase.

3.4.1.4 Approval procedures and permits

The automotive industry is a strategic sector within the European Union, encompassing numerous applications reliant on fluoropolymer. Components depending on fluoropolymer cover a wide range of applications such as the here presented uses as high-pressure sealing materials (Section 3.2) and as inner layers of fuel hoses (Section 3.3). In general, testing procedures as part of approval procedures (e.g. set by OEM or based on legal frameworks) involve rigorous testing and validation; when fluoropolymer and related products are phased out, and all affected components must be re-validated with suitable alternative materials.

Opportunities for introducing changes are limited to specific periods, aligned with type-approval timelines during the development of new vehicle series, which typically spans at least 5 years and is due to contractual obligations being standard in the automotive industry. This phase includes, among others, preparatory studies, component re-design, and extensive testing (including vehicle, endurance, and field tests). The testing, particularly vehicle and field tests, is notably time-consuming and normally reduced to ready-to-use alternatives.

A key fact for drawing the timeline of a substitution process in the Transport sector is based on the lifecycle of a vehicle which in general ranges over approximately 22 years. This time-period normally comprises a development phase (approx. 5 years), a production phase (≥ 7 years), and a spare part guarantee period of at least 10 years. Final approval (and signing of new contracts) occurs at the end of the development phase before production begins.

Please note, that type approval regulations required for substitution in the automotive industry are available on the webpage "Technical harmonisation in the EU - Internal Market, Industry, Entrepreneurship and SMEs". These regulations are governed by the Whole Vehicle Type-Approval System (WVTA), based on the legal framework set by Regulation (EU) 2018/858 (*REGULATION (EU) 2018/ 858 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL - of 30 May 2018 - on the*

Approval and Market Surveillance of Motor Vehicles and Their Trailers, and of Systems, Components and Separate Technical Units Intended for Such Vehicles, Amending Regulations (EC) No 715/ 2007 and (EC) No 595/ 2009 and Repealing Directive 2007/ 46/ EC, 2018) of 30 May 2018, effective across the EU from 1 September 2020.

Further, efficient supply of service parts for past models must be maintained for at least 10 years beyond the end of serial production to meet warranty obligations. However, commonly, service parts are available for vehicles not further produced for over 20 years which relate to the long lifetime of vehicles. This extends the substitution timeline, as spare parts must be available for a specified period due to contractual agreements.

3.4.2 List of Actions and Substitution Timeline with Milestones (Substitution Plan)

As outlined above, replacing fluoropolymer as high-pressure sealing materials in GDI systems and as inner layers of fuel hoses for high-temperature applications in the Transport sector is a complex and time-consuming process. At present, no feasible alternative exists, and developing an appropriate substitute may still demand considerable time. Thus, and due to a lack of information from stakeholders, the following timeline has been developed based on general data available from the automotive sector and general assumptions concerning the eventual alternative. This timeline indicates that industry will still require time to achieve a complete transition.

If substitution were technically feasible, it would necessitate a series of phases and a detailed timeline. It is important to note that the presented timeline assumes a best-case scenario, and various challenges may arise that could potentially hinder the progress.

To transition to non-fluoropolymer-based alternatives, the following phases can be considered. However, depending on the respective party involved in the transition (fluoropolymer manufacturer, DU, OEMs, end-user etc.) phases must be adjusted and added or removed to develop a more specific timeline. Please find a graphical presentation of these phases in Figure 12.

Phase I: Research & Development (at least 5 years)

Ia) Identification of Most Suitable Alternatives

The initial stage in the substitution process involves extensive research and development to identify the most suitable alternative materials for replacing fluoropolymers. This begins with a comprehensive literature review, as detailed in sections 3.2 and 3.3, to understand the current landscape and potential candidates. Based on current information available, HNBR and NBR are considered the most promising alternatives, as they are already commercially in use for certain automotive applications. However, they do not meet the necessary technical requirements for the investigated case studies. Hence, substitution might only be possible once new materials are developed.

This phase also involves consultation with various stakeholders, including end-users, OEM, and suppliers of raw materials and technical equipment, to extend the level of information and confirm or amend the current status of potential alternatives. Accordingly, results from laboratory-scale testing, if available, will be reviewed to support the selection process.

Beyond the technical point of view, economic aspects for the alternatives under consideration will assist in the identification of suitable alternatives. Although not all information is likely available at this stage, consultations will provide a rough estimate of the expected costs and investments needed for the transition, considering factors such as whether new facilities or locations will be required.

Ib) Market Analysis

A thorough market analysis allows screening of the availability of alternative materials. This involves checking providers for raw materials and technical equipment, as well as evaluating component producers, OEM, and end-users (depending on the respective position in the supply chain) to understand the feasibility of transitioning to new materials and the associated timeframes.

The market analysis will help identify reliable sources for components and equipment required, ensuring that the transition process can proceed smoothly once a suitable alternative is found.

Ic) Research Projects

Based on the information gathered from previous work and extended efforts, the most probable alternatives will be defined and validated. Subsequently, research projects will be initiated to conduct comprehensive tests for key functionalities.

This phase includes initial trials evaluating selected key functionalities on test samples, followed by extended laboratory tests to assess the full set of key functionalities. Internal validation with prototypes is also part of this phase.

Vehicle and field testing plays a critical role in this process. Controlled field tests, such as engine tests, will be conducted in cooperation with selected partners to recreate real engine conditions. These testing phases can vary in duration, such as 50 hours and 300 hours. Longer engine testing requires careful preparation, significant time, and financial resources. Therefore, only alternatives that already have provided promising results in initial tests will proceed to these extended testing. The reproducibility of respective components in manufacturing and usage will be thoroughly checked.

Id) Alternative Selection

Once all trials, laboratory tests, and vehicle tests are completed, the results for all key functionalities - including long-term tests - will be analysed. Alternatives that demonstrate the best technical performance will be compared.

An economic feasibility analysis will be conducted, considering the costs required for transitioning to each alternative. Detailed information on costs will be gathered during this sub-phase through discussions with suppliers. This approach ensures that resources are focused on the most promising candidates, avoiding unnecessary efforts on less viable options.

The final milestone of Phase I involves obtaining the final test results and selecting the most suitable shortlisted alternative(s). This selection will form the foundation for Phase II and subsequent steps in the substitution process. Having the final test results helps to determine that the chosen alternative can meet all required standards and functionalities, paving the way for a successful transition.

Phase II: Implementation Scenario (at least 1 year)

Upon finalizing the selection of alternative materials for substituting fluoropolymers in sealing materials and fuel hoses, this phase focuses on planning and preparation for industrial implementation.

Initially, detailed manufacturing specifications must be drafted, and the first design for industrialization prepared. This stage involves coordinated efforts across multiple departments within a company, which may impact the business operations of affected parties.

Selection of partners for implementation at this stage, may include suppliers of technical equipment and raw materials. Review of the staffing situation helps to determine whether potentially hiring new staff or providing additional training for existing employees is needed for readiness of the transition.

Approvals from management and alignment between departments must be obtained for smooth implementation. Requirements for locations and facilities need to be defined, which might involve rebuilding, extending, or establishing new facilities.

Depending on their position in the supply chain, companies must proactively contact and inform related or affected partners about the upcoming changes, ensuring all stakeholders are adequately prepared for the transition and well informed.

The milestone of this phase is to finalise the implementation scenario and notify all partners. This comprehensive planning and coordination phase is the basis for efficiently managing and effectively executing the transition to the new alternative material(s).

Phase III: Validation and Approval (at least 5 years)

Phase III represents a key step in the overall substitution process. For many years, automotive components have relied on well-established fluoropolymer-based materials, which have been successful in providing sealing materials and fuel hoses with the required properties. These suitable component properties allow automotive systems to perform safely and correctly.

Automotive components typically require specific approvals, as outlined in Section 3.4.1.4. Additionally, OEMs have their own internal validation processes for the acceptance of newly manufactured components.

The first step in this phase is to inform affected companies, such as downstream users and OEM, to initiate the validation and approval procedures. Re-validation of new components requires significant investment of time and money, and these stakeholders must be convinced of the new materials' suitability. This involves presenting the results of alternatives assessment and information gathered during Phase I, as well as detailing the upcoming process. Test samples must be provided for internal validation.

The validation process involves rigorous internal test procedures under extreme conditions to investigate the properties of components made from alternative materials. This phase includes the final assessment of the applicability of alternative components. Importantly, OEMs have varying testing requirements, which means there is no exact timeline for Phase III; however, based on experience and general information available, a rough estimate for the entire phase is at least 5 years.

Feedback from OEMs is needed during the validation process. If a new component fails to meet specifications, re-evaluation and optimization may be triggered, assuming the failures can be addressed. In a worst case, the component made from the alternative material may be rejected.

Validation can commence once alternative components are available, meaning that at least a pilot plant must be operational to produce these components. Importantly, due to a shift from combustion engines to electric engines, a combined validation set for engine-related components, such as sealing materials, can be expected. In the future, OEM are anticipated to focus more on electrification, aiming to carry over as many engine parts as possible to reduce the number of validation tests, thereby minimizing required time and costs.

The reliability of the alternative material is proven if all requirements are met and no risks arise during industrial-scale production, indicating that series maturity of products and components has been achieved. Consequently, the implementation phase (Phase IV) can begin.

The successful completion of this phase leads to the signing of new contracts for components made from the alternative material, allowing the production start.

Phase IV: Alternative Implementation (at least 2.5 years)

The primary aim of Phase IV is the implementation of fluoropolymer-free processes, products and components (depending on the respective position in the supply chain) and the industrialization of these processes. This phase comprises the following important aspects:

- Ordering the equipment required for the new production processes.
- Creating additional space in existing production halls, which may involve dismantling old process equipment, or alternatively, constructing new production halls (in a worst case). This step involves obtaining the necessary permissions from authorities.
- Assembling the new equipment and setting up the process or production line.
- Adjusting process parameters to ensure reliable industrial production using the alternative material.

Formalistically, the earliest start of production and use for fluoropolymer-free components is dependent on the adoption of new contracts for these new components. This adoption (contract signing) takes place at the end of Phase III, even if Phase IV has not been fully completed. It is important to note that for components covered by earlier contractual obligations, fluoropolymer-based components cannot yet be substituted.

During the transitional period, there might be an overlap between old and new contracts, leading to the parallel production and use of both fluoropolymer-based and fluoropolymer-free components. This situation depends on the business decisions of the respective companies involved. Such parallel production and/or use of different components may also necessitate additional equipment and/or space, potentially requiring the establishment of a new facility.

This phase is necessary to prepare the industry for the transition to fluoropolymer-free components, with all necessary infrastructure and process adjustments in place to support the transition.

Phase V: Final Transition to Alternative Process (at least 6 years)

The aim of Phase V is to fully phase out the use of fluoropolymers in the production and use of the discussed use cases and to establish comprehensive processes for manufacturing and using components made from alternative materials.

This phase involves a gradual transition, which may begin as soon as Phase III is completed and new contracts for using components made from alternative materials are signed. Regarding customer use, fluoropolymer-based components will continue to be used until the last production series based on those components expires. The timing of this transition may vary for different automotive parts, depending on the contractual agreements between the respective parties.

However, delays in the transition timeline may occur due to local issues related to technical equipment, permits, or supplier problems. Any issues arising in the newly installed industrialised process or with the components directly must be addressed; this facilitates for a quick resolution and ensures complete transition.

In the automotive sector, planning security for future production series is mandatory. Contracts are signed several years in advance, typically at least 3 years, which serves as the contractual lead time. Please note that this takes place first at the end of Phase III. Following this, there is a period for series production of at least 3 years.

Thus, successful execution of Phase V ensures that the industry can fully transition to fluoropolymer-free components within the established timeline, supported by robust planning and proactive problem-solving.

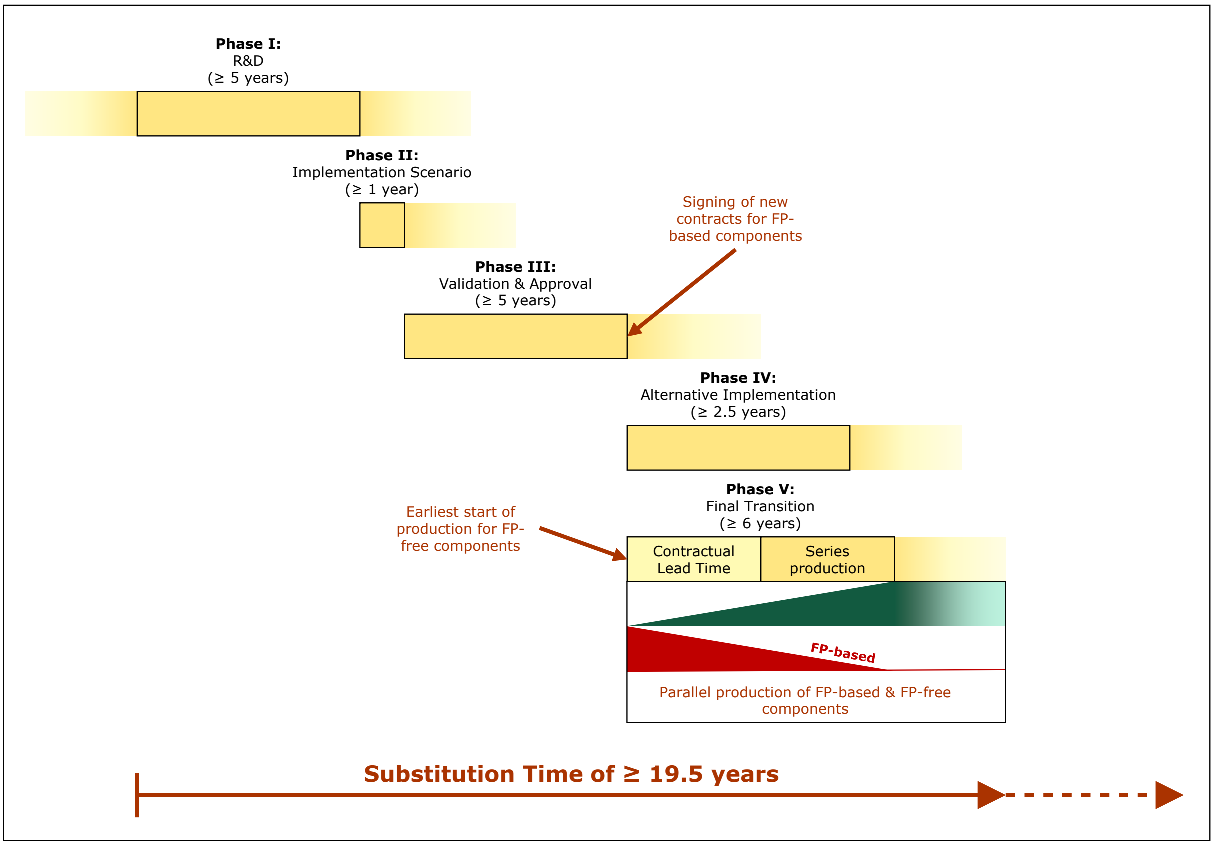


Figure 12: Graphical presentation of Substitution Timeline

4. Electronics & Semiconductor Sector

4.1 Sector overview

The European semiconductor and electronics sector is a foundational pillar of the EU economy, generating a combined market value of roughly EUR 103 billion in 2025. The semiconductor segment contributes more than EUR 50 billion, while the broader electronics market covering consumer, automotive, and industrial applications reaches an estimated EUR 350 to EUR 400 billion. The industry directly employs more than 200,000 people and provides the technological backbone for critical downstream sectors including automotive, telecommunications, medical devices, and defence (Asma Adhimi, 2025; Market Data Forcast, 2025).
Growth is supported by rapid digital transformation, the rollout of 5G networks, the electrification of the vehicle fleet, and the expansion of the industrial Internet of Things (IoT), as well as by the rapid growth of data centres. Together these trends are driving sustained demand for specialized, high-performance electronic components across the European economy (Mordor Intelligence, 2025).

The European semiconductor and electronics market is highly segmented, reflecting diverse industrial structures and evolving technology needs. The region maintains strong positions in automotive, analog, and industrial semiconductors, while trailing global leaders in advanced logic and memory manufacturing. Production and supply capacity are concentrated in Germany, France, and the Netherlands, which account for more than 30 % of Europe’s component sales.

Recent market dynamics show the fastest expansion in memory and analog devices, supported by automotive sector recovery, electrification trends, and accelerating industrial automation. 2025 (Mordor Intelligence, 2025).

Semiconductors

Integrated Circuits (ICs) remain the dominant semiconductor category, accounting for approximately 85.7 % of total European semiconductor revenues in 2024–2025 (Mordor Intelligence, 2025). This segment encompasses microprocessors, microcontrollers, and memory devices used across automotive systems, consumer electronics, industrial automation, and telecommunications (Market Data Forcast, 2025). Memory products represent nearly a quarter of the total market value, with particularly strong momentum in DRAM and NAND (Market Data Forcast, 2025). High-bandwidth memory (HBM) is expanding its share at an accelerated pace, driven by demand from data centres, artificial intelligence workloads, and advanced high-performance computing (Asma Adhimi, 2025). Analog components, which include power management circuits, sensor interfaces, and mixed-signal devices, recorded quarterly growth of 7.1 % (Asma Adhimi, 2025). They are key to automotive and industrial electronics. Microcontrollers are forecast to grow at a compound annual rate of 15.8 % through 2030. This expansion is supported by rising adoption in Internet of Things (IoT) devices, embedded automation platforms, smart appliances, and mobility systems. Active compounds make up 55.8 % of the broader electronic components market in Europe, including application-specific ICs, operational amplifiers, and other signalling devices (Market Data Forcast, 2025).

Electronics

Consumer electronics makes up to 36 % of the overall electronics market, including smartphones, laptops, and smart home devices. This segment is driven by large-volume sales and ongoing household adoption (Market Data Forcast, 2025). Automotive electronics is the largest individual end-use segment for European semiconductors, covering advanced driver-assistance, infotainment, power management, and control systems. Automotive chips represent the biggest market share within semiconductor end-uses (Mordor Intelligence, 2025). Industrial automation and systems is considered a major growth area, powered by factory automation, robotics, and industrial IoT. Germany leads with over 25 % market share across automation segments (Market Data Forcast, 2025).

Fluoropolymer Use in Semiconductors & Electronics

The global market for fluoropolymers used in semiconductor manufacturing is forecast to expand from USD 1.5 billion in 2024 to around USD 3.2 billion by 2034. The projected growth is fuelled by rising demand for next-generation semiconductor solutions, surging output of electronic devices worldwide, and an intensified push toward smaller, more efficient component designs (Reports and Data, 2025). In the electrical and electronics sector, the global market for fluoropolymers in 2024 was worth around USD 2.2 to 2.3 billion (SkyQuest Technology, 2024).

Fluoropolymers deliver exceptional resistance to aggressive etching chemicals, stability under high-temperature fabrication conditions, and ultra-low levels of contamination required for cleanroom semiconductor production. Their superior dielectric properties ensure reliable insulation for high-frequency components, data cables, and microprocessors, supporting continued miniaturization and faster signal transmission. Enhanced flame resistance improves safety in high-density electronic assemblies, data-centre infrastructure, and mission-critical systems. These performance advantages increase equipment uptime, extend component lifetimes, and improve yield stability, generating substantial operational savings for Europe’s semiconductor and electronics manufacturers (AGC Chemicals Americas, 2025; Fluoropolymers Product Group (FPG), 2025b; Juliana Montoya, 2024).

Primary fluoropolymers used in the semiconductor and electronics sector are critical for enabling high-purity, reliable, and high-performance manufacturing and products. The main groups include:

- PTFE (Polytetrafluoroethylene): Used for tubing, piping, seals, and insulation layers in semiconductor fabrication and electronics assembly due to its high chemical resistance, thermal stability, electrical insulation properties, and flexibility at low temperatures (AGC Chemicals Americas, 2025; Chemours, 2025; Fluoropolymers Product Group (FPG), 2025b).
- PVDF (Polyvinylidene fluoride): Used for tubing, piping, seals, and insulation layers in semiconductor fabrication, for example for ultra-pure water systems (see case study described in section 4.2 for further details)
- PFA (Perfluoroalkoxy alkane): Applied in fluid-handling systems such as pipes, valves, pumps, and protective linings. Its melt-processible nature and high purity make it essential for chip manufacturing equipment (AGC Chemicals Americas, 2025; Chemours, 2025; Fluoropolymers Product Group (FPG), 2025b).
- FEP (Fluorinated ethylene propylene): used mostly in wires and cables
- Foamed FEP is also often used in data cables
- ETFE (Ethylene tetrafluoroethylene): Used in films for moulding release, protective coatings, and semiconductor packaging. Its heat resistance, dielectric properties, and non-stick behaviour support defect-free component production.
- FKM/FFKM (Fluoroelastomers): Used for high-performance seals in environments involving aggressive chemicals and elevated temperatures where contamination control is critical (AGC Chemicals Americas, 2025).

- Other Fluoropolymers (e.g., ECTFE, PCTFE, Amorphous Fluoropolymers):
  Used in printed circuit boards to enhance insulation, signal integrity, mechanical durability, and flame resistance (AGC Chemicals Americas, 2025; Chemours, 2025; Fluoropolymers Product Group (FPG), 2025b).

These fluoropolymers enable critical functions such as chemical resistance against harsh etching agents, electrical insulation for high-frequency components, high purity to avoid contamination, thermal resistance to withstand processing conditions, and flame retardancy for safety and reliability in electronic devices and manufacturing environments.

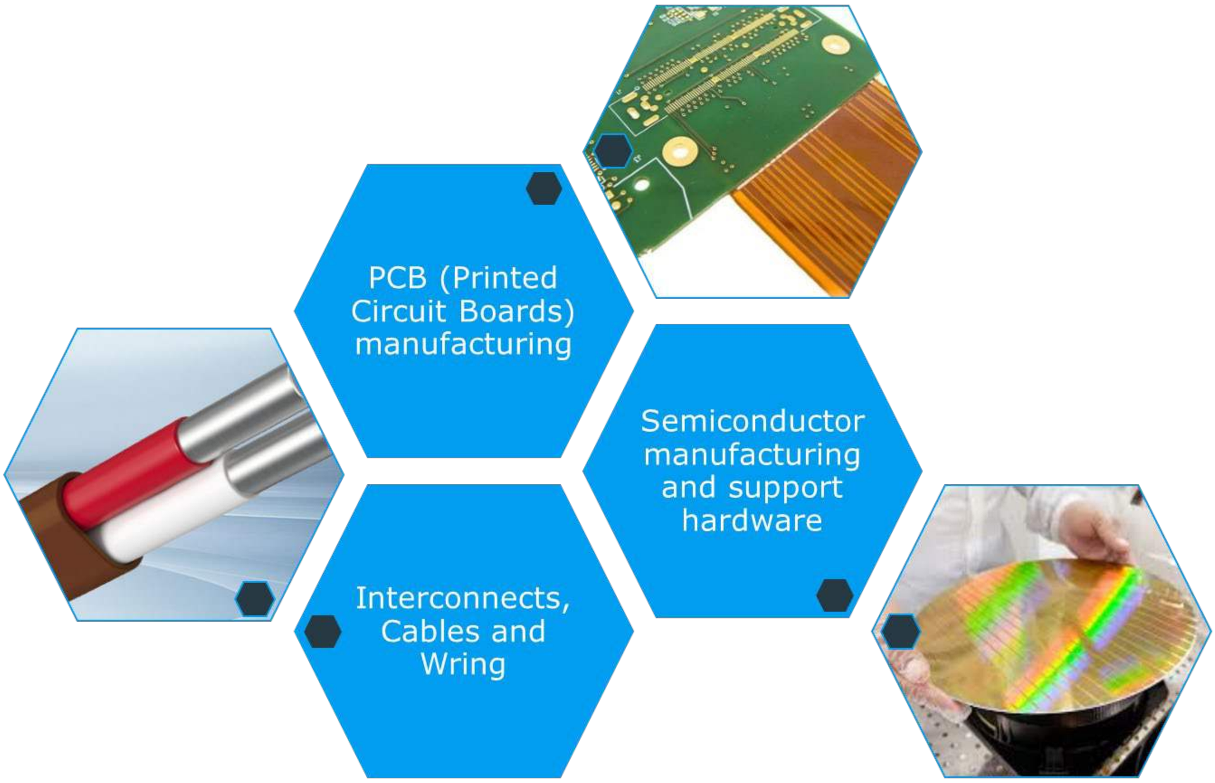


Figure 13: Use of Fluoropolymers in Electronics and Semiconductors.

Semiconductors & Electronics Sector in Annex XV Proposal

Annex XV restriction proposal report includes Electronics and Semiconductors as one of the main sectors of PFAS use. As in transport sector, for Semiconductors and Electronics some specific time-limited derogations were suggested in the restriction proposal, which affect:

- Direct electronics/semiconductor uses: Components and systems in chip manufacturing, printed circuit boards, and high-frequency interconnects where fluoropolymers contribute to sealing, insulation, chemical resistance, and thermal stability (ECHA, 2025a).
- Production machinery and equipment: Complex manufacturing tools, pumps, valves, high-purity fluid handling and process modules used in semiconductor and electronics fabrication that rely on PFAS-based materials for containment, cleanliness and performance (REACH-CLP-Biozid Helpdesk & Bundesanstalt für Arbeitsschutz und Arbeitsmedizin (BAuA), 2025; Steve Ranger, 2025).

The Background Document explicitly recognises that many fluoropolymer applications in the electronics/semiconductor arena are cross-sectoral: fluorinated seals, gaskets, insulation materials and specialty polymers are used not only in electronics but also in transport, energy, medical devices and industrial manufacturing. For the electronics and semiconductor value chain this means:

- Semiconductor modules depend on fluoropolymer-containing materials in boards, connectors, insulation and packaging linking to the broader electronics industry.
- Production equipment and components (seals, hoses, membranes) rely on fluoropolymers assessed under sealing and machinery sectors but are used in downstream electronics fabrication.
- Coatings, films and high-performance plastics used in electronics manufacturing overlap with supply chains in other sectors (e.g., energy, transport, medical) which are also regulated in the PFAS framework (ECHA, 2025a; ESIA, 2023; KIRKLAND & ELLIS, 2025).

As a result, the final design of the PFAS restriction regime and its derogations in adjacent sectors will have direct implications for semiconductor and electronics OEMs and suppliers, especially where safety-critical parts or regulatory compliance (for example in cleanroom manufacturing, high-voltage electronics, ultra-high-speed data transmission) depend on fluoropolymer-based materials.

In the following chapter the selected case study is described:

(1) Case study "Use of Fluoropolymer-based (PVDF) Piping in Ultra-pure Water (UPW) Systems for Semiconductor Manufacturing" (section 4.2)

This exemplary application was chosen as representative, economically significant within the sector, as well as provide adequate data and downstream-user access for alternative assessment. More details on the reasoning behind can be found in the section 2.1.

4.2 Case study "Use of Fluoropolymer-based (PVDF) Piping in Ultra-pure Water (UPW) Systems for Semiconductor Manufacturing"

Fluoropolymers are used in multiple applications throughout semiconductor manufacturing wherever ultra-pure, highly corrosive chemicals, high temperatures, and strict cleanliness requirements come together. A SEMI investigation has identified over 80 use cases for fluoropolymers in semiconductor manufacturing and related equipment (SMRE) and more than 200 for support facilities, encompassing thousands of uniquely tailored applications (SEMI, 2023). Fluoropolymers can be used in various stages of the semiconductor manufacturing process, as exemplified in the following table.

Table 20: Examples for fluoropolymers used in different applications of semiconductor manufacturing (SEMI, 2023)

Application group	**Examples of fluoropolymers used**	**Article**
Chemical delivery	PFA, PTFE, PVDF, ECTFE, FEP	e.g. distribution pipes/tubes, vessels, storage tanks, sensors, distribution pumps, valves
UWP distribution (piping systems)	PVDF, PFA, ETFE, ECTFE, PTFE	e.g. pipes, valves, tubes
Treatment of UPW	PVDF, ECTFE, PFA, PTFE	e.g. filtration/ultrafiltration, pumps, storage, fittings
Plasma etching	PTFE	e.g. transmission devices, sheathed coaxial cables
Chemical-mechanical planarization (CMP)		e.g. coatings on polisher platens, O-rings, gaskets, CMP pads
Electroplating	PFSA membranes reinforced with PTFE	e.g. separating membranes
Assembly, Test and Packaging		e.g. lubricants, insulation, mechanical gears, dielectric in coaxial cables, chemical handling parts

This study specifically investigates fluoropolymer-based (PVDF) piping in Ultra-pure Water (UPW) systems due to their extensive use and significant impact on the semiconductor industry's stringent purity needs. It must be highlighted that the technical requirements are likely more demanding for other uses, such as plasma etching or chemical delivery due to the contact to aggressive media. Nonetheless, this case study was selected for further investigation as it presents alternatives that show promising technical feasibility but at the same time exemplifies the challenges associated to regulatory and technical standards, as well as to customer requirements. However, it is important to acknowledge that substitution of fluoropolymers in semiconductor manufacturing needs to be assessed beyond a single case study and should include the vast number and diverse range of fluoropolymer applications present in semiconductor manufacturing.

4.2.1 Overview of the application, its relevance and description of key components

Ultra-pure water (UPW) piping systems are important infrastructures in semiconductor manufacturing, delivering water with extremely low contamination levels to various critical process steps. These systems are crucial for ensuring high product quality and process yields. The semiconductor industry demands high purity due to the sensitivity of precision instruments. UPW must meet stringent criteria, including an electrical resistivity of at least 18 MΩ cm at 25 °C and extremely low pollutant levels (Lee et al., 2016).

Semiconductor manufacturing frequently requires large quantities of high-purity water, as many fabrication stages require the use of UPW. Specifically, UPW rinses chemicals off wafer surfaces during backgrinding, washes away non-hardened materials during photolithography, and cleans during the etching process and planarization/post planarization. Residual impurities can lead to significant changes in conductivity or accidental breakdowns, ultimately reducing product yield. One stakeholder (I06) stated that according to their expertise the consumption of a semiconductor facility can range between 9 to 18 million litres of UPW per day. According to (Lee et al., 2016), a typical semiconductor fabrication process can even consume between 3 and 60 million litres of UPW daily.

Several applications within semiconductor manufacturing require UPW, examples including (AXEON Water Technologies, 2025; Lee et al., 2016):

- **Wafer Cleaning and Surface Preparation:** UPW is utilized in pre-diffusion cleaning, slurry preparation, in-process and post-chemical mechanical planarization (CMP) rinsing, and other final rinsing steps to remove particles, metallic ions, organic contamination, and abrasive residues from wafer surfaces, ensuring optimal surface planarity and cleanliness for further processing.
- **Wet Etching and Chemical Dilution:** UPW ensures precise dilution of etchants, consistent bath purity, and post-etch rinsing to prevent chemical carryover and thus protect device integrity.
- **Photolithography:** Immersion lithography uses UPW as a medium, while resist development relies on UPW for consistent mixture and cleaning.
- **Final Rinse and Packaging:** At the end of the manufacturing process, wafers are rinsed with UPW to eliminate any remaining contaminants before testing, quality assurance, and packaging.

An example how a UPW piping system can look like is depicted in Figure 14 (for individual components see Table 21).

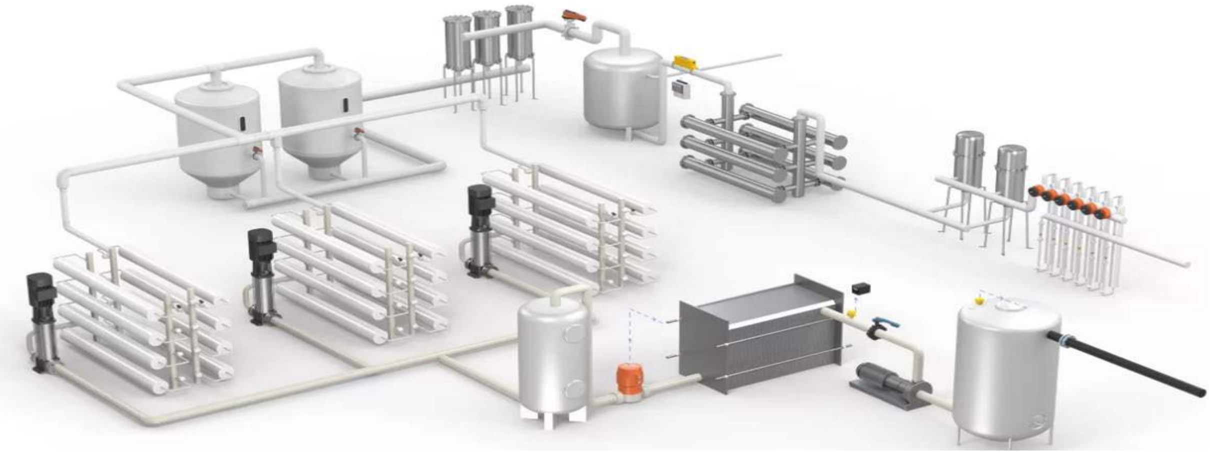
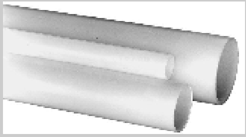


Figure 14: Example for a UPW piping system (picture provided by I09).

Table 21: Components of a typical fluoropolymer UPW piping system

Component	Picture (provided by I09)	Fluoropolymer Material	Description
Piping		PVDF[a]	Extruded pipe for UPW systems.
Fitting		PVDF; PFA	Different types and sizes e.g. elbows, tees, reducers. Connect different sections of pipe, change direction (elbows), allow branching (tees), join different sizes (reducers), or provide means for maintenance (unions, couplings).
Single Valves		PVDF; PFA; ETFE; ECTFE PTFE	Different types and sizes. Control, stop, or regulate the flow within the system. Types include gate. Depending on the field of application / place within system, different materials can be in place.
Other components, customer specific parts		PVDF; PFA; ETFE; ECTFE PTFE; FKM; FFKM	Examples are customer specific valve block systems.

[a] PVDF is a commonly used plastic in piping systems, offering a cost advantage by being 30 % cheaper than PFA and superior mechanical properties (Teesing, 2025). According to a stakeholder (I09), PFA is usually not used in the infrastructure of a UPW system.

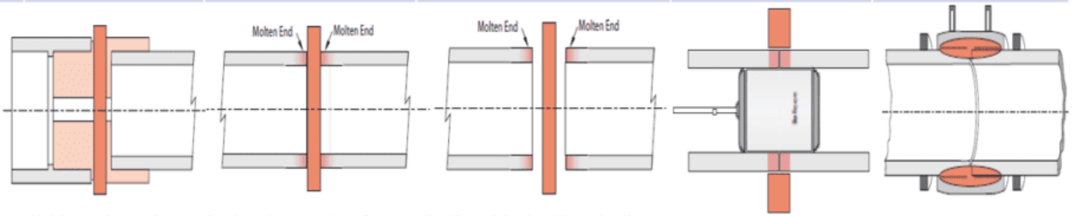
Although UPW is often considered less aggressive, it has the potential to corrode metals such as stainless steel under certain conditions (Cavallini et al., 2022; Dong et al., 2010; Yahia, 2016). Notably, this corrosive effect is more pronounced at elevated temperatures or in environments with high oxygen levels. Fluoropolymers are materials that are frequently used for UPW piping in semiconductor manufacturing. Fluoropolymer piping material is mainly produced by extrusion for pipes and by injection moulding for valves and fittings, as well as CNC-made precision parts from extruded block solutions (I09, I07).

Similar piping systems are used in the pharmaceutical, food and medical industries. Some piping systems are designed for a broader range of applications, including chemical storage and delivery systems, as well as tank linings and distribution tubing (I06).

Installation and system integration

When building up a piping system out of different thermoplastic components, selecting a suitable welding method or mechanical joint is important to maintain the system's performance. According to a manufacturer of piping systems (I07), components are usually welded because threaded fittings are susceptible to instability, pressure drops and leakage. Therefore, welding is preferred for safety and process stability. Figure 15 shows common welding techniques, which are described in more detail below (Asahi/America, 2021).

	Socket Welding	Butt Fusion (contact)	IR Fusion (non-contact)	Beadless Welding	Electrofusion
Bead Size	Large	Medium	Small	None	None[1]
Reliability	Good	Excellent	Excellent	Excellent	Fair
Cost	\$	\$\$	\$\$\$	\$\$\$\$	\$\$\$\$\$



1) Note that electrofusion is crevice free only if welded with a balloon.

Figure 15: Common Weld Methods Comparison (Asahi/America, 2021).

Socket Welding

For less critical applications or small jobs where the cost of Infrared (IR) welding is prohibitive, socket welding offers a simpler solution. This method uses a heater bushing and coupling to fuse the pipe together, resulting in large internal beads and crevices that may support biofilm growth. While socket welding is not suitable for bio/pharmaceutical applications requiring full drainage, it can be used in specific instances, allowing contractors greater flexibility for difficult locations such as final tie-ins or inaccessible joints.

Contact Butt Fusion

Contact butt fusion is suitable for various applications, producing an internal bead larger than IR welding but smaller than socket welding. This process is less sensitive to air circulation and can be performed in diverse fabrication environments. Despite its practicality, contact butt fusion may introduce contamination into the bead, making it less suitable for high-purity systems but viable for chemical, double containment, or industrial applications.

IR Fusion Welding

IR fusion is a highly effective welding method known for its small bead size and repeatability. This technique employs force-control technology that uses a pressure transducer, worm drive, and preprogrammed parameters. The pressure transducer limits the joining force, preventing excess molten material from being expelled from the heat-affected zone, which could result in a cold weld. In addition, the non-contact heating method avoids contaminant introduction into the bead. Given these advantages, IR fusion is often the optimal solution for high-purity applications.

Beadless Welding

Beadless welding is another technique that is preferred for systems requiring complete drainability or sensitivity to biofilm growth, such as water for injection or chromatography systems. This method utilizes a specially designed balloon inside the piping to eliminate any internal bead during the welding process, thus forming one homogenous material without crevices. However, beadless welding is relatively slow and expensive, requiring meticulous planning and specialized training for successful implementation as the internal balloon must be removed post-weld. Automated welding equipment enhances reliability but can be daunting for contractors unaccustomed to the process.

Electrofusion Welding

Electrofusion involves heating the resistance of an electrical coil embedded within the coupling when power is applied. While this method is generally reserved for situations where no other option is viable and is excellent for difficult tie-ins, it is limited in its role in high purity systems. Electrofusion may create small crevices between pipe ends that can harbour biofilm, making it unsuitable for applications requiring low leaching of total organic carbon (TOC). Despite being primarily industrial grade, electrofusion components should be used cautiously in high-purity applications.

The choice of welding techniques significantly impacts the effectiveness and purity of UPW systems in semiconductor manufacturing. Each method has specific advantages and limitations, requiring careful consideration and adherence to industry standards. Stakeholders (I07, I09) have highlighted that infrared welding is usually the preferred welding technique for high-purity UPW piping systems.

Sanitization of piping system

From time-to-time sanitization of the UPW piping system is essential to maintain the highest levels of purity required in semiconductor manufacturing, preventing the growth of bacteria and microorganisms, and ensuring that no contaminants compromise the integrity and performance of the fabrication processes.

In general, different sanitization methods are available (GF, 2025a):

Autoclave Sterilization

Autoclave sterilization involves subjecting piping components to high temperatures and pressure within an autoclave. This method effectively ensures sterilization without altering the physical properties of most piping materials, although it's not advisable for certain valve constructions due to material compatibility issues.

In-Line Steam Sterilization

In-line steam sterilization leverages high-temperature steam, typically up to 134 °C, to sanitize piping systems. This process is highly effective for eliminating microorganisms, provided the piping system is properly supported to withstand the thermal stresses. Insulation properties of the pipe material can impact its efficiency compared to metal counterparts.

Hot Water Sanitization

Hot water sanitization uses water heated up to 140 °C for sanitizing piping systems without requiring chemical additives. This method is commonly used to maintain high-purity systems in pharmaceutical environments, ensuring thorough cleanliness. Proper support is essential for piping that operates at elevated temperatures to maintain structural integrity.

Ozone Sanitization

Ozone sanitization utilizes ozone concentrations, typically up to 0.2 ppm, to sterilize the piping systems. Ozone can be effectively neutralized using UV light sources, eliminating the need for additional cleaning agents or post-process rinsing. The installation of deflection devices ensures proper treatment and prevents unwanted substances from entering the water. One stakeholder stated that ozone sanitization is the most used sanitization method in UPW systems for semiconductor applications (I09).

Chemical Sanitization

Chemical sanitization involves circulating solutions like 10 % hydrogen peroxide through the piping system to achieve sterilization. This method requires the valves to be open and the solution to flow through all system branches at a rate of 5 fluoropolymers. After chemical treatment, thorough flushing with deionized water is necessary until residual chemical levels are reduced to safe limits, verified by test strips.

4.2.2 PVDF properties and Key functionalities within the application

The semiconductor industry demands high-safety and high-precision manufacturing environments. Robust materials and environments that enhance the process without impeding production are essential. For transitioning to advanced semiconductor nodes stringent fluid purity standards are required to mitigate contamination risks and preserve wafer yield performance, thus placing greater demands on fluid-handling systems (I06). Target purity levels must be established for all chemicals used in manufacturing, ensuring no contamination from the chemical storage or transportation systems. The purity of UPW is directly impacted by the materials used for its storage and transport.

For more than 30 years, PVDF-UHP (Ultra High Purity Polyvinylidene Fluoride) pipe systems have been used very successfully in the semiconductor industry due to its exceptional chemical resistance, purity, thermal stability, and resistance to leaching or contamination (IPS Flow Systems, 2025a; SOLVAY, 2018). PVDF does not require additives or fillers that can leach out, offers high chemical and thermal resistance, and minimizes biofilm formation and measurable organic carbon leaching. PVDF pipes also provide exceptionally smooth internal surfaces to prevent particle or bacterial adhesion. One big advantage of PVDF is its outstanding mechanical properties such as a high tensile strength and stiffness, even at high temperatures. Other fluoropolymers that were identified to be used for piping systems are PFA (I07) or ECTFE (AGRU Kunststofftechnik GmbH, 2017). PFA is ~30 % more expensive compared to PVDF, but preferred for applications requiring transparency or high chemical resistance, such as chemical delivery systems, due to its superior chemical resistance compared to PVDF (Teesing, 2025). On the other hand, tensile strength which describes the maximum of stress before failure of PVDF (54 MPa) is typically higher compared to PFA (27 MPa) and ECTFE (48 MPa) (Fluorotherm™, 2025). For this study the focus was set to PVDF (see section 2.1 for more information).

Standards

Industry standards dictate the materials and methods used in UPW systems to meet stringent contamination thresholds, fire safety criteria, and long-term durability requirements.

Two relevant standards are listed below

- **SEMI F57** - Specification for Polymer Materials and Components Used in Ultrapure Water and Liquid Chemical Distribution Systems
- **FM 4910** - Cleanroom Materials Flammability Test Protocol

Additional SEMI standards relevant to UPW systems in semiconductor manufacturing include:[11]

- **SEMI E49**: Guidelines for ultrapure water systems design and operation.
- **SEMI F61**: Specification for fluid system components.
- **SEMI F104**: Guidelines for piping materials.

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[11] Please note that the content of these standards was not checked due to limited access.

- **SEMI S2**: Environmental, health, and safety guidelines for semiconductor manufacturing equipment.

In addition, there is an ISO standard on plastic piping systems available that was mentioned by stakeholders (I09):[10]

- ISO 9080 - Plastics Piping and Ducting Systems

ISO 9080 outlines the determination of long-term hydrostatic strength of thermoplastics materials in pipe form by extrapolation. This standard is used for assessing the reliability and durability of materials used in UPW systems (CEN, 2012).

Requirements for UPW

The standards for ultra-pure water used in the semiconductor sector are set by

- **ASTM D5127** - Standard Guide for Ultra-Pure Water Used in the Electronics and Semiconductor Industries
- **SEMI F63** - Guide for Ultrapure Water Used in Semiconductor Processing

Selected requirements from both standards are presented in Table 22.

Table 22: Requirements for UPW at the point of distribution in the semiconductor industries according to standards ASTM D5127 and SEMI F63

	ASTM D5127[a] **Type E-1.3B (Harshest Type)**	**SEMI F63 (version 0213)[b]**
Linewidth (µm)	0.065–0.032	< 0.065
Silica (µg/L)	< 0.5 (total), < 0.5 (dissolved)	< 0.5 (total), < 0.5 (dissolved)
TOC (µg/L)	1	< 1
On-line dissolved oxygen (µg/L)	10	< 10
On-line dissolved nitrogen (ppm)		8-18
On-line particles >0.05 µm (/L)	500	
Bateria (GFU/L in 100 mL)	N/A	< 1
Ions (ppt)	50 (Ammonium, Chloride, Phosphate)	<50 (Ammonium, Bromide, Chloride, Fluoride, Nitrate, Nitrite, Sulfate), <20 (Phosphate)
Metals (ppt)	1 (Al, Ca, Na), 50 (B)	< 1 (Al, Ca, Cr, Cu, Fe, Li, Mg, K, Na, Ti, Zn), < 10 (Sb, As, Ba, Cd, Pb, Mn, Ni, Zn, V), < 50 (B)
Resistivity at 25 °C (MΩ cm)	18.2	> 18.18

[a]ASTM D5127 standards were extracted from (Lee et al., 2016), [b]SEMI F63 standards were extracted from (SEMI, 2016). Please note that requirements might be outdated as no access to the recent version of the standards was available.

Compliance with these standards is essential for achieving the exacting demands of semiconductor fabrication processes, ultimately influencing the overall product yield and performance.

According to a manufacturer of piping components (I07), material and design specifications are mainly defined by semiconductor customers according to their needs. This includes exact material (e.g. PVDF/PFA) and geometry of piping components to ensure conformity with remaining systems. If no customer requirements are available, the company has developed internal standards. New materials must undergo a minimum of 2 years of validation and certification.

Key product and process functionalities

The following key product and process functionalities were identified for UPW piping systems in semiconductor manufacturing. A detailed description of the key functionalities and (if applicable) test procedures is provided below.

Table 23: Key performance functionalities of fluoropolymer for piping in UPW systems

Key functionality	Requirement(s)	Justification
Low leaching potential / purity	Leaching limits in compliance with SEMI F57 (for more information see Table 24): • TOC ≤ 40,000 µg/m^2 • Limits for 22 metals • Limits 8 ions	Ensuring ultra-pure water (UPW) remains free of impurities is critical in semiconductor manufacturing.
Low Surface Roughness	Ra ≤ 0.25 µm - ≤ 1 µm (depending on component type as outlined in SEMI F57 standard).	Smooth surfaces inhibit bacterial growth, keeping water uncontaminated throughout semiconductor manufacturing.
Temperature resistance	Continuous operating temperature of 20 °C to 100 °C	UPW transport materials must endure the operational temperatures of semiconductor processes.
Fire resistance	Compliance with FM4910 standard.	Cleanrooms in semiconductor facilities face significant fire risks due to high voltages and complex automated processes.
Mechanical strength/pressure resistance	Minimum pressure resistance of 5-7 bars	UPW systems require robust materials that can withstand the pressure of transported water.
Processability	Suitable for processing	Efficient manufacturing of UPW components is influenced by the material’s processability.
Weldability	A suitable welding technique can be applied	Efficient installation of UPW systems by connecting the individual components is influenced by the material’s weldability.
Resistance to Sanitization	Resistance to a suitable sanitization method such as Ozone (up to 0.2 ppm), hot water or steam.	Material must be resistant to sanitization agents as the infrastructure must occasionally be sanitized to eliminate microorganisms.

Low leaching potential / purity

Purity is the most critical aspect for UPW systems in the semiconductor industry, as even slightest impurity can incur costly amounts of damage or downtime to semiconductor fabrication plant. The high purity of UPW ensures operational reliability and higher production yields. According to a manufacturer of piping components (I07), production and packaging of individual components for the piping system is usually done under ISO 8 cleanrooms conditions using high-purity materials to maintain strict contamination control and prevent particle contamination or outgassing of volatile organic compounds (VOCs). It should be noted that UPW can be corrosive to metals such as stainless steel under certain conditions (Cavallini et al., 2022; Dong et al., 2010; Yahia, 2016). PVDF intrinsically offers a high purity level because it can be processed without the need of additives such as fillers, antioxidants or flame retardants.

Depending on the requirements of the facility, several parameters for UPW can be monitored including Total Organic Carbon (TOC), dissolved oxygen (DO), total silica, particulate, bacteria, ions and metals, resistivity (see also Table 22).

The industry standard **SEMI F57** sets forth specifications for polymer materials and components in UPW systems, defining contamination thresholds to maintain purity of UWP. This standard outline required leaching limits of substances such as metallic and ionic contaminants (limits for 22 metals and 8 ions are specified) including an overall contribution level for TOC (Table 24).

Table 24: SEMI F57 requirements for Polymer Materials and Components Used in Ultrapure Water and Liquid Chemical Distribution Systems (version 0120) (SEMI, 2019)

Criteria	**Parameter**
Trace Metallic Extraction Limits [µg/m²]	Al: 5, As: 2, Sb: 2, Ba: 15, B: 30, Cd: 2, Ca: 10, Cr: 1, Cu: 10, Fe: 5, Pb: 1, Li: 2, Mg: 2, Mn: 5, Ni: 1, K: 10, Na: 10, Sr: 0.5, Ti: 2, Sn: 2, V: 2, Zn: 5
Ionic Extraction Limits [µg/m²]	Ammonium: 100, Bromide: 100, Chloride: 100, Fluoride: 20000, Nitrate: 100, Nitrite: 100, Phosphate: 100, Sulfate: 100
Total Organic Carbon (TOC) Extraction Limit	Overall contribution levels ≤ 40,000 µg/m²

Low Surface Roughness

In UPW systems, low surface roughness is critical. Even and smooth surfaces prevent the growth of bacteria and microorganisms, ensuring that water remains uncontaminated throughout the semiconductor manufacturing process. The **SEMI F57** standard specifies surface roughness requirements for different components.:

- Extruded Pipe: (< 250 mm OD) = ≤ 0.25 µm; (≥ 250 mm OD, < 315 mm OD) = ≤ 0.45 µm
- Injection Molded: (< 250 mm OD) = ≤ 0.35 µm; (≥ 250 mm OD, < 315 mm OD) = ≤ 0.50 µm
- Machined: (< 250 mm OD) = ≤ 0.60 µm; (≥ 250 mm OD, < 315 mm OD) = ≤ 1.00 µm

Temperature Resistance

It is important that the substance used within UPW transport can withstand the temperatures in which the applications operate without deformation or softening under the thermal load. Hot ultrapure water has a temperature between 70 °C to 80 °C (GF, 2025a). According to a manufacturer of piping components (I07), continuous operating temperature even > 100 °C are common. PVDF systems can withstand temperature up to 150 °C (ARKEMA, 2022). No additional data was available to verify the required maximum operation temperature. Based on the available information, a required operation temperature of 20 °C to 100 °C is assumed.

Low Flammability / Fire Resistance

The industry faces significant fire risks due to the presence of high voltage electrical equipment, and complex automated processes within cleanrooms. Fire resistance standards such as **FM4910** which define cleanroom materials flammability test protocol are used. In this standard the materials are tested and evaluated using tests based on two criteria (KEIM, 2024):

- Flame propagation (FPI: Fire Propagation Index)
- The FPI (m/s)/(kW/m) is used as a criterion for limiting fire spread beyond the ignition zone. A value of ≤ 6 has been established for materials intended for use in cleanrooms.
- Smoke density/smoke development (SDI: Smoke Density Index)
- The SDI (m/s)(g/g)/(kW/m) is used as a criterion for limiting smoke development in non-propagating fires beyond the ignition zone. Materials intended for cleanrooms require a value of ≤ 0.40.

PVDF is a typical FM4910 certified plastic (KEIM, 2024), whereas many other plastics require fire-resistant additives to meet fire safety standards. These additives may leach out over time, potentially compromising the purity of the system.

Mechanical strength/ pressure resistance

Mechanical strength is critical to ensure that pressurized ultra-pure water does not compromise the piping structure. PVDF can be processed through simple extrusion or molding methods to produce self-standing structures capable of withstanding high pressures (up to 5 to 10 bars) (I09), offering an effective ratio between diameter and wall thickness.

Available PVDF piping on the market are generally rated for up to 16 bar for smaller diameters (d16-d225 mm) and 10 bar for larger diameters (d90-d450 mm) when measured at 20 °C (GF, 2025a).

According to a manufacturer of piping components (I07), valves and actuators are exposed to 5 to 7 bars pressure and mechanical testing is performed according to internal testing protocols to check pressure resistance.

Based on all the available information, a minimum required pressure resistance of 5 to 7 bars is assumed.

Processability

A material's melting temperature, viscosity, and rheology impact its processability. PVDF's properties allow it to be easily extruded, injection-moulded, or compression-moulded into the desired end product. The final component must pass leak and burst tests. A nitrogen leak test is an effective method for identifying leaks in various systems, utilizing nitrogen gas due to its inert properties and safety advantages (NiGen, 2021).

Weldability

A suitable connection method is required to ensure piping units can be precisely assembled according to the facility layout without weakening the piping or creating gaps between units. According to stakeholders (I09), Infrared welding (IR welding) is usually preferred for connecting piping systems, as this contactless technique minimizes contamination, especially metal contamination, and avoids degradation of the material, thereby preventing pollution with organics or fluorides. PVDF's well-established processing capabilities through extrusion, injection moulding, and compression moulding make it extremely versatile for welding processes (I09). PVDF's non-hygroscopic nature further simplifies the IR-welding process.

Resistance to Sanitization

Despite predominantly circulating ultra-pure water in these systems, the infrastructure must occasionally be sanitized to eliminate microorganisms. For PVDF, a wide range of sanitization methods is suitable such as ozone, hot water or steam (GF, 2025a). According to a stakeholder (I09), this is usually done by ozonization. PVDF demonstrates excellent chemical resistance to ozonated water up to 3-6 parts per million (ppm) (I07), whereas many other plastic materials would be completely corroded under such conditions. It was demonstrated that PVDF pipes and fittings can withstand 6 months of exposure to water containing 3 ppm of ozone (Biressi & Neubauer, 2012). This is a much higher concentration than the few parts per billion (ppb = 10^{-3} ppm) normally adopted for sterilising ultrapure water distribution lines. Furthermore, PVDF is inherently resistant to oxidation and UV light which can be used to effectively neutralized ozone. In contrast, many other thermoplastic materials require additives to resist degradation, which can eventually compromise their purity.

Other criteria to consider that are not directly related to key functionality:

Durability / Corrosion Resistance

Durability has a direct impact on operational reliability, cost efficiency, environmental sustainability, process consistency, and resilience against environmental and chemical factors. PVDF exhibits intrinsic resistance to environmental aging and oxidation (I09). By choosing durable materials like PVDF, manufacturers can ensure long-term performance often exceeding 25 years (I09), reduced maintenance costs, and uninterrupted high-quality production, all of which are crucial for maintaining competitive edge and operational excellence in the semiconductor industry.

4.2.3 General overview of alternatives

According to a technical data sheet of a fluoropolymer manufacturer (SOLVAY, 2018), historically, other piping materials such as stainless steel, polyvinyl chloride (PVC) and polypropylene (PP) have been used in UPW piping systems, but these can compromise purity. Over time, chemical attack and corrosion can result in rouging (iron), stress cracking, or biofilm adhesion. This does not happen with PVDF piping systems.

In the current industrial landscape, various fluoropolymer-free materials are being explored as alternatives to fluoropolymers across several sectors, including automotive, aerospace, electronics, and more. Materials such as polyether-ether-ketone (PEEK), polyphenylene sulphide (PPS), high-performance polyamides, and silicones are gaining traction for specific applications. However, stakeholders stated that within the electronics and semiconductor sectors, these alternatives do not necessary possess the comprehensive combination of properties offered by fluoropolymers.

Main Technical Challenges in Replacing Fluoropolymers

The key technical challenges in replacing fluoropolymers for UPW piping systems include

a. meeting ultra-high purity requirements,
b. maintaining thermal stability for high-temperature applications,
c. maintaining mechanical integrity at pressure > 5 bar,
d. maintaining chemical resistance,
e. achieving low surface roughness,
f. ensuring fire resistance
g. ensuring cleanroom compatibility and obtaining regulatory and customer qualification.

According to a manufacturer of piping components (I07), fluoropolymers are favoured because of their comprehensive performance envelope in harsh, high-purity, and regulated environments. Substitution efforts must carefully consider trade-offs between performance and process safety, reliability of high quality UPW, certification challenges, and total cost of ownership (including reduced component life or increased maintenance). It was assumed by the stakeholder that the substitution process in these sectors can extend over a significant timeframe, with industry estimates suggesting it might take as long as 10 to 15 years. This lengthy period is due to the rigorous requirements for chemical resistance, thermal stability, purity, and overall performance that fluoropolymers uniquely fulfil (see also chapter 4.2.7 for more details).

One manufacturer of UPW piping systems (I07) stated that they are actively exploring the use of PEEK, PPS, and silicone-based materials, primarily for partial replacements rather than full system substitutions. It was stated that while these materials show promise in certain areas, they fail to address the complex combinations of high-purity, high-temperature, and aggressive-media resistance required in semiconductor manufacturing. Additionally, cleanroom and purity standards are becoming increasingly customer-specific, further limiting the flexibility for material substitution without substantial requalification efforts.

Discussion of potential alternatives identified

The following section offers an overview of the general alternatives (longlist) identified throughout the project. Their advantages and limitations, as highlighted by stakeholders or uncovered during the literature review, are briefly discussed below.

The potential alternatives PP, PVC, and PEEK were mentioned more frequently by stakeholders and subsequently shortlisted for a more detailed assessment in the following chapters. Due to limited data availability on each potential alternative, the selection of the shortlisted alternatives was based not only on their suitability but also on the extent of available data.

Table 25: Overview of potential alternatives for fluoropolymer-based piping in UPW systems

Alternative	Categorized
Polypropylene (PP)	Shortlisted, chapter 4.2.4
Polyvinyl chloride (PVC)	Shortlisted, chapter 4.2.5
Polyether-Ether-Ketone (PEEK)	Shortlisted, chapter 4.2.6
Polyethylene (PE)	Longlisted
Metal Piping (e.g., Tantalum, Hastelloy)	Longlisted
Elastomers (e.g., EPDM, NBR & Silicone)	Longlisted
Glass	Longlisted
Silicate-Based Materials	Longlisted

Polyethylene (PE)

Temperature tolerance is one critical aspect where PE falls short. According to a stakeholder, PE degrades and loses its mechanical integrity above 60 °C (I08), making it unsuitable for UPW systems that require higher operation temperatures.

Metal Piping (e.g., Tantalum, Hastelloy)

Metal piping, especially specific alloys like tantalum and Hastelloy, offers excellent chemical resistance and can handle also harsh chemicals used in semiconductor manufacturing. One stakeholder (I08) has indicated that while these metals could potentially replace plastics due to their durability, full system compatibility with fittings, valves, and welding is required. A significant limitation is the presence of metal ions, which compromise the integrity of ultrapure water circuits (I08). Although metal piping has its advantages for several applications, the compatibility and contamination issues, along with high costs, make it less suitable for widespread use in semiconductor UPW systems.

Elastomers (e.g., EPDM, NBR & Silicone)

Elastomers like EPDM, NBR, and silicone are known for their flexibility and cost-effectiveness. Due to their mechanical properties, they are generally not suitable as piping material. However, they can be potentially used for certain components of the piping system, such as sealing parts. One stakeholder (I08) has noted that they are unsuitable for use in oxidizing media often found in semiconductor manufacturing processes. Significant research and development investment is required to develop elastomer alternatives that match the chemical resistance and mechanical integrity provided by fluoropolymers (I07, I08). One stakeholder indicated that elastomers such as EPDM are most likely already in use in parts of the system wherever suitable, as the material is well known in the semiconductor industry (I09).

Piping Made from Glass

Glass piping is mainly used in laboratory environments where high purity maintenance is critical. One stakeholder (I08) has noted that while glass can maintain very high levels of purity, it poses significant safety hazards in manufacturing environments due to the risk of breakage. Furthermore, glass is incompatible with certain chemicals like hydrofluoric acid used in semiconductor manufacturing processes and faces complex installation challenges, including jointing and structural weight constraints (I08).

Silicate-Based Materials

According to a stakeholder (I07), silicate-based materials are currently under early-stage research and development. Ongoing tests for partial subcomponents are promising, but there is insufficient significant data to confirm their suitability and effectiveness for UPW systems in semiconductor manufacturing. Stakeholders are closely monitoring this research, but adoption of these materials is not yet feasible.

4.2.4 Assessment of Polypropylene (PP) as an alternative to PVDF in UPW systems for SC Manufacturing

4.2.4.1 Description

Specialized and high-purity grades of polypropylene, for example marketed as PP-Pure, Polypure (PP-n) or PROGEF, are accepted piping materials for UPW systems in semiconductor manufacturing, especially when balanced against cost and chemical resistance needs. The cost-effectiveness is listed as one advantage compared to other materials (AGRU Kunststofftechnik GmbH, 2017). According to stakeholders, PP is costing approximately 3 EUR/kg (I07). PP systems can be considered as possible drop-in solutions for certain applications, though PVDF is usually preferred for the highest-purity or most sensitive applications (AGRU Kunststofftechnik GmbH, 2017).

Polypure

Polypure is manufactured from a natural random copolymer polypropylene (PP-R) offering superior mechanical properties compared to homopolymer polypropylene (PP-H). It offers good chemical resistance and excellent weldability. It is most suitable for use in less critical UPW systems up to 50 °C, where significant chemical resistance is required (IPS Flow Systems, 2025b).

PP-Pure

High purity polypropylene (PP-Pure) is manufactured from grey random copolymer polypropylene (PP-R) offering superior mechanical properties compared to homopolymer polypropylene (PP-H) similar to Polypure (IPS Flow Systems, 2025b). The system is advertised to be suitable for applications in the chemical and semiconductor industries for high-purity media of lower quality. Ideal applications for PP-Pure include UPW reclaim systems, industrial applications with high operating temperatures and high media purtiy and UPW distribution for less critical applications than PVDF (AGRU Kunststofftechnik GmbH, 2017; IPS Flow Systems, 2025b).

PROGEF

PROGEF Natural Polypropylene is another polypropylene random co-polymeride (PP-R) which is offered by GF and recommended for less demanding purity requirements and all other industrial applications, especially those involving aggressive media, high impact and temperature stress (GF, 2025a).

4.2.4.2 Technical performance

The following table and section summarise the performance of PP according to the key technical functionalities that were defined for UPW systems in previous chapters.

Low leaching potential / purity

Stakeholders (I07, I08) indicated that the material's purity does not meet customer requirements, but no testing data was provided to support this claim. Piping solutions of PP are advertised as suitable for less demanding purity requirements (GF, 2025a). According to a supplier (AGRU Kunststofftechnik GmbH, 2017), the material exhibits very low leach out behaviour at media temperatures below 50 °C, though specific details or quantitative data were not disclosed. Therefore, no conclusion can be made on this criterion.

Low Surface Roughness

For the PROGEF system an inner surface Ra of 1.0 µm (for components d20-d110) and 1.5 µm (for components d125-d315) is reported. These values do not meet the required upper limits of 0.45 µm (extruded pipe) and ≤ 0.50 (injection moulded parts) as outlined in the SEMI F57 standard.

Fire resistance

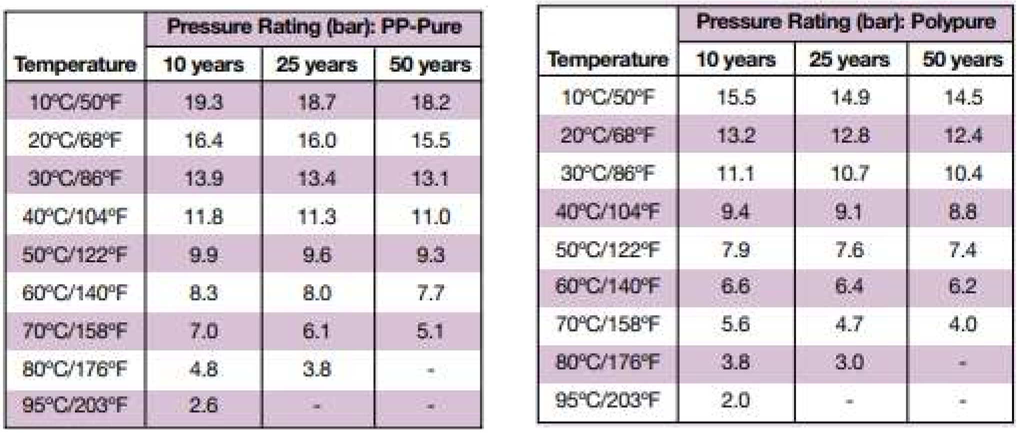
Polypropylene is a flammable plastic (GF, 2025a). To meet the FM4910 fire resistance criteria, PP requires the addition of flame-retardant additives. Copolymer PP can contain up to 30 % filler to achieve compliance with FM4910, which can impact purity and lead to leaching issues (Port Plastics, 2025). One FM4910-compliant type of Polypropylene is the fibreglass-reinforced polypropylene FRP-3 (Plastic Design Industries, 2024) (no further data could be identified to evaluate suitability for UPW piping, especially leaching data).

Table 26: Key functionalities of UPW systems as defined in chapter 4.2.2 and performance of PP

Key functionality	Requirement(s)	Performance of Alternative
Low leaching potential / purity	Leaching limits in compliance with SEMI F57 (for more information see Table 24): • TOC ≤ 40,000 µg/m^2 • Limits for 22 metals • Limits 8 ions	Stakeholders stated that purity is not sufficient to meet customer requirements (I07, I08) (no testing data was shared). Suitable for less demanding purity requirements (GF, 2025a). According to supplier, **very low leach out behaviour at media temperature < 50 °C** (not specified) (AGRU Kunststofftechnik GmbH, 2017).
Low Surface Roughness	Ra ≤ 0.25 µm - ≤ 1 µm (depending on component type as outlined in SEMI F57 standard).	Ra = 1.0 µm (for components d20-d110), 1.5 µm (for components d125-d315) (GF, 2024)
Temperature resistance	Continuous operating temperature of 20 °C to 100 °C	PP-Pure: 0 °C to 95 °C Polypure: 0 °C to 50 °C (for more details see respective chapter below)
Fire resistance	Compliance with FM4910 standard.	Compliance can be achieved with flame retardant additives. However, these compromise purity.
Mechanical strength/pressure resistance	Minimum pressure resistance of 5-7 bars	2-19.3 bar (depending on operation temperature) (for more details see respective chapter below)
Processability	Suitable for processing	No data available, assumed that processability is sufficient as PP piping systems are on the market.
Weldability	A suitable welding technique can be applied	Very good weldability (for more details see respective chapter below)
Resistance to Sanitization	Resistance to a suitable sanitization method such as Ozone (up to 0.2 ppm), hot water or steam.	Resistant to < 0.5 ppm ozone for < 3 h; hot water sanitization with a maximum temperature of 77 °C; not suitable to steam sanitization (GF, 2025a)

Temperature resistance vs. pressure resistance

The pressure resistance of the system is dependent on the operating temperature. A stakeholder (I07) has noted that the PP systems fail at temperatures above 100 °C. According to a supplier (IPS Flow Systems, 2025b), PP-Pure can be used at operating temperatures up to 95 °C (Figure 16). At this temperature, a maximum pressure of 2.6 bar is possible with an operational lifespan of 10 years. At lower operating temperatures, higher pressure ratings and longer operational lifetimes are achievable. Generally, Polypure can also operate at temperatures up to 95 °C. However, at such high temperatures, discoloration of the material may occur. This discoloration is reported to have no effect on the mechanical, thermal, or electrical properties. Nevertheless, the supplier recommend a maximum operating temperature of 50 °C (IPS Flow Systems, 2025b).



Temperature	Pressure Rating (bar): PP-Pure 10 years	25 years	50 years
10°C/50°F	19.3	18.7	18.2
20°C/68°F	16.4	16.0	15.5
30°C/86°F	13.9	13.4	13.1
40°C/104°F	11.8	11.3	11.0
50°C/122°F	9.9	9.6	9.3
60°C/140°F	8.3	8.0	7.7
70°C/158°F	7.0	6.1	5.1
80°C/176°F	4.8	3.8	-
95°C/203°F	2.6	-	-

Temperature	Pressure Rating (bar): Polypure 10 years	25 years	50 years
10°C/50°F	15.5	14.9	14.5
20°C/68°F	13.2	12.8	12.4
30°C/86°F	11.1	10.7	10.4
40°C/104°F	9.4	9.1	8.8
50°C/122°F	7.9	7.6	7.4
60°C/140°F	6.6	6.4	6.2
70°C/158°F	5.6	4.7	4.0
80°C/176°F	3.8	3.0	-
95°C/203°F	2.0	-	-

Figure 16: Pressure rating of PP-Pure (left) and Polypure (right) depending on operation temperature and years of operation (IPS Flow Systems, 2025b).

The trend is in line with pressure-temperature diagrams from another supplier. However, maximum operation pressure based on a 25-year service life in general is a little bit lower with values of 1.5-2 bar at 80 °C and 3-4 bar at 60 °C (GF, 2025a).

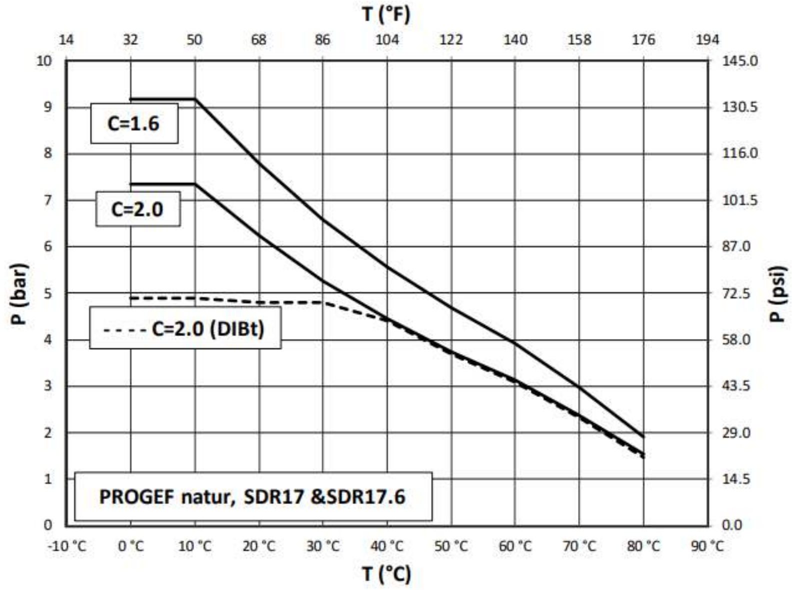


Figure 17: Pressure-temperature diagram of working temperature and pressures for different types of PROGEF Natural (PP-H) based on a 25-year service life (GF, 2025a).

It is unclear whether the temperature and pressure resistance of PP piping are sufficient for all UPW systems, as the required operating conditions can vary significantly between individual systems. For systems that demand pressures up to 10 bar and operating temperatures exceeding 100 °C, the PP piping system will not be suitable and may fail under such conditions.

Processability

No data is available, but it is assumed that processability is sufficient since PP piping systems are already available on the market.

Weldability

According to a supplier, both Polypure and PP-Pure systems can be assembled using infrared non-contact butt fusion (IR) or conventional butt fusion methods (IPS Flow Systems, 2025b). Both techniques offer superior mechanical properties that surpass the strength of socket fusion. However, IR welding is the preferred method, as it produces smaller weld beads, contributing to cleaner system operations. Additionally, IR fusion provides higher repeatability in the welding process and ensures complete traceability for each welded joint. Five different fusion methods including conventional socket fusion, electrofusion, conventional contact butt fusion, IR Plus® butt fusion and BCF® (Bead and Crevice Free) fusion are available for polypropylene piping systems from another supplier (GF, 2025a).

Overall, the weldability of Polypure and PP-Pure systems is regarded as very good and sufficient for their application in UPW systems.

Resistance to Sanitization

Due to the high temperatures, PP cannot be sanitized with steam. For hot water sanitization, a maximum injection temperature would be 170 °F (77 °C) and recommended 3-4 hour cycle with (GF, 2025a). Best practice installations in the industry are showing that PP can be successfully sanitized by using ozone in concentrations of < 0.5 ppm and sanitization times of less than 3 hours (including flushing) at ambient temperature (GF, 2025a). However, PP can be damaged by UV light which can used to effectively neutralize ozone after the cleaning process. PP can also be sterilized at system startup using a 10 % concentration hydrogen peroxide solution circulated for 12 hours, or 1 % concentration Minncare (by Minntech) solution for 1-2 hours (GF, 2025a). According to stakeholders (I07, I08, and I09), the material in general exhibits significant limitations in terms of chemical resistance when exposed to concentrated oxidizing agents such as sulfuric acid, nitric acid, and chlorine dioxide. However, relevance to UPW systems is unclear. Overall, there is unclear evidence whether there is limited resistance to suitable sanitization conditions that would restrict its use as a UPW piping material.

4.2.4.3 Hazard Assessment

Polypropylene as a finished polymer is generally regarded as a low-toxicity, relatively safe plastic under normal use, but it can present hazards as dust, at high temperatures, and through environmental microplastic pollution. Solid PP articles used for food contact and consumer products are considered among the safer plastics; migration of additives and oligomers under intended conditions is usually low and within regulatory limits.

Its main monomer, propylene (CAS 115-07-1), is a flammable gas with higher hazard potential than the polymer itself.

4.2.4.4 Assessment of suitability

Stakeholders have indicated that the purity levels are insufficient to meet the stringent requirements for demanding applications in semiconductor manufacturing that require high purity. This might also be attributed to the fact that PP needs flame-retardant additives to meet flammability criteria relevant to clean-room environments. Consequently, PP systems are regarded only suitable for less demanding applications, consistent with the suppliers' marketing claims. However, this assumption could not be verified due to the lack of testing data on leaching behaviour.

For systems requiring pressures up to 10 bar and operating temperatures exceeding 100 °C, PP piping systems are not suitable and may fail under these conditions.

Regarding economic aspects, PP systems generally have lower material costs compared to PVDF. However, despite the lower initial cost, stakeholders have noted that the lack of long-term reliability and mechanical performance leads to increased maintenance costs and higher levels of waste. Therefore, despite lower upfront expenses, the overall cost-effectiveness of PP systems may be compromised.

4.2.5 Assessment of Polyvinyl chloride (PVC) as an alternative to PVDF in UPW systems for SC Manufacturing

4.3.5.1. Description

There are different modifications of PVC available, including unplasticized PVC (PVC-U) and chlorinated PVC (PVC-C). Unplasticized PVC (PVC-U) is hard and brittle, commonly used for various standard applications where its rigidity and structural integrity are beneficial. On the other hand, chlorinated PVC (PVC-C) offers enhanced chemical resistance and temperature tolerance compared to standard PVC, making it more suitable for demanding applications.

One stakeholder (I08) has noted that PVC is partially suited for applications involving moderate temperatures and some chemical exposure. However, its limitations include susceptibility to oxidation, embrittlement, and issues with jointing when solvent cements are used, which accelerate corrosion.

A supplier was identified that is offering low-extractable PVC piping components for ultra-pure water systems (brand name Spears®) (Spears Manufacturing Company, 2025). The piping systems are advertised to provide a cost-effective alternative to other piping materials typically used for ultra-pure water applications in semiconductor, electronics, biotechnology and other industries.

4.2.5.1 Technical performance

The following table and section summarise the performance of PVC according to the key technical functionalities that were defined for UPW systems in previous chapters.

Low leaching potential / purity

While one stakeholder (I08) has indicated that PVC does not meet customer requirements for purity (without providing testing data) leaching tests from two other sources have been identified: a recent scientific study and information from the manufacturer of an alternative (Spears Manufacturing Company, 2025). According to the scientific study, the PVC system failed to meet SEMI F57 requirements for TOC levels under dynamic conditions, which was attributed to the bonding agents used in assembling the piping system. Conversely, SPEARS® reported that their specially formulated one-step cement significantly reduces leaching compared to other PVC systems. Data from SPEARS® suggested that, under static conditions, the levels of extractables were comparable to high-purity PVDF, and low leaching was observed under dynamic conditions as well. However, due to differences in reporting units, it is not possible to fully compare these levels to the SEMI F57 requirements.

Table 27: Key functionalities of UPW systems as defined in chapter 4.2.2 and performance of PVC

Key functionality	Requirement(s)	Performance of Alternative
Low leaching potential / purity	Leaching limits in compliance with SEMI F57 (for more information see Table 24): • TOC ≤ 40,000 µg/m^2 • Limits for 22 metals • Limits 8 ions	Stakeholder stated that PVC fails customer requirements on purity (no testing data was shared. Leaching tests by (Park et al., 2025): • TOC < 40,000 µg/m² at static conditions • TOC > 75,000 µg/m² at dynamic conditions SPEARS® piping system shows low extractables at both static and dynamic conditions (Spears Manufacturing Company, 2025).
Low Surface Roughness	Ra ≤ 0.25 µm - ≤ 1 µm (depending on component type as outlined in SEMI F57 standard).	Ra ≤ 0.25 µm (Spears Manufacturing Company, 2025)
Temperature resistance	Continuous operating temperature of 20 °C to 100 °C	Maximum operation temperature of 60 °C (140 °F) (Spears Manufacturing Company, 2025)
Fire resistance	Compliance with FM4910 standard.	Compliance can be achieved with flame retardant additives. However, these compromise purity.
Mechanical strength/pressure resistance	Minimum pressure resistance of 5 to 7 bars	No data available.
Processability	Suitable for processing	Correct processing techniques ensure proper dispersion and fusion of the compound, resulting in a homogenous melt with uniform properties (Spears Manufacturing Company, 2025)
Weldability	A suitable welding technique can be applied	One-step solvent-cementing system (Spears Manufacturing Company, 2025). According to the supplier, this system contains fewer contaminants than conventional PVC solvent cements and cures quickly.
Resistance to Sanitization	Resistance to a suitable sanitization method such as Ozone (up to 0.2 ppm), hot water or steam.	No data available.

Scientific study (Park et al., 2025)

In the scientific study investigating the pipe leaching of CPVC compared to PVDF in UPW systems, leaching tests at static (batch) and dynamic (loop-pilot) conditions were conducted (Park et al., 2025). For each material two pipes were investigated, CPVC-1 and CPVC-2 were sourced from different manufacturers with varying surface finishing methods, while PVDF-1 and PVDF-2 represented two commercial-grade products with differences in production batches and processing history. Batch leaching tests were conducted by filling and sealing pipe samples with UPW. To further investigate the impact of pipe joining methods on leaching behaviour under actual UPW operational conditions, a pilot-scale loop leaching test was performed. CPVC pipes were connected using a bonding method with a primer, whereas PVDF pipes employed the fusion welding technique, mirroring real-world installation practices. Overall, in this study the leaching limit of 40 mg/m² for TOC, as set out in SEMI F57, was not met, as CPVC pipes released more than 75 mg/m² of organic contaminants — over 18 times the amount released by PVDF pipes. The results of the study underscore the necessity of assessing not just the base materials of piping systems, but also the possible contributions of bonding agents and other auxiliary materials to contamination levels. In contrast to PVDF, CPVC pipe joints use adhesives or solvents, which can contribute to additional organic matter leaching (Park et al., 2025).

More detailed testing results are discussed in the following:

Leaching of organic matter

The scientific study measured dissolved organic carbons (DOC) concentrations leached from CPVC and PVDF pipes over 7 days at 25 °C and 50 °C in batch leaching tests (Figure 18). At batch testing conditions, both pipe types met the SEMI F57 standard, not exceeding 40 mg/m² TOC leaching. Overall, at 50 °C, leaching levels were nearly double those at 25 °C for all pipes. PVDF pipes completed leaching within one day at both temperatures, whereas CPVC pipes continued leaching for all 7 days, indicating longer duration of organic matter release from CPVC pipes. According to the authors, this shows that PVDF pipes offer more effective and manageable control of organic leaching in UPW systems, particularly under elevated temperature conditions (Park et al., 2025).

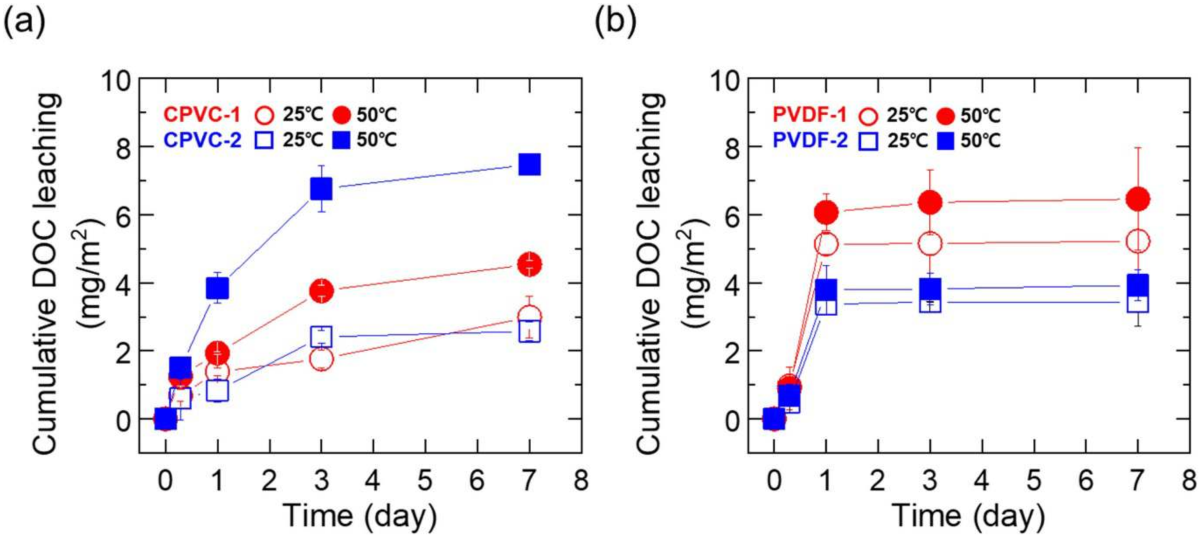


Figure 18: The cumulative DOC concentration for 7 days at 25 °C (empty shape) and 50 °C (filled shape) for CPVC (a) and PVDF (b) pipes in batch leaching tests (Park et al., 2025).

During the loop leaching test, cumulative DOC leaching from CPVC was 75 mg/m², which is 18 times higher than from PVDF (4 mg/m²) (Figure 19). PVDF stopped leaching organic matter after one day, whereas CPVC continued for 14 days. PVDF's leaching levels matched batch experiments, but CPVC's leaching significantly surpassed the SEMI F57 standard of 40 mg/m² for surface TOC extraction. It was suggested by the authors that this discrepancy is likely attributable to the bonding materials used in CPVC pipe joints, which involve adhesives and primers (Park et al., 2025).

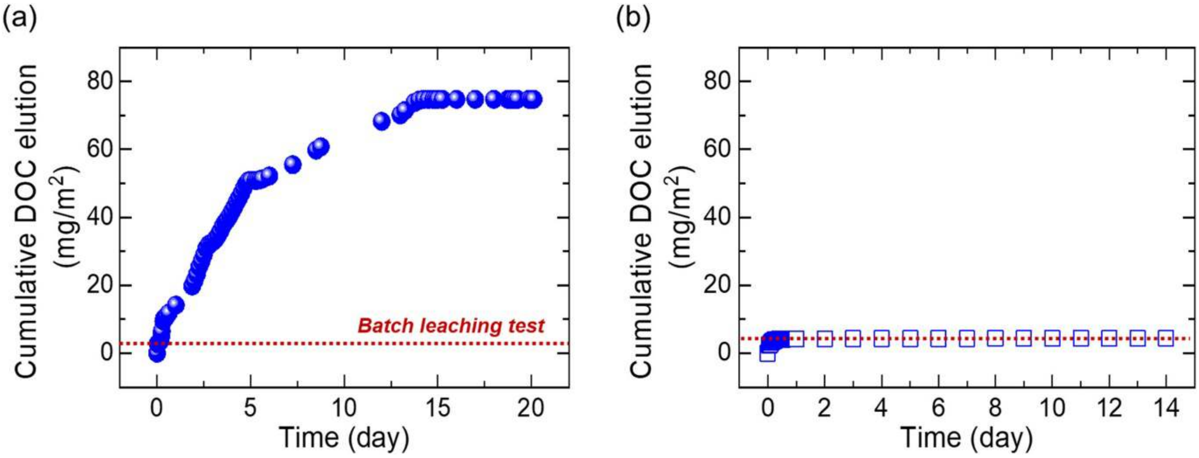


Figure 19: Cumulative DOC leaching from CPVC-2 (a) and PVDF-2 (b) on the loop leaching test (Park et al., 2025).

Leaching of inorganic matter

Both CPVC and PVDF pipes leached various metals, including Na, Si, K, Ca, Mg, and Cu at batch (Figure 20) and loop testing (Figure 21) conditions. The data suggests that rigorous cleaning protocols are necessary for both CPVC and PVDF pipes in UPW systems, including at least three days of flushing with UPW to reduce inorganic leaching and meet purity standards. According to the authors, results from both static and dynamic conditions however indicate that PVDF showed quicker stabilization, demonstrating better material stability and consistency in UPW quality, especially during flow changes and thermal cycling in semiconductor manufacturing.

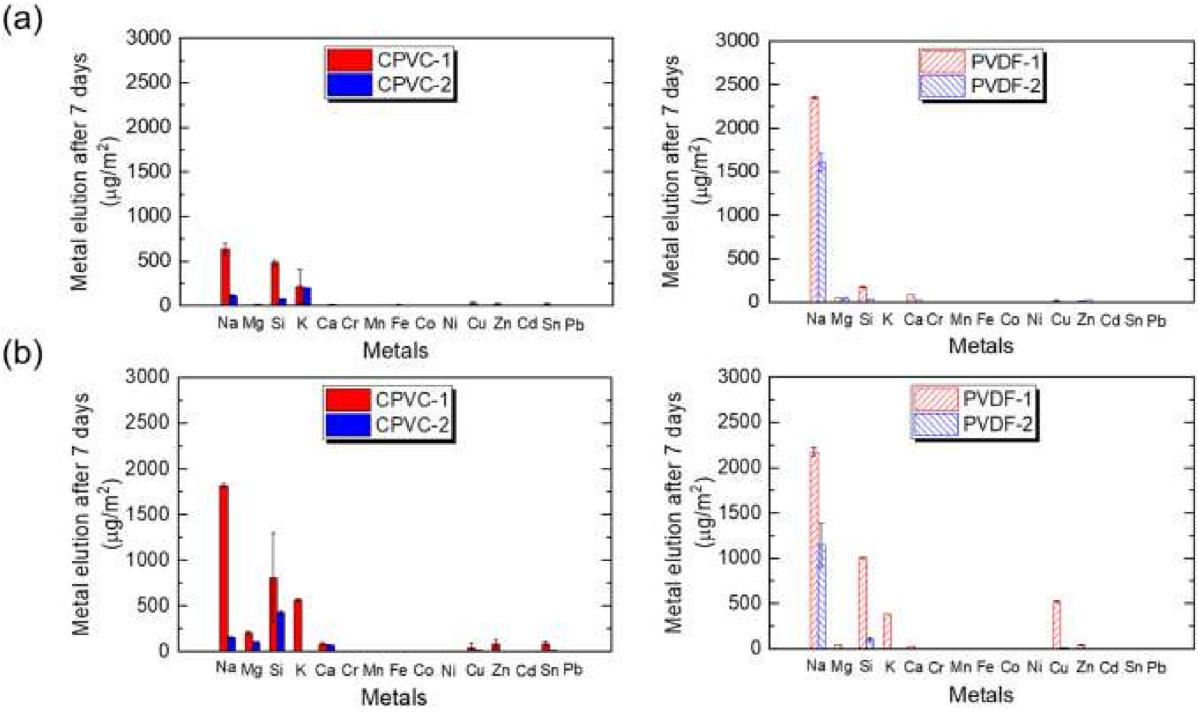


Figure 20: Cumulative metal leaching from CPVC-2 and PVDF-2 pipes at 25 °C (a) and at 50 °C (b) for 7 days (Park et al., 2025).

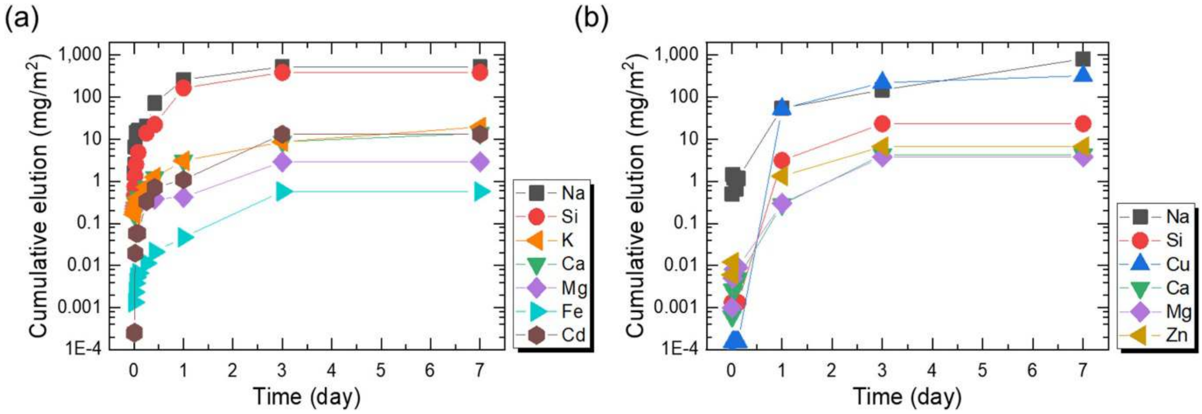
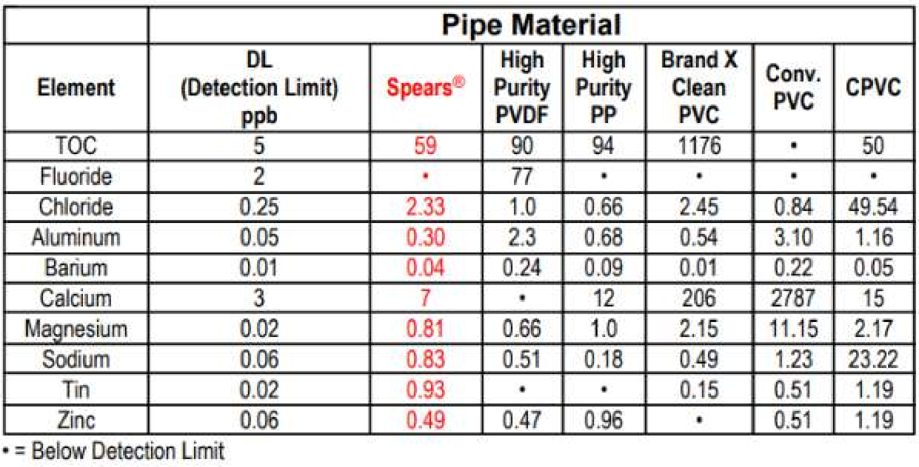


Figure 21: Cumulative metal leaching from CPVC-2 and PVDF-2 on the loop leaching test (Park et al., 2025).

Leaching tests of SPEARS®

Low leaching was identified for the SPEARS® system according to the manufacturer (Spears Manufacturing Company, 2025). Their technical data sheet indicated that leaching tests were conducted on their PVC system under both static and dynamic conditions. Figure 22 presents the results of the static leach tests, comparing the SPEARS® system to other high-purity materials such as PVDF, PP, and PVC from other brands. The manufacturer noted that UPW used in a seven-day leaching test can be extremely aggressive, thus affecting the amount of leachable substances. The SPEARS® system demonstrated comparable levels of extractables to high-purity PVDF and much lower levels compared to other branded PVC under static conditions. However, a direct comparison with SEMI F57 requirements is not possible due to differences in reporting units.



	Pipe Material						
Element	DL (Detection Limit) ppb	Spears®	High Purity PVDF	High Purity PP	Brand X Clean PVC	Conv. PVC	CPVC
TOC	5	59	90	94	1176	•	50
Fluoride	2	•	77	•	•	•	•
Chloride	0.25	2.33	1.0	0.66	2.45	0.84	49.54
Aluminum	0.05	0.30	2.3	0.68	0.54	3.10	1.16
Barium	0.01	0.04	0.24	0.09	0.01	0.22	0.05
Calcium	3	7	•	12	206	2787	15
Magnesium	0.02	0.81	0.66	1.0	2.15	11.15	2.17
Sodium	0.06	0.83	0.51	0.18	0.49	1.23	23.22
Tin	0.02	0.93	•	•	0.15	0.51	1.19
Zinc	0.06	0.49	0.47	0.96	•	0.51	1.19

• = Below Detection Limit

Figure 22: Extractable analysis after seven-day static leaching at ambient temperature (120-square-inch wet surface contact area) utilizing 450 mL 18.2 megohm UPW (Spears Manufacturing Company, 2025).

For dynamic testing, the manufacturer reported that in a freshly assembled SPEARS® pipe system, assemblies using a specially formulated one-step cement did not significantly contribute to particle generation or leachable contamination under flowing conditions throughout the test duration. According to the manufacturer, the SPEARS® system achieved background TOC levels of 3 ppb after 4 hours of testing (Figure 23), confirming the fast cure time of their specially formulated cement. This is in contrast to conventional solvent cements and primers, which typically increase

TOC contamination. However, it is important to note that ASTM D5127 and SEMI F63 standards require TOC levels of less than 1 ppb in an online system.

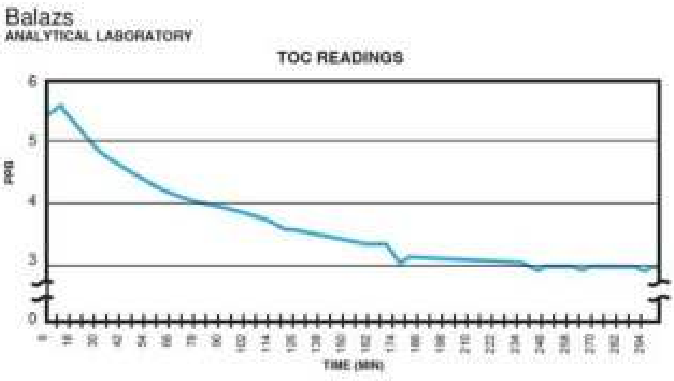


Figure 23: TOC levels at dynamic leaching conditions in a SPEARS system (Spears Manufacturing Company, 2025).

Furthermore, during dynamic conditions, the manufacturer measured 68 trace metals (not specified), all of which were below the detection limit except for aluminium, which reached levels of up to 0.012 ppb in one measurement. Additionally, ionic compounds were tested under dynamic conditions (not specified), with maximum values of 0.15 ppb for sulphate and 0.05 ppb for ammonium (Spears Manufacturing Company, 2025).

Low Surface Roughness

A supplier is offering a PVC piping system with a roughness average (Ra) of ≤ 0.25 µm (Spears Manufacturing Company, 2025), which meets the requirements of SEMI F57. Therefore, this criterion is fulfilled.

Temperature resistance

According to a supplier, the maximum operating temperature for the material is specified as 60 °C (140 °F) (Spears Manufacturing Company, 2025). This aligns with stakeholder statements indicating that PVC needs fibre-reinforced plastic reinforcement at temperatures above 60 °C, which increases the complexity and cost of implementation (I08). For semiconductor facilities where operating temperatures exceed 100 °C, PVC piping would consequently be unsuitable.

Fire resistance

Incorporating chlorinated or brominated flame retardants, phosphorous-based retardants, or antimony trioxide enhances the flame resistance of the PVC. Some chlorinated PVC (PVC/C) and Type 1 PVC (CRP-1) meet FM4910 standards (Plastic Design Industries, 2024). However, no information on the applied additives and suitability for UPW applications could be identified.

Mechanical strength/pressure resistance

No data was available to assess the mechanical strength/pressure resistance of PVC.

Processability

A supplier is stating that the correct processing techniques ensure proper dispersion and fusion of the compound, resulting in a homogenous melt with uniform properties (Spears Manufacturing Company, 2025). Consequently, it is assumed that the processability criterion is met.

Weldability

CPVC pipes are typically connected using a bonding method with a primer rather than fusion welding techniques (Park et al., 2025). The use of additional bonding agents can increase the risk of system contamination. To address this concern, a supplier offers a one-step solvent-cementing system (Spears Manufacturing Company, 2025). According to the supplier, this system contains fewer contaminants compared to conventional PVC solvent cements and cures quickly.

Resistance to Sanitization

A supplier is stating that PVC shows good chemical and corrosion resistance (Spears Manufacturing Company, 2025). However, no specific data is available to access its resistance to a suitable sanitization method. Based on the limited temperature resistance of PVC, it is expected that hot water sanitization or steam sanitization might be challenging. However, no conclusion can be made on this criterion.

4.2.5.2 Hazard Assessment

Polyvinyl chloride (PVC) is a widely used polymer with a broad range of technical applications. Regulatory scrutiny of PVC is primarily driven by concerns related to its additives (such as plasticisers and stabilisers) and aspects of its production and end-of-life management, rather than the polymer itself, which is generally not considered intrinsically hazardous in its pure form. For example, ECHA found that risks are mainly linked to certain additives (e.g. ortho-phthalates, organotin stabilisers), while risks from PVC resin under current conditions are considered adequately controlled (ECHA, 2023).

Earlier formulations of flexible PVC frequently contained low molecular weight ortho-phthalate plasticisers and metal-based stabilisers such as lead and cadmium. However, these substances have largely been phased out of PVC manufacture in the EU over the past two decades and are now subject to strict authorisation or restriction under REACH (ECHA, 2023).

The monomer vinyl chloride (VCM; CAS 75-01-4), used in the manufacture of PVC, is classified as a human carcinogen (Carc. 1A), and its production and handling are therefore subject to stringent industrial controls. Under normal conditions of use, PVC is not expected to revert to vinyl chloride monomer. When PVC is exposed to elevated temperatures, its primary degradation pathway is dehydrochlorination, resulting in the release of hydrogen chloride and the formation of conjugated polyene structures in the polymer. Further degradation products may form under more severe thermal conditions(Oxoplast^{TM}, 2015).

At high temperatures, such as during uncontrolled burning or certain end-of-life scenarios, PVC can contribute to the formation of hydrogen chloride and, under specific conditions, chlorinated organic by-products including dioxins. According to (ECHA, 2023) the PCDD/Fs generation does not seem proportional to the chlorine content, but to depend mainly on furnace types, their operating conditions and the type and efficiency of air pollution control systems. In the EU, emissions of dioxins and furans, where relevant, are controlled under the EU Industrial Emissions Directive Framework and BAT requirements set design and emission limits for waste-gas treatments involving chlorine-containing contents.

4.2.5.3 Assessment of suitability

It is important to note that the installation of the piping system requires a bonding agent, which can impact leaching and notably increase TOC contributions. However, contradictory results regarding the leaching potential of PVC under dynamic conditions have been reported. While a scientific study found that PVC failed to meet TOC levels under dynamic conditions, a manufacturer of a PVC system claims that their system achieves background TOC levels after just 4 hours of dynamic conditions. This discrepancy may be attributed to differences in the bonding agents used.

Based on the available data, it remains unclear whether high purity requirements can be consistently met.

PVC piping systems seem to be unsuitable for applications requiring operating temperatures exceeding 100 °C, as their maximum operational temperature was found to be 60 °C, which may lead to system failure under higher temperature conditions.

Another major drawback mentioned by one stakeholder are high maintenance costs due low durability and the need to change piping systems every few years (I09).

4.2.6 Assessment of Polyether-Ether-Ketone (PEEK) as an alternative to PVDF in UPW systems for SC Manufacturing

4.2.6.1 Description

PEEK is highly regarded for its exceptional mechanical and thermal performance, with the ability to withstand temperatures above 200 °C and high pressure. It is advertised, for example by Synesgo and Victrex, as an ideal material for semiconductor components, due to its high strength, stiffness, dimensional stability and temperature resistance (Syensqo, 2026a; VICTREX, 2024). PEEK components demonstrate remarkable chemical resistance, ensuring integrity and longevity, and possess low outgassing characteristics, which are crucial for contamination control in cleanroom environments. Additionally, components made from PEEK have an extended lifespan, reducing downtime and increasing operational efficiency. It should be noted that PEEK plastic is currently much more expensive than other materials, including PVDF. The cost of PEEK was estimated to be 200 USD/kg in 2023 (Beeplastic, 2023). This is partly due to the current limited supply and high demand for PEEK resin, but also because of its complex, high-temperature synthesis process and the specialised equipment and expertise required for processing and manufacturing PEEK plastic (Beeplastic, 2023).

PEEK extruded pipes are commercially available and have been adopted for various high-performance applications, including the semiconductor sector (YUWEI, 2021a). According to a manufacturer, PEEK resin exhibits excellent chemical resistance, thermal stability, and mechanical strength, which enable its use in the conveyance and storage of ultra-pure water at the µg/L concentration level (YUWEI, 2021b). It can be employed in the fabrication of components such as pipes, valves, pumps, and positioners. Moreover, PEEK has been utilized in the production of large-scale integrated circuits in Japan.

Despite its many advantages, one manufacturer of piping components (I07) has noted that PEEK's chemical resistance to strong acids like hydrofluoric acid and hydrochloric acid is limited. Over time, PEEK tends to release particles, which can compromise the purity required for semiconductor manufacturing. The stakeholder still considers PEEK to be the best partial alternative currently available; however, it still fails to meet purity and chemical tests. Very recently, the manufacturer GF has announced a High Purity PEEK piping system called SYGEF Ultra for hot and ambient UPW systems to be launched in 2026 (GF, 2025b).

4.2.6.2 Technical performance

The following table and section summarise the performance of PEEK according to the key technical functionalities that were defined for UPW systems in previous chapters.

Low leaching potential / purity

One manufacturer has noted that PEEK is suitable for UPW piping systems at the µg/L (ppb) level (YUWEI, 2021b). However, no further data was available on the specific leach-out behaviour to definitively assess whether purity requirements can be fulfilled. One stakeholder (I07) indicated that current purity requirements are not being met, although research is ongoing to address this issue.

GF has introduced the SYGEF Ultra, asserting that its purity “far exceeds” the SEMI F57 standards (GF, 2026). Despite this claim, the publicly available information is currently limited to this announcement. Detailed leaching curves or tables of extractables for SYGEF Ultra have not been published yet.

Low Surface Roughness

GF claims that SYGEF Ultra will have very smooth surface finishes (GF, 2025b). However, no public Ra numbers for SYGEF Ultra have been disclosed so far.

Based on the mechanical properties of PEEK, low surface roughness values are generally possible. One study has measured a very low Ra of 0.078 µm for machined PEEK (Ji et al., 2015) which is far below the requirements outlined in the SEMI F57 standard.

Table 28: Key functionalities of UPW systems as defined in chapter 4.2.2 and performance of PEEK

Key functionality	Requirement(s)	Performance of Alternative
Low leaching potential / purity	Leaching limits in compliance with SEMI F57 (for more information see Table 24): • TOC ≤ 40,000 µg/m^2 • Limits for 22 metals • Limits 8 ions	Suitable for µg/L UPW (YUWEI, 2021b), stakeholders stated that purity requirements cannot be reached yet. Recently, SYGEF Ultra was announced that should according to its manufacturer "far exceeds" SEMI F57 requirements (GF, 2026).
Low Surface Roughness	Ra ≤ 0.25 µm - ≤ 1 µm (depending on component type as outlined in SEMI F57 standard).	Very smooth surface finishes (GF, 2025b). Ra = 0.078 µm for machined PEEK reported (Ji et al., 2015).
Temperature resistance	Continuous operating temperature of 20 °C to 100 °C	Continuous service temperature up to 260 °C (Syensqo, 2026a; YUWEI, 2021a)
Fire resistance	Compliance with FM4910 standard.	Compliant with FM4910 (VICTREX, 2024).
Mechanical strength/pressure resistance	Minimum pressure resistance of 5-7 bars	High mechanical strength (not specified) (VICTREX, 2024)
Processability	Suitable for processing	Suitable for a variety of processing techniques, including injection moulding and extrusion (Syensqo, 2026b; YUWEI, 2021a).
Weldability	A suitable welding technique can be applied	SYGEF Ultra will we launched with welding technologies engineered for ultrapure applications (GF, 2025b)
Resistance to Sanitization	Resistance to a suitable sanitization method such as Ozone (up to 0.2 ppm), hot water or steam.	No data available. Overall high chemical resistance (not specified for ozone) and high temperature resistance (relevant to hot water/ steam).

Temperature resistance

Suppliers claim a continuous service temperature of up to 260 °C (Syensqo, 2026a; YUWEI, 2021a), which significantly exceeds a continuous operating temperatures of 100 °C.

Fire resistance

According to a supplier PEEK is compliant with FM4910 standards (VICTREX, 2024).

Mechanical strength/pressure resistance

High mechanical strength (not specified) (VICTREX, 2024).

Processability

Can be compressed by injection moulding, compression moulding, extrusion moulding, blow moulding and melt spinning (Syensqo, 2026b; YUWEI, 2021a) or extruded into a variety of shapes using standard extrusion equipment (Syensqo, 2026b).

For injection moulding, the equipment should be capable of achieving and maintaining the required processing temperatures of up to 385 °C on the injection unit and up to 205 °C on the mould (Syensqo, 2026b).

Weldability

Common welding techniques suitable for KetaSpire® PEEK include spin welding, vibration welding, ultrasonic welding, and laser welding (Syensqo, 2026b).

GF claims that SYGEF Ultra will we launched with welding technologies engineered for ultrapure applications (GF, 2025b). Detailed specifications have not been published yet.

Resistance to Sanitization

While PEEK generally demonstrates in general high chemical resistance (VICTREX, 2024), one stakeholder (I07) has reported that its resistance to strong acids like hydrofluoric acid and hydrochloric acid is limited. Nevertheless, it is assumed that this limitation will not directly affect its applicability on sanitization in UPW systems. No data on the resistance of PEEK to ozone as a sanitization agent is available. Based on its high temperature resistance, the material might further be suitable to hot water sanitization or steam sanitization methods. Due to the lack of any specific data, no conclusion can be made on this criterion.

4.2.6.3 Hazard Assessment

PEEK is generally regarded as a very low-hazard, biocompatible engineering plastic in its solid form, with most risks arising only during high-temperature processing or machining as fine dust. In vitro and in vivo studies show that medical-grade PEEK and its extracts do not exhibit relevant cytotoxicity or mutagenicity under recommended conditions, supporting its use as an implant material (Chon et al., 2019; Katzer et al., 2002). PEEK is chemically very stable and insoluble in water; aquatic toxicity is expected to be low, but like other stable polymers it may contribute to solid waste accumulation if not recovered or recycled.

PEEK is synthesized from two primary monomers: hydroquinone (CAS 123-31-9) (or its disodium salt) and 4,4'-difluorobenzophenone (CAS 345-92-6). These monomers require careful handling due to toxicity and high-temperature processing risks. Hydroquinone is classified as eye and skin sensitizer, acute toxic if swallowed and very toxic to aquatic species. There is further some evidence for long-term carcinogenic and genotoxic effects. 4,4'-Difluorobenzophenone is acute toxic is swallowed and toxic to aquatic organisms.

4.2.6.4 Assessment of suitability

PEEK meets several of the required criteria, for example those relating to processability, temperature resistance, surface roughness and fire resistance. Furthermore, a PEEK UPW piping system with a purity that should 'far exceeds' the SEMI F57 standards is set to launch in 2026. However, the available information is qualitative at this stage, and there is no quantitative data to enable a full assessment. Overall, PEEK is a promising technical alternative to PVDF. However, the current higher price of PEEK compared to PVDF should be considered in the substitution process.

4.2.7 Substitution timeline at the Case study level

Several subsequent phases need to be considered before complete substitution can be achieved. The assessment of PVDF substitution provides information on factors affecting substitution, potential timelines for transitioning to fluoropolymer-free alternatives, and the consequences of a potential ban. The detailed review highlights the complexity of identifying a replacement material that meets all the stringent requirements of semiconductor manufacturing while maintaining the essential properties relevant for UPW piping.

4.2.7.1 Factors affecting substitution

When considering the use of PVDF piping in UPW systems for semiconductor manufacturing, several factors affect the potential substitution of these materials. One significant barrier is the technical requirements necessary for semiconductor manufacturing. Alternative materials often fail to meet the stringent demands for e.g., purity, low surface roughness, and temperature resistance, particularly combined in one material. These properties are crucial for maintaining the high standards required in the industry. Another substantial challenge lies in the regulatory and quality-related barriers. Many customers in the semiconductor sector insist on qualifications according to SEMI standards or proprietary in-house approvals, which are typically tailored to fluoropolymer-based materials. Switching to new materials would necessitate lengthy and costly requalification processes, often with uncertain outcomes. Qualifications per SEMI F57, or specific customer norms typically take several years each. Additionally, alternative materials would require new cleanroom validation and tooling qualification. The industry is notably risk-averse, such that even proven materials need years of field validation. Importantly, as semiconductor manufacturing technology progresses toward smaller chip architectures on the nanometre scale and below, the material requirements continue to become more stringent (I07).

Switching away from fluoropolymers would necessitate full requalification and validation, often by external customers, posing another challenge. For example, a global chip manufacturer might require up to two years of testing, including chemical compatibility, cleanroom trials, and reliability studies before approving a non-fluoropolymer component (given the fact that the alternative is suitable and in general available). This process would lead to significant project delays, cost risks, and a level of uncertainty that can be difficult to manage.

In the highly conservative semiconductor industry, acceptance for material changes is extremely low, even for functionally equivalent alternatives. Customers often associate PVDF materials with "zero risk," and alternatives need to demonstrate their reliability over many years in real-world operations. Customer-driven specifications mainly leave no room for material flexibility.

The development, testing, and implementation of new materials generate high direct and indirect costs, including equipment modifications, staff training, and additional quality assurance. Fluoropolymers are typically one order of magnitude more expensive than polyolefins such as PP. Although PP is cheaper, this cost advantage is irrelevant if it does not meet the necessary specifications. By contrast, PEEK is very expensive, so using this material would be costly and offer no economic advantage. Further, different polymers exhibit varying shrinkage behaviours, which would necessitate new moulds for all parts. The tooling cost per part ranges from EUR 50,000 to 100,000, and each material substitution would require redesigning, new tooling, and qualification for each component. Consequently, the number of product variants could increase significantly from approximately 1,500 to over 4,000.

Requalification and process changes would demand EUR multi-million investments. If fluoropolymers were restricted or banned, companies producing PVDF-based piping equipment for UPW-systems could lose their semiconductor business entirely. Moreover, US and Asian competitors could continue supplying fluoropolymer products, resulting in a competitive disadvantage for EU companies. It may even necessitate relocating production outside the EU. Switching to non-fluoropolymer materials would require redesigning and separate tooling for each variant, further complicating the transition.

In summary, the substitution of fluoropolymer-based piping in UPW systems for semiconductor manufacturing faces significant technical, regulatory, customer acceptance, and economic barriers. These factors contribute to the complexity and high costs associated with transitioning to alternative materials, indicating that a cautious and well-planned approach is essential for any material substitution efforts.

4.2.7.2 List of Actions and Substitution Timeline with Milestones (Substitution Plan)

As previously described, substitution of fluoropolymer-based piping in UPW systems for semiconductor manufacturing is complex and time-demanding. Based on information gathered from stakeholders related to UPW systems for semiconductor manufacturing and data research, a timeline could have been developed to illustrate that industry still needs considerable time until a full transition can be achieved.

If substitution is technically feasible, a series of steps and a detailed timeline would be necessary. Importantly, this presented timeline assumes a best-case scenario, and various obstacles may still occur that could potentially slow down the process.

To perform the transition to non-fluoropolymer-based alternatives, the following steps need to be taken.

Phase I: Research & Development, Material Selection and Pre-screening (at least 2 years)

The first phase in the substitution process involves comprehensive research and development (R&D), as well as the selection and pre-screening of potential alternative materials (I07, I09). Identifying suitable alternatives is critical toward replacing fluoropolymer-based piping in UPW systems for semiconductor manufacturing. Potential alternatives under consideration include high-performance polymers based on PP, PVC, and PEEK (refer to chapter 4.2.3).

One of the initial steps involves assessing the purity of potential alternative materials through leach-out tests, following the SEMI F57 guidelines (I09). Once purity requirements are confirmed, mechanical properties and chemical resistance must be evaluated, especially in conditions with O_3 water concentrations of 3 to 6 ppm (I09). These initial media compatibility tests are critical to determine the material's suitability for semiconductor applications. Moreover, long-term mechanical properties must be tested in accordance with ISO 9080 standards (I09). If these requirements are met, further assessment of the processing capabilities, such as ease of extrusion and injection moulding, is necessary as well as demonstrating easy weldability using IR-welding technology (I09).

It is essential that any potential alternative sufficiently fulfils every key functionality required for UPW systems. Although promising alternatives such as PEEK are already known, further investigation is needed not only into material variants but also into identifying other potential substitutes for PVDF. Engaging material suppliers and producers is crucial, as they provide the necessary materials and insights into their properties. Input from downstream users and end-users is equally important, as they collaboratively define the required material characteristics. One effective approach to navigating these challenges would be a collaborative effort among affected companies across the entire supply chain. This collaboration would facilitate the sharing of knowledge and resources, ensuring a comprehensive and coordinated response to the complex requirements of substituting fluoropolymer-based piping in semiconductor manufacturing. Further, incentives for the significant R&D efforts would be needed to offset the competitive advantages held by non-EU semiconductor manufacturing plants that benefit from the performance achieved with current PVDF-based technology.

Phase II: Prototype Development & Lab Testing (1-2.5 years)

Once suitable alternatives have been identified, the next phase involves developing prototypes for further testing. Eventually, new manufacturing components need to be created. To manufacture piping components by extrusion, new tooling must eventually be developed and validated because each polymer grade shows distinct melt-flow and shrinkage behaviour. For parts prepared by injection moulding, new moulds need to be created as different polymers exhibit varying shrinkage behaviours (I07). These moulds are used to investigate the dimensions of the prototypes to ensure they meet the necessary specifications. After achieving suitable dimensions, moulds can be employed to produce prototype samples.

Small batches of test samples (prototypes) are then produced to facilitate thorough evaluation (I07). These samples undergo a series of tests to assess for example their leakage behaviour, particle emission, chemical resistance, and thermal stability. Additionally, direct benchmark tests are conducted to compare the performance of these prototypes against existing fluoropolymer-based products (I07). This phase is crucial for ensuring that the new materials can meet the stringent requirements of semiconductor UPW systems.

If satisfying results are obtained from prototypes, the transition from a PVDF-based system to a fluoropolymer-free alternative can be initiated with Phase III.

Phase III: Process Integration and Validation (1–2.5 years)

Importantly, this phase II (process integration and validation) can only be started once testing via the prototypes has yielded satisfactory results. The first step involves adjusting manufacturing processes, including tool modifications such as mould adjustments, to ensure that the new materials can be integrated seamlessly into production (I07).

Initial tests and process adjustments will depend heavily on the results obtained from sample parts (Phase II), ensuring that every step of integration and validation is accurately executed to achieve optimal outcomes.

To prevent any potential pollution, contamination, or degradation of the materials, it is crucial that all raw material suppliers and possible customers (including parts manufacturers) possess the necessary skills and experience to maintain the highest level of purity in their production processes. Subsequently, comprehensive long-term tests must be conducted to evaluate lifecycle, burst pressure, and cleanroom release performance (I07). Ensuring that these new materials match or exceed the durability and reliability of existing fluoropolymer-based products is essential.

Phase IV: Customer Approval and Certification (1-2 years)

Customer approval and certification are of utmost importance, as products can only be utilized in UPW systems for semiconductor manufacturing once they have been validated (I07). Ensuring that the quality and performance of the new materials meet customer requirements is essential during this phase. Validation is performed in the customers' own laboratories, located in various regions such as Korea, Japan, and Taiwan, under real-world conditions (I07). These rigorous tests are crucial to demonstrate that the new materials can reliably function within the stringent parameters required for semiconductor UPW systems.

Additionally, thorough documentation and compliance with sector-specific standards such as SEMI, USP, and others are mandatory, as previously described (I07). Meeting these standards ensures that the new materials are not only effective but also adhere to industry regulations, providing a foundation for customer trust and acceptance.

Phase V: Commercialisation (0.5-1 year)

Following successful lab testing, validation, as well as customer approval and certification, fluoropolymer-free products are ready to be commercialized and introduced to the market. Customer approval is the most critical criterion for proceeding with commercialization, as semiconductor manufacturers often have stringent requirements that must be met for their production processes (I07). If these criteria cannot be met, products will not be selected for use in their systems.

It is crucial to keep in mind that semiconductor manufacturers predominantly decide on the materials needed and the requirements that must be met; these decisions are not typically made by the product suppliers or raw material manufacturers. However, if Phases I-IV have been successfully completed, the commercialization process can be initiated.

Training sales and application teams is an essential step to ensure they are well-prepared to support and promote the new products (I07). Launching trust-building marketing campaigns is another critical aspect to foster customer confidence in the new materials. Additionally, closely monitoring in-field performance through systematic field tracking is necessary to ensure the products meet expectations and address any potential issues promptly (I07).

These actions help to ensure that the transition to new materials is smooth and that the products gain acceptance and trust within the sector, paving the way for successful market introduction. Commercialisation activities on new products typically take at least 0.5-1 year (I07).

4.2.7.3 Effects of a full ban of Fluoropolymers

A sudden ban of fluoropolymers could have significant impacts on many companies. As an example, a significant portion of the product portfolio of companies producing PVDF-based equipment, including high-purity valves, membranes, and seals, is fundamentally designed around fluoropolymer materials such as PVDF, but also PTFE and PFA (I07). A ban would render these products non-compliant and commercially unviable, necessitating immediate product discontinuation or multi-year redevelopment cycles. Substantial investments in research and development, tooling, and process requalification would be needed without any guarantee of achieving comparable performance (I07).

At sector level, the semiconductor industry relies heavily on fluoropolymers for their high purity, chemical resistance, and thermal stability, which are vital for processes like CMP, etching, and UPW distribution. Currently, no functionally equivalent, validated alternative meet the stringent performance and cleanliness standards required by the industry for the large variety of different use cases (I07). A ban would likely disrupt supply chains, stop production in semiconductor fabs, and significantly delay equipment qualification, potentially causing global ripple effects (I07).

Strategically, a unilateral ban in the EU could place European equipment and component manufacturers at a competitive disadvantage. Global customers might shift to suppliers outside the EU who can continue offering fluoropolymer-based products, accelerating de-industrialization and driving innovation out of the European market (I07).

Therefore, a full ban on fluoropolymers under current conditions would be highly disruptive to the EU semiconductor industry. It would compromise product integrity, disrupt global chip production, and damage Europe’s position in high-tech manufacturing.

4.2.8 Conclusion on Case study "Use of Fluoropolymer-based (PVDF) Piping in Ultra-pure Water (UPW) Systems for Semiconductor Manufacturing"

The selection of materials for UPW systems in semiconductor manufacturing requires careful consideration of trade-offs between performance and economic impacts. Fluoropolymers, particularly PVDF, are well-accepted materials used in UPW systems for semiconductor manufacturing due to their high purity, low surface roughness, and temperature resistance, among other properties. The combination of various functionalities in one product makes PVDF a preferred material for this application. This unique combination of properties makes finding a suitable alternative challenging.

Despite these challenges, there are potential alternatives currently being researched and developed. However, information on these potential alternatives is limited. Consequently, the assessment not only considered suitability but also the availability of data. While alternatives such as polyolefins, and other advanced materials such as silicate-based materials are being explored and undergoing R&D, according to stakeholders none yet provide the comprehensive benefits needed for semiconductor processes. The shortlisted alternatives include Polypropylene (PP) (chapter 4.2.4), Polyvinyl Chloride (PVC) (chapter 4.2.5), and Polyether-Ether-Ketone (PEEK) (chapter 4.2.6). Based on input from stakeholders and literature research, PEEK appears to be the most promising technical alternative to PVDF for UPW piping systems. Despite its promising technical feasibility, the current high cost of PEEK is a significant factor to consider when contemplating substitution. A PEEK UPW piping system is anticipated to be launched in 2026. At present, however, some of the available information regarding its performance in relation to critical functionalities, such as purity requirements, remains qualitative. This limitation prevents a comprehensive assessment at this time.

Substitution efforts must weigh the technical challenges, certification hurdles, and total cost of ownership, including reduced component life or increased maintenance. Even if a suitable material is available in a commercially produced thermoplastic grade, the process of replacing fluoropolymer-based piping with alternative materials in UPW systems for semiconductor manufacturing could still take five to ten years to complete, given the complexity and cost involved. The stringent requirements of the industry are leading to time-consuming approval processes. Additionally, the substitution process is cost-intensive, with expenses estimated to be at least EUR 50 million for each case, considering broad portfolios and approval costs (I08).

In addition, and as mentioned previously, semiconductor manufacturing includes many more applications that use fluoropolymers. Hence, any substitution requires considerable time for systematic replacement given the prolonged lifetime of the fluoropolymer articles, as well as the sheer number of articles involved and the level of disruption in manufacturing.

Given these challenges, any restrictions on the use of fluoropolymers should incorporate targeted risk mitigation strategies for critical sectors such as semiconductor manufacturing. A sudden or blanket ban on fluoropolymer use for UPW piping in semiconductor manufacturing could lead to disruptions, loss of market access, delays in global semiconductor production, and significant strategic disadvantages for EU-based companies.

5. Conclusion

The assessment of alternatives to fluoropolymers across high-technology sectors presents a challenge rooted in the unique combination of properties these materials offer and the complexity of their applications. Fluoropolymers underpin critical processes in both the Transport and Electronics & Semiconductor industries, where their high purity, chemical resistance and thermal stability are required. The impetus for substitution arises from regulatory pressures and safety concerns, yet the path to replacement is charged with technical, organisational and socioeconomic obstacles that demand careful consideration.

A central barrier in the alternatives assessment process is the limited availability of use-case specific data. Scientific literature often lacks detailed studies tailored to the requirements of individual applications. Confidentiality concerns among downstream users further compound these limitations, restricting the sharing of proprietary information. Successful evaluation and implementation of alternatives therefore necessitate full engagement across the supply chain, from material suppliers and component manufacturers to end users and regulators. Only through this collaborative approach can the requisite data be generated, technical feasibility thoroughly assessed, and sector-specific needs effectively addressed.

Case studies within the transport sector, such as O-Rings for Gasoline Direct Injection (GDI) systems and fuel hoses for high-temperature applications, illustrate the difficulties inherent in substitution. While Nitrile Butadiene Rubber (NBR) and Hydrogenated Nitrile Butadiene Rubber (HNBR) are commonly deployed materials, they fall short of meeting the demanding technical requirements posed by these applications. Key limitations include insufficient chemical resistance, thermal stability, and durability under prolonged exposure to aggressive fuels and elevated temperatures. As a result, neither NBR nor HNBR can be considered suitable alternatives to fluoropolymers in these contexts. The development of new materials tailored to these needs is not only technically intensive but also time-consuming, with an estimated minimum substitution timeline of approximately 20 years to achieve comparable performance, regulatory approval, and widespread adoption.

In semiconductor manufacturing, the selection of materials for ultra-pure water (UPW) systems is governed by stringent criteria: high purity, low surface roughness, and temperature resistance. The shortlisted alternatives Polypropylene (PP), Polyvinyl Chloride (PVC), and Polyether-Ether-Ketone (PEEK) have been evaluated for their suitability. Among these, PEEK shows promise and meets the most relevant technical performance criteria, yet information is still sparse, particularly for performance under real use conditions and long-term reliability. Moreover, semiconductor manufacturing relies on fluoropolymers for a wide array of applications, each with distinct technical requirements, making a one-size-fits-all solution unlikely. Substitution efforts must therefore be undertaken with a holistic view, aiming to minimise disruption and address sector-wide needs.

Transitioning to alternative materials demands a multi-step process that is both rigorous and resource intensive. Key stages may include regulatory approvals, certification of materials and components, extensive customer testing, adaptation of manufacturing processes, and eventual market introduction. Each phase is subject to its own challenges, such as lengthy approval cycles, compatibility testing, and customer acceptance. The complexity is further heightened by the need to maintain continuous production, ensure product integrity, and meet global standards. The high substitution expenses reflect not only the direct costs of material and process changes but also the indirect costs associated with reduced component life or increased maintenance requirements.

Across both transport and semiconductor sectors, the assessment underscores that substitution is not merely a technical exercise but a strategic challenge, as not only the impacts of a single company should be considered in the process but also potential impacts on the EU.

For the Transport sector, the absence of viable, validated alternatives for certain applications may disrupt supply chains, delay production, and impact the competitive position of European manufacturers in case that fluoropolymers are not available anymore. In the fast-growing and highly competitive Electronics & Semiconductor industry, substitution (where possible) should aim to minimise production disruptions, and where substitution is not yet possible, a restriction on fluoropolymers should consider the impacts on competitiveness and innovation of the European market.

Given these complexities, the assessment shows that a collaborative approach across the supply chain and with policymakers is necessary to distinguish applications where substitution of fluoropolymers is technically feasible from those where potential for substitution has not yet been demonstrated, particularly in view of potential implications for production continuity, safety, and competitiveness.

6. References

Abbey Polymers Ltd. (2024). *High-Performance Polymer Suppliers | Abbey Polymers*. Abbey Polymers - Specialist Suppliers of Polymers. https://www.abbeypolymers.co.uk/products/high-performance-polymers/

AGC Chemicals Americas. (2025). High-Purity AGC Fluoropolymers for Semiconductor Production. *AGC Chemicals Americas Blog*. https://www.agcchem.com/blog/fluoropolymers-for-semiconductor-production/

AGRU Kunststofftechnik GmbH. (2017). *High Purity Piping Systems: PURAD*. AGRU Kunststofftechnik GmbH. https://www.agru.at/fileadmin/user_upload/produkte/purad/downloads/Prospekte_PRO/EN/AGRU_Purad_EN.pdf

Apple Rubber. (2016). Understanding the Composition of a Nitrile (Buna-N) Rubber Compound. *Apple Rubber (Hot Topics for Engineers)*. https://www.applerubber.com/hot-topics-for-engineers/understanding-the-composition-of-a-nitrile-buna-n-rubber-compound/

Apple Rubber. (2023). Comparison of The Different Grades of FKM Polymers. *Apple Rubber (Hot Topics for Engineers)*. https://www.applerubber.com/hot-topics-for-engineers/comparison-of-the-different-grades-of-fkm-polymers/

Apple Rubber Products. (2025). *Material Selection Guide: Ethylene/Acrylic (Vamac®)*. Apple Rubber Products. https://www.applerubber.com/seal-design-guide/material-selection-guide/vamac/

Araneo, L., Coghe, A., Brunello, G., & Dondé, R. (2000). *Effects of Fuel Temperature and Ambient Pressure on a GDI Swirled Injector Spray*. 2000-01–1901. https://doi.org/10.4271/2000-01-1901

ARKEMA. (2022). *KYNAR® PVDF COMPONENTS DURABLE SOLUTIONS FOR WATER CHALLENGES*. https://hpp.arkema.com/files/live/sites/shared_arkema/files/downloads/HPP/market-brochures/water-and-filtration/2022%20-%20Kynar%20Water%20Components.pdf

Asahi/America. (2021, May 1). *High Purity Piping Systems: Material Selection and Welding*. Asahi/America. https://www.asahi-america.com/high-purity-piping-systems-material-selection-and-welding/

Asma Adhimi. (2025, November 8). *Europe's semiconductor market grows 7.2% in Q3 2025*. https://www.eenewseurope.com/en/europes-semiconductor-market-grows-q3-2025/

AXEON Water Technologies. (2025). *Critical Applications for Ultrapure Water Systems in Semiconductor Manufacturing*. https://www.axeonwater.com/blog/critical-applications-for-ultrapure-water-systems-in-semiconductor-manufacturing/

Beeplastic. (2023, June 19). *Why Is PEEK Plastic So Expensive? Key Factors & Unique Benefits*. Beeplastic. https://www.beeplastic.com/blogs/plastic-insights/why-peek-plastic-is-more-expensive-than-other-materials

Biressi, G., & Neubauer, B. (2012). *Sterilization of polyvinylidene fluoride piping systems for ultrapure water distribution – Part 2: Ozone sterilization*. https://www.ultrapurewater.com/articles/misc/part-2-ozone-sterilization-of-pvdf-piping-systems-for-high-purity-water-distribution

Biron, M. (2016). Thermoplastic Specific Properties. In *Material Selection for Thermoplastic Parts* (pp. 39–75). Elsevier. https://doi.org/10.1016/B978-0-7020-6284-1.00002-7

Bosch GmbH. (2026). *GDI (Gasoline Direct Injection)*. Bosch Auto Parts. https://www.boschautoparts.com/p/gdi-gasoline-direct-injection-

BRP Manufacturing. (2025). *Epichlorihydrin Rubber | BRP Manufacturing*. BRP Manufacturing. https://brpmfg.com/epichlorihydrin-rubber/

Buck, R. C., Franklin, J., Berger, U., Conder, J. M., Cousins, I. T., de Voogt, P., Jensen, A. A., Kannan, K., Mabury, S. A., & van Leeuwen, S. P. (2011). Perfluoroalkyl and polyfluoroalkyl substances in the environment: Terminology, classification, and origins. *Integrated Environmental Assessment and Management*, *7*(4), 513–541. https://doi.org/10.1002/ieam.258

CarExamer. (2025). Euro 7 Emissions Standards: How 2025's New Rules Will Impact. *CarExamer.Com*. https://carexamer.com/blog/euro-7-emissions-standards-how-2025s-new-rules-will-impact/

Cavallini, C., Gasparrini, C., Zaupa, M., Agoastinetti, P., Dalla Palma, M., Rizzieri, R., Montagner, F., Zin, V., Miorin, E., Badocco, D., & Pastore, P. (2022). Corrosion and Metal Release of Copper and Stainless Steel Exposed to Ultrapure Water. *IEEE Transactions on Plasma Science*, *50*(11), 4491–4495. https://doi.org/10.1109/TPS.2022.3182804

CEN. (2012). *Plastics piping and ducting systems—Determination of the longterm hydrostatic strength of thermoplastics materials in pipe form by extrapolation (ISO 9080:2012)*. https://ewb.ihs.com/tmp_stamp/00637239949/KWLPBFAAAAAAAAAA.pdf?sess=00637239949&prod=SPECS4

Chemours. (2025). *Fluoropolymers, the Crucial Link in Semiconductor Manufacturing*. Chemours. https://www.chemours.com/en/pfas-advocacy/semiconductors

Chon, J. W., Yang, X., Lee, S. M., Kim, Y. J., Jeon, I. S., Jho, J. Y., & Chung, D. J. (2019). Novel PEEK Copolymer Synthesis and Biosafety—I: Cytotoxicity Evaluation for Clinical Application. *Polymers*, *11*(11), 1803. https://doi.org/10.3390/polym11111803

Clwyd Compounders. (2023). *ECO - Epichlorohydrin | Clywd Compounders*. Clwyd Compounders. Clwyd Compounders Ltd. https://www.clwydcompounders.com/polymer/epichlorohydrin/

Clwyd Compounders Ltd. (2023). *ACM - Polyacrylic Rubber*. Clwyd Compounders. https://www.clwydcompounders.com/polymer/acm-rubber/

Data Bridge Market Research. (2025). *Gasoline direct injection Market Size, Share, and Analysis Report 2032*. https://www.databridgemarketresearch.com/reports/global-gasoline-direct-injection-market

Ding, S.-J., Wang, P.-F., Wan, X.-G., Zhang, D. W., Wang, J.-T., & Lee, W. W. (2001). Effects of thermal treatment on porous amorphous fluoropolymer film with a low dielectric constant. *Materials Science and Engineering: B*, *83*(1), 130–136. https://doi.org/10.1016/S0921-5107(01)00504-9

DLSEALS. (2024). *Basic properties and application areas of chloroprene rubber*. GUANGDONG DLSEALS TECHNOLOGY CO.,LTD. https://rubber.dlseals.net/articles/basic-properties-and-application-areas-of-chloroprene-rubber

Dong, X., Iacocca, R. G., Bustard, B. L., & Kemp, C. A. J. (2010). Investigation of Stainless Steel Corrosion in Ultrahigh-Purity Water and Steam Systems by Surface Analytical Techniques. *Journal of Materials Engineering and Performance*, *19*(1), 135–141. https://doi.org/10.1007/s11665-009-9430-x

Duronio, F., De Vita, A., Montanaro, A., & Villante, C. (2020). Gasoline direct injection engines – A review of latest technologies and trends. Part 2. *Fuel*, *265*, 116947. https://doi.org/10.1016/j.fuel.2019.116947

Eastern Seals (UK) Ltd, & UK Seals. (2023). *ASTM D2000 Test Standard Explained*. Eastern Seals. https://www.easternseals.co.uk/information/material-data-sheets/

ECHA. (2023). *ECHA identifies risks from PVC additives and microparticle releases*. ECHA Newsroom. ECHA. https://echa.europa.eu/de/-/echa-identifies-risks-from-pvc-additives-and-microparticle-releases

ECHA. (2025a). *Background Document to the Opinion on the Annex XV dossier proposing restrictions on Per- and polyfluoroalkyl substances (PFASs)* (No. 14). ECHA.

ECHA. (2025b). *ECHA publishes updated PFAS restriction proposal*. ECHA Newsroom. ECHA. https://echa.europa.eu/de/-/echa-publishes-updated-pfas-restriction-proposal

Elastotech Srl. (2025). *Gaskets—Sealing solutions: Production of O-rings, industrial rubber* [Text]. Elastotech Srl. (Italy). https://www.elastotechgaskets.com/

ERIKS. (2015). *FKM 75 Compound 514273—Compound Datasheet*.

ERIKS. (2025a). *FKM and FPM Elastomer*. https://eriks.com/en/what-we-do/rubber-materials-overview/fkm.html

ERIKS. (2025b). *VMQ (Silicone)—Rubber Materials Overview*. //o-ring.info/en/materials/silicone-vmq/

ESIA. (2023). *ESIA comments on Annex XV restriction report*. https://www.eusemiconductors.eu/sites/default/files/20230602_ESIAComments-PFASConsulation.pdf

European Alternative Fuels Observatory. (2025). *European policies and legislation*. European Commission. https://alternative-fuels-observatory.ec.europa.eu/policymakers-and-public-authorities/european-policies-and-legislation

European Commission. (2025). *EU agrees on a 2040 Climate target that sets a clear path towards a decarbonised and competitive economy*. European Commission Press Corner. https://ec.europa.eu/commission/presscorner/detail/en/ip_25_2967

European Commission. Directorate General for Mobility. (2024). *EU transport in figures: Statistical pocketbook 2024*. Publications Office. https://doi.org/doi:10.2832/42772

European Environment Agency (EEA). (2025). *Transport and mobility*. European Environment Agency (EEA). https://www.eea.europa.eu/en/topics/in-depth/transport-and-mobility#:~:text=In%202022%2C%20greenhouse%20gas%20emissions,greenhouse%20gas%20emissions%20in%202022.

European Union. (2024a). *Reduction in CO2 emissions of new passenger cars and of new light commercial vehicles | EUR-Lex*. https://eur-lex.europa.eu/EN/legal-content/summary/reduction-in-co2-emissions-of-new-passenger-cars-and-of-new-light-commercial-vehicles.html

European Union. (2024b). *Worldwide harmonised Light-duty vehicles Test Procedure (WLTP) and Real Driving Emissions (RDE)*. EUR-Lex / Publications Office of the European Union. EUR-Lex. https://eur-lex.europa.eu/EN/legal-content/summary/worldwide-harmonised-light-duty-vehicles-test-procedure-wltp-and-real-driving-emissions-rde.html

EUROSTAT. (2025). *Key figures on european transport: 2024 edition*. Publications Office of the European Union.

Fluoropolymer Product Group of PlasticsEurope, Wood Group UK Limited, Nicolas Robin, Benjamin Croad, Julius Kreissig, & Caspar Corden. (2022). *Update of market data for the socio-economic analysis (SEA) of the European fluoropolymer industry*.

Fluoropolymers Product Group (FPG). (2025a). *Automotive industry*. Plastics Europe. https://fluoropolymers.eu/essential-uses-of-fps/automotive/

Fluoropolymers Product Group (FPG). (2025b). *Electronics industry*. Plastics Europe. https://fluoropolymers.eu/essential-uses-of-fps/electronics-industry/

Fluorotherm™. (2025). *All Material Comparison*. Materials Overview. https://www.fluorotherm.com/technical-information/materials-overview/material-comparison/

Freudenberg FST GmbH. (2025). *ACM Material Properties—What is ACM*. https://www.fst.com/materials/acm/

Freudenberg Sealing Technologies. (2024). *Dichtomatik O-Rings*.

GF. (2024). *PROGEF Plus—System Specification*.

GF. (2025a). *Technical Handbook for Pressure Piping Systems* (Technical Handbook for Pressure Piping Systems). https://www.gfps.com/content/dam/gfps/us/products/price-lists/gfps/gfps-us-eps-pressure-piping-systems-tech-handbook.pdf

GF. (2025b, December 3). *Maximized purity and minimized rinsing times: GF unveils PFAS-free piping system for next-generation semiconductor manufacturing*. News Powered by Cision. https://news.cision.com/gf-piping-systems/r/maximized-purity-and-minimized-rinsing-times--gf-unveils-pfas-free-piping-system-for-next-generation,c4276656

GF. (2026). *SYGEF Ultra*. GF Industry and Infrastructure Flow Solutions. https://www.gfps.com/com/en/products-solutions/innovation/sygef-ultra.html

Global O-Ring and Seal, LLC. (2025). *Material Description: Hydrogenated Nitrile Rubber (HNBR)—Compound HNBR90*. GLOBAL O-RING AND SEAL, LCC.

GMORS. (2019). *Ultra-low temperature FKM for better sealing life*. GMORS (Ge Mao Rubber Industrial Co., Ltd.). https://www.gmors.com/article/ultra-low-temperature-fkm-for-better-sealing-life/detail

GMORS. (2025). *Silicone / VMQ / PVMQ*. GMORS (Ge Mao Rubber Industrial Co., Ltd.). https://www.gmors.com/material/vmq-silicone/detail

Guillaume Ragonnaud. (2025). *Circularity requirements for vehicle design and management of end-of-life vehicles*.

Haseeb, A. S. M. A., Jun, T. S., Fazal, M. A., & Masjuki, H. H. (2011). Degradation of physical properties of different elastomers upon exposure to palm biodiesel. *Energy*, *36*(3), 1814–1819. https://doi.org/10.1016/j.energy.2010.12.023

Henry, B. J., & Timmer, N. (2025). Environmental fate and behavior studies of a polymeric PFAS, polytetrafluoroethylene (PTFE) – results and application to risk assessment. *Chemosphere*, *385*, 144569. https://doi.org/10.1016/j.chemosphere.2025.144569

HEPAKO GmbH. (2020). HNBR (Hydrogenated Nitrile Butadiene Rubber). *HEPAKO Präzisionsgummiartikel*. https://www.hepako.de/en/blog/hnbr-hydrogenated-nitrile-butadiene-rubber/

Holscot Fluoropolymers. (2022). Fluoropolymers and the Automotive Industry. *Holscot Fluoropolymers*. https://holscot.com/fluoropolymers-and-the-automotive-industry-2/

Infineum International Limited. (2016). Infineum Insight—Winter operability. *Insight from Infineum International Limited*. https://www.infineuminsight.com/en-gb/articles/winter-operability/

IPS Flow Systems. (2025a). *High Purity*. https://www.ipsflowsystems.com/high-purity

IPS Flow Systems. (2025b). *High Purity Thermoplastic Piping Systems*. https://cms.esi.info/Media/documents/IPSF_High_ML.pdf

Ji, S., Yu, H., Zhao, J., & Liang, F. (2015). Comparison of mechanical property and machinability for polyetheretherketone and glass fiber–reinforced polyetheretherketone. *Advances in Mechanical Engineering*, *7*(4), 1687814015578357. https://doi.org/10.1177/1687814015578357

Jimmy. (2024, July 9). Different type of Fluoroelastomers (FKM) Rubber. *CUSTOM RUBBER PRODUCTS MANUFACTURE*. https://rubberproducer.com/2024/07/09/different-type-of-fluoroelastomers-fkm-rubber/

Juliana Montoya. (2024). Fluoropolymers Explained: Basics and Applications. *Plastics Engineering*. https://www.plasticsengineering.org/2024/08/fluoropolymers-explained-005977/

Jung, J. K. (2024). Review of Developed Methods for Measuring Gas Uptake and Diffusivity in Polymers Enriched by Pure Gas under High Pressure. *Polymers*, *16*(5), 723. https://doi.org/10.3390/polym16050723

Kalwar, A., & Agarwal, A. K. (2020). Overview, Advancements and Challenges in Gasoline Direct Injection Engine Technology. In A. P. Singh, N. Sharma, R. Agarwal, & A. K. Agarwal (Eds.), *Advanced Combustion Techniques and Engine Technologies for the Automotive Sector* (pp. 111–147). Springer Singapore. https://doi.org/10.1007/978-981-15-0368-9_6

Katzer, A., Marquardt, H., Westendorf, J., Wening, J. V., & Von Foerster, G. (2002). Polyetheretherketone—Cytotoxicity and mutagenicity in vitro. *Biomaterials*, *23*(8), 1749–1759. https://doi.org/10.1016/S0142-9612(01)00300-3

KEIM. (2024, July 4). *Die Norm FM4910 – Alles, was Sie wissen müssen! - Keim Kunststoffe*. https://keim-kunststoffe.de/materialien/fm4910/die-norm-fm4910-alles-was-sie-wissen-muessen/

Kelly (K.) C. (2025). What Is the Difference Between NBR and ACM Rubber? *Julong Rubber*. https://rubberandseal.com/nbr-vs-acm-rubber/

Key Solutions Group. (2025). *Hydrogenated Nitrile Butadiene Rubber (HNBR)*. Key Solutions Group. https://www.keysolutionsgroup.com.sg/solution/hydrogenated-nitrile-butadiene-rubber-hnbr/

KIRKLAND & ELLIS. (2025). *PFAS Update: Scrapping Prior Broader Proposal, EU Publishes Updated Narrower Proposal to Restrict the Manufacture, Use and Marketing of PFAS Chemicals*. KIRKLAND & ELLIS. https://www.kirkland.com/publications/kirkland-alert/2025/10/pfas-update-scrapping-prior-broader-proposal-eu-publishes-updated-narrower-proposal-to-restrict-the?utm_source=chatgpt.com

Kremer Technology GmbH. (2025). *Acrylate rubber (ACM) | Lexikon*. https://kremer-tec.de/en/about-us/lexicon-silicone/lexicon-of-elastomer-technology/term/acrylate-rubber-acm-106.html

Lee, H., Jin, Y., & Hong, S. (2016). Recent transitions in ultrapure water (UPW) technology: Rising role of reverse osmosis (RO). *Desalination*, *399*, 185–197. https://doi.org/10.1016/j.desal.2016.09.003

Levine, Y., Chetrit, E., Fishman, Y., Siyum, Y., Rabaev, M., Fletcher, A., & Tartakovsky, K. (2023). A novel approach to plasticizer content calculation in an acrylonitrile-butadiene rubber real-time aging study (NBR). *Polymer Testing*, *124*, 108091. https://doi.org/10.1016/j.polymertesting.2023.108091

Manager. (2010, March 1). ASTM D 1414 Standard Test Methods for Rubber O-Rings—Testing Equipment. *AHP PLASTIK MAKINA*. https://ahp-makina.com/standard-test-methods-for-rubber-o-rings/

Marco Sealing Solutions. (2025). *O-Ring Permeation Chart*. Marco Sealing Solutions. https://www.marcorubber.com/o-ring-permeation.htm

Market Data Forcast. (2025). *Europe Electrical Components Market Size & Share, 2033* (p. 130). Market Data Forcast. https://www.marketdataforecast.com/market-reports/europe-electrical-components-market

Martini, G., Manfredi, U., Rocha, M., & Marotta, A. (2012). *Review of the European test Procedure for Evaporative Emissions: Main Issues and Proposed Solutions*. Publications Office of the European Union. https://data.europa.eu/doi/10.2788/72123

Mordor Intelligence. (2025). *Europe Semiconductor Device Market Size & Share Analysis—Growth Trends And Forecast (2025—2030)*. Mordor Intelligence. https://www.mordorintelligence.com/industry-reports/europe-semiconductor-device-market

Mule, A., Deshmukh, D. S., & Shilwant, S. C. (2013). Reliable Fuel Lines Design Considerations And Validation In A Passenger Car. *International Journal of Engineering Research*, *2*(7).

NETZSCH Polymers. (2025). *NBR: Acrylonitrile-butadiene rubber*. https://polymers.netzsch.com/Materials/Details/57

NH O-RING. (2025). Compression set in O-rings [NH O-RING GmbH & Co. KG]. *NH O-RING GmbH & Co. KG*. https://nh-oring.de/en/compression-set-o-ring-lexicon/

NH O-RING GmbH & Co. KG. (2022, September 29). HNBR O-rings | Materials explained simply | Sealing Academy. *NH O-RING - Einfacher Geht´s Nicht*. https://nh-oring.de/en/hnbr-o-rings-materials-simply-explained/

NH O-RING GmbH & CO. KG. (2025). *Technical Material Data Sheet*. NH O-RING GmbH & CO. KG.

NiGen. (2021, February 23). Nitrogen Leak Testing & Pressure Testing—Why & How to Do It. *NiGen*. https://nigen.com/how-to-pressure-test-with-nitrogen-gas-leak-test-detect/

OECD. (2021). *Reconciling Terminology of the Universe of Per- and Polyfluoroalkyl Substances: Recommendations and Practical Guidance*. OECD. https://doi.org/10.1787/e458e796-en

OringsUSA. (2021). *Permeation rate—OringsUSA*. OringsUSA - O-Rings since 1958. https://www.oringsusa.com/o/permeation/

Oxoplast^{TM}. (2015). *Stability of poly(vinyl chloride)*. Grupa Azoty ZAK S.A. https://oxoplast.com/en/stability-of-polyvinyl-chloride/

Park, H., Kim, S., Choi, S., Park, J., Lee, K.-H., & Kang, S. (2025). Comparative Evaluation of PVC and PVDF Pipe Leaching in Ultrapure Water (UPW) Using Batch and Loop Pilot Systems. *KSCE Journal of Civil Engineering*, 100366. https://doi.org/10.1016/j.kscej.2025.100366

Patsnp Eureka. (2025). *GDI Engine vs PFI Engine: Fuel Efficiency Comparison*. https://eureka.patsnap.com/report-gdi-engine-vs-pfi-engine-fuel-efficiency-comparison

Plastic Design Industries, P. D. (2024, November 25). What is the FM4910 Standard? *Plastic Design Industries*. https://www.plasticdesigninc.com/blog/what-is-the-fm4910-standard/

PlasticsEurope. (2023). *Socioeconomic Impact Assessment for fluoropolymers: FPG response to the PFAS draft restriction proposal*. PlasticsEurope Fluoropolymer Products Group (FPG). https://fluoropolymers.eu/wp-content/uploads/2023/09/FPG-Socioeconomic-Impact-Assessment-fluoropolymers-EU-PFAS-restriction-proposal-for-publication-Sept-2023.pdf

Port Plastics. (2025). Polypropylene The Ultimate Value Polymer. *Port Plastics*. https://portplastics.com/blog/polypropylene-the-ultimate-value-polymer/

Precision Polymer Engineering Ltd. (2023). *Comment 4501 on PFAS restriction proposal* [Comment on PFAS restriction proposal].

PTFE Competence Center GmbH. (2025). *O-rings*. Home. https://www.ptfe-cc.de/en/products/seals/static-seals/o-rings

PwC. (2025). *Decarbonization of transport in the EU*. PwC. https://www.pwc.pl/en/publikacje/decarbonization-of-transport-in-the-eu.html#:~:text=The%20transport%20sector%20is%20the,of%20the%20EU's%20climate%20policy.

QA Group. (2025). *Differential scanning calorimetry (DSC)*. QA Group Glossary. https://www.qa-group.com/en/glossary/differential-scanning-calorimetry-dsc/

RADO Gummi GmbH. (2025a). *Acrylic rubber (ACM)*. RADO Gummi GmbH. https://www.rado-rubber.com/specialities/acm/

RADO Gummi GmbH. (2025b). *Epichlorohydrin rubber (ECO)*. RADO Gummi GmbH. https://www.rado-rubber.com/specialities/eco/

RADO Gummi GmbH. (2025c). *Ethylene acrylic rubber (AEM)*. RADO Gummi GmbH. https://www.rado-rubber.com/specialities/aem/

Rahco Rubber, Inc. (2025a). CR - Neoprene Rubber. *Rahco Rubber, Inc.* https://rahco-rubber.com/materials/cr-neoprene-rubber/

Rahco Rubber, Inc. (2025b). *EA – Vamac® Rubber*. Rahco Rubber. Rahco Rubber. https://rahco-rubber.com/materials/ea-vamac-rubber/

Rahco Rubber, Inc. (2025c). ECO - Epichlorohydrin (Hydrin) Rubber. *Rahco Rubber*. https://rahco-rubber.com/materials/eco-epichlorohydrin-hydrin-rubber/

REACH-CLP-Biozid Helpdesk, & Bundesanstalt für Arbeitsschutz und Arbeitsmedizin (BAuA). (2025). *What you need to know about the updated PFAS restriction dossier*. https://www.reach-clp-biozid-helpdesk.de/SharedDocs/Downloads/DE/REACH/Verfahren/Beschr%C3%A4nkung/PFAS_Dokument_Hintergrund.pdf?__blob=publicationFile&v=2

Regulation (EU) 2018/858 of the European Parliament and of the Council of 30 May 2018 on the Approval and Market Surveillance of Motor Vehicles and Their Trailers, and of Systems, Components and Separate Technical Units Intended for Such Vehicles, Amending

Regulations (EC) No 715/2007 and (EC) No 595/2009 and Repealing Directive 2007/46/EC (2018). http://data.europa.eu/eli/reg/2018/858/oj

Regulation (EU) 2019/631 of the European Parliament and of the Council of 17 April 2019 Setting CO2 Emission Performance Standards for New Passenger Cars and for New Light Commercial Vehicles, and Repealing Regulations (EC) No 443/2009 and (EU) No 510/2011, 13 (2019). http://data.europa.eu/eli/reg/2019/631/oj

REIFF Technische Produkte GmbH. (2025). *Technisches Wissen*. https://www.reiff-tp.de/technisches-wissen.html

ReportLinker. (2024). *Transportation Market Outlook 2024—2028*. ReportLinker. https://www.reportlinker.com/clp/global/6307

Reports and Data. (2025). *Fluoropolymers for Semiconductors Market* [Market Report]. Reports And Data. https://www.reportsanddata.com/report-detail/fluoropolymers-for-semiconductors-market

Richter, B. (2014). Evaluation of Stability Tests for Elastomeric Materials and Seals. *International Polymer Science and Technology*, *41*(5), 1–6. https://doi.org/10.1177/0307174X1404100501

Robert (R.) Lee. (2025). Engineering Plastics: Properties, Types and Uses. *DEK*. https://www.dekmake.com/engineering-plastics/#:~:text=Engineering%20plastics%20are%20special%20types%20of%20plastics%20made,parts.%20Engineering%20plastics%20work%20well%20in%20demanding%20environments.

Rogers Corporation. (2025). *Stress Relaxation and Why Its Important in Elastomeric Seals*. https://rogerscorp.com/blog/2025/stress-relaxation-and-why-its-important-in-elastomeric-seals

Rubber & Seal. (2025). How Much Pressure Can an O-ring Withstand? *Https://Rubberandseal.Com/*. https://rubberandseal.com/how-much-pressure-can-an-o-ring-withstand/

SEMI. (2016). *BACKGROUND STATEMENT FOR SEMI DRAFT DOCUMENT #5944 REVISION TO SEMI F63-0213, GUIDE FOR ULTRAPURE WATER USED IN SEMICONDUCTOR PROCESSING*. https://downloads.semi.org/web/wstdsbal.nsf/0/cd6f11dd4bf7b80088257f320070d637/$FILE/5944.pdf

SEMI. (2019). *SEMI F57-0120 SPECIFICATION FOR HIGH PURITY POLYMER MATERIALS AND COMPONENTS USED IN ULTRAPURE WATER AND LIQUID CHEMICAL DISTRIBUTION SYSTEMS*.

SEMI. (2023). *PFAS-Containing Articles Used in Semiconductor Manufacturing*. Semiconductor PFAS Consortium Articles Working Group.

Shinobu Kanbe, Masashi Kondo, & Motohide Nishimura. (2004). *Fuel hose* (Patent No. EP 1 096 190 B1). https://patentimages.storage.googleapis.com/b7/23/0b/883c78ec81edfe/EP1096190B1.pdf

SkyQuest Technology. (2024). *Gloal Fluoropolymers Market*. SkyQuest Technology. https://www.skyquestt.com/report/fluoropolymers-market

Solvay. (2014). *Tecnoflon® FKM Peroxide-Curable Fluoroelastomers for Improved Sealing and Processability*. Solvay Speciality Polymers.

SOLVAY. (2018). *High-Performance-Polymers-for-Semicon_EN* (High-Performance Polymers for the Semiconductor and Electronics Industry). https://www.solvay.com/sites/g/files/srpend616/files/2018-10/High-Performance-Polymers-for-Semicon_EN-v2.0_0.pdf

Spears Manufacturing Company. (2025). *Low Extractable Technical: Technical Information & Testing*. Spears Manufacturing Company. https://parts.spearsmfg.com/sourcebook/LXTECH_LX-2_T_TECH_INFO_T.pdf

Steve Ranger. (2025). *PFAS: Europe updates its proposals for restricting 'forever chemicals'*. SCI. https://www.soci.org/news/2025/8/europe-updates-its-pfas-restriction-proposal?utm_source=chatgpt.com

Syensqo. (2026a). *KetaSpire® PEEK - Applications*. Syensqo. https://www.syensqo.com/en/brands/ketaspire-peek/applications

Syensqo. (2026b). *KetaSpire® PEEK - Properties*. Syensqo. https://www.syensqo.com/en/brands/ketaspire-peek/properties

Teesing. (2025). *All about fluoropolymers*. Teesing. https://teesing.com/en/library/publications/clean-gases-fuel-the-semiconductor-production

Thomas Delille, Gerard McElwee, Peter Sellar, Valerio Giovannini, & Marie Escorneboueu. (2025, August 22). *Update on EU PFAS Restriction Proposal – Key Developments and Implications for Businesses*. Sustainability in Business. https://www.sustainabilityinbusiness.blog/2025/08/update-on-eu-pfas-restriction-proposal-key-developments-and-implications-for-businesses/

Ti Insight. (2024). *European Road Freight Transport Market Forecasts: 2024&2025*. Ti Insight. https://ti-insight.com/wp-content/uploads/2024/12/Mid-Year-ERFT-Market-Forecasts-for-2024-2025-whitepaper.pdf

Transport & Environment. (2024). *The state of European transport 2024: An overview of the EU's largest climate problem*. Transport & Environment. https://www.transportenvironment.org/articles/the-state-of-european-transport-2024

Trelleborg Sealing Solutions. (2012). *Materials Chemical Compatibility Guide*.

UIC, & UIRR. (2024). *2024 Report on Combined Transport in Europe*.

Universal Technical Institute. (2024). *How Direct Injection Engines Work*. UTI Corporate. https://www.uti.edu/blog/automotive/what-are-direct-injection-engines

VICTREX. (2024). Unlocking the Potential of Victrex PEEK in Semiconductor Manufacturing. *Silicon Saxony*. https://silicon-saxony.de/unlocking-the-potential-of-victrex-peek-in-semiconductor-manufacturing/

Weltschev, M., Heming, F., Haufe, M., & Heyer, M. (2015). Compatibility of Sealing Materials with Biofuels and Biodiesel-heating Oil Blends. *CORROSION 2015*, 1–13. https://doi.org/10.5006/C2015-05535

Yahia, M. (2016). *Effect of demineralized water on carbon steel and stainless steel* [Unpublished]. https://doi.org/10.13140/RG.2.2.22719.71845

YUWEI. (2021a). *PEEK extruded pipe-Nanjing Yuwei New Material Co., Ltd.* https://www.njywpeek.com/en/product/productinfo/106.html

YUWEI. (2021b). *PEEK is used in electrical and electronic-Nanjing Yuwei New Material Co., Ltd.* https://www.njywpeek.com/en/application/application/13.html

Zeon Chemicals L.P. (2025). *Hydrin® ECO (Epichlorohydrin-Elastomers)*. Zeon Chemicals. https://www.zeonchemicals.com/products/hydrin-eco/

Zeon Corporation. (2025). *ECO (Epichlorohydrin Rubber)*. Zeon Mobility Solutions. Mobility Solutions Website. https://www.zeon-solutions.com/en/products/eco/

Annex I Search Terms

General search term

(fluoropolymer* OR ectfe OR fep OR pfa OR ptfe OR pvdf OR pctfe OR ptfce OR pfpe OR etfe OR ffkm OR ffpm OR fkm OR fpm OR (pfas AND polymer*)) AND (alternative* OR replacement)

Excluded: "Pharmacology, Toxicology and Pharmaceutics", "Medicine", "Biochemistry, Genetics and Molecular Biology", "Immunology and Microbiology", "Psychology", "Neuroscience", "Veterinary", "Nursing", "Dentistry", "Health Professions"

Scopus: 1210 Hits (2020-2025) (search conducted on 16.06.2025)

Cables and wiring

("fluorine-free" OR "PFAS-free" OR (PFAS OR PFTE OR polytetrafluoroethylene OR FEP OR "Fluorinated Ethylene Propylene" OR ETFE OR "Ethylene Tetrafluoroethylene" OR PFA OR Perfluoroalkoxy OR fluoropolymer* OR (pfas AND polymer*)) AND alternative)

AND (cable* OR wiring OR insulation OR airplane OR thermoplastic* OR elastomer* OR insulation OR "high-voltage")

Scopus: 88 Hits (2010-2025) (14.07.2025)

Sealing systems

("fluorine-free" OR "PFAS-free" OR (FKM OR fluoroelastomer* OR THV OR "Tetrafluoroethylene-Hexafluoropropylene-Vinylidene fluoride" OR ETFE OR "Ethylene Tetrafluoroethylene" OR PTFE OR "Polytetrafluoroethylene" OR fluoropolymer* OR (pfas AND polymer*)) AND alternative)

AND (engine OR "O-ring" OR "fuel injector" OR leakage OR sealing OR "friction plates" OR seals OR bearing*)

Scopus: 119 Hits (2010-2025) (14.07.2025)

Hoses and liners

("fluorine-free" OR "PFAS-free" OR (FKM OR fluoroelastomer* OR THV OR "Tetrafluoroethylene-Hexafluoropropylene-Vinylidene fluoride" OR FTPV OR "Fluorothermoplastic Vulcanizate" OR PTFE OR "Polytetrafluoroethylene" OR TFE OR "Tetrafluoroethylene" OR fluoropolymer* OR (pfas AND polymer*)) AND alternative)

AND (hoses OR liners OR ABS OR "Anti block systems" OR tube* OR "brake lines" OR coolant OR "Anti-corrosive liners")

Scopus: 76 Hits (2010-2025) (14.07.2025)

Batteries

("fluorine-free" OR "PFAS-free" OR (PVDF OR "Polyvinylidene Fluoride" OR PTFE OR polytetrafluoroethylene OR fluoropolymer* OR (pfas AND polymer*)) AND alternative) AND

(battery OR batteries OR binder OR "electric vehicle" OR gaskets OR "lithium-ion")

Scopus: 335 Hits (2010-2025) (14.07.2025)

Cables and wiring

(“fluorine-free” OR “PFAS-free” OR (PTFE OR polytetrafluoroethylene OR FEP OR “Fluorinated Ethylene Propylene” OR PFPE OR Perfluoropolyether OR fluoropolymer* OR (pfas AND polymer*)) AND alternative)

AND (cable* OR wiring OR “data centre” OR computing OR insulation OR “silicone-based” OR electrical)

Scopus: 92 Hits (2010-2025) (14.07.2025)

Semiconductor Manufacturing – UPW Water

(“fluorine-free” OR “PFAS-free” OR (PTFE OR polytetrafluoroethylene OR PFA OR Perfluoroalkoxy OR FEP OR “Fluorinated Ethylene Propylene” OR ETFE OR “Ethylene Tetrafluoroethylene” OR PVDF OR “Polyvinylidene Fluoride” OR FFKM OR “Perfluoroelastomer” OR fluoropolymer* OR (pfas AND polymer*)) AND alternative)

AND (“ultra-pure water” OR fitting* OR piping OR rinsing OR cleaning OR (semiconductor* AND manufacturing) OR etching OR wafer OR hoses OR tubes OR CMP OR “Chemical Mechanical Polishing” OR UPW OR SMRE OR “Semiconductor manufacturing and related equipment”)

Scopus: 198 Hits (2010-2025) (14.07.2025)

Semiconductor Manufacturing – Components

(“fluorine-free” OR “PFAS-free” OR (PTFE OR polytetrafluoroethylene OR PFA OR Perfluoroalkoxy OR FEP OR “Fluorinated Ethylene Propylene” OR ETFE OR “Ethylene Tetrafluoroethylene” OR PVDF OR “Polyvinylidene Fluoride” OR FFKM OR “Perfluoroelastomer” OR fluoropolymer* OR (pfas AND polymer*)) AND alternative)

AND (semiconductor OR valve* OR fitting* OR liner* OR tray* OR pump OR lithography OR tubing OR hoses OR stereolithography OR Photolithography OR chip OR “delivery system*” OR SMRE OR “Semiconductor manufacturing and related equipment”)

Scopus: 276 Hits (2010-2025) (14.07.2025)

Electronic components

(“fluorine-free” OR “PFAS-free” OR (PTFE OR polytetrafluoroethylene OR PVDF OR “Polyvinylidene Fluoride” OR fluoropolymer* OR (pfas AND polymer*)) AND alternative)

AND (laminate* OR “electronic component*” OR “high-frequency” OR “high-speed” OR radar OR telecommunication OR “printed circuit board*” OR PCB* OR capacitor* OR wafer OR Photolithography OR “wire insulation” OR automotive)

Scopus: 161 Hits (2010-2025) (14.07.2025)

Annex II List of Downstream User Associations

Transport Associations

- European Automobile Manufacturers’ Association (ACEA)
- European Association of Motorcycle Manufacturers (ACEM)
- European Aerospace, Security and Defence (ASD)
- European Agricultural Machinery (CEMA)
- European Association of Automotive Suppliers (CLEPA)
- European Tyre & Rubber Manufacturers Association (ETRMA)
- European Association of Internal Combustion Engine Manufacturers (EUROMOT)
- The Shipyards' & Maritime Equipment Association of Europe (SEA Europe)
- Association of the European Rail Supply Industry (UNIFE)
- German Association of the Automotive Industry (VDA)

Electronics & Semiconductor Associations

- DIGITAL Europe
- European Electronic Component Manufacturers' Association (EECA) (part ESIA)
- European Semiconductor Industry Association (ESIA)
- European Data Centre Association (EUDCA)
- Association Connecting Electronics Industries (IPC)
- Europe's Technology Industries (Orgalim)
- European Association of the Advanced Rechargeable & Lithium Batteries Value Chain (RECHARGE)
- Association serving the manufacturing supply chain for the micro- and nano-electronics industries (SEMI)
- German Electrical and Electronic Manufacturers' Association (ZVEI e.V.)